TROUBLESHOOTING
ROTATING MACHINERY

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Troubleshooting Rotating Machinery

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Troubleshooting Rotating Machinery

Including Centrifugal Pumps and Compressors, Reciprocating Pumps and Compressors, Fans, Steam Turbines, Electric Motors, and More

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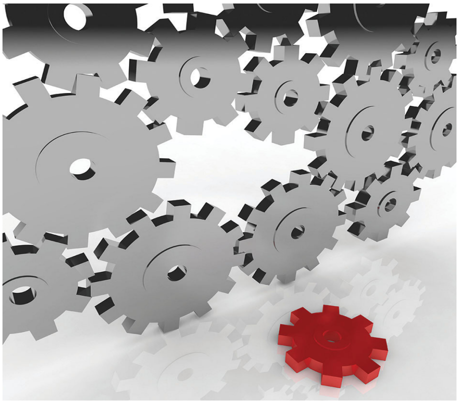
Preface



Troubleshooting is part science and part art. Simple troubleshooting tables or decision trees are rarely effective in solving complex, real-world machine problems. For this reason, the authors wanted to offer a novel way to attack machinery issues that can adversely affect the reliability and efficiency of your plant processes. The methodology presented in this book is not a rigid "cookbook" approach but rather a flexible and dynamic process aimed at exploring process plant machines holistically in order to understand and narrow down the true nature of the problem. Throughout this book, the term *process machinery* will be used to refer to rotating machinery commonly encountered in processing plants, such as centrifugal pumps and compressors, reciprocating pumps and compressors, fans, steam turbines, and electric motors.

Our first book in this series, *Is My Machine OK?* deals, in large part, with assessing process machinery in the field. This guide takes the assessment process to the next level by helping operators, mechanics, managers, and machinery professionals better troubleshoot process machinery *in-situ*, i.e., in the field. To cover the topic of troubleshooting, the authors will cover the following topics in this book:

- What field troubleshooting means and entails
- How to use this guide as a complement to *Is My Machine OK?*
- Using the "who, what, when, where, why" troubleshooting methodology
- How to use cause maps to investigate possible causes
- Real-world case studies
- How to use machine-specific troubleshooting tables

To be successful, the troubleshooter must be persistent, open-minded and disciplined. Once field data is collected, an unbiased, logical approach to the finding is required to hone in on the most probable source of an observed symptom (or symptoms). Without a comprehensive and logical analysis of the findings, the investigator is only guessing, which wastes valuable time and resources. We hope those reading and using this guide will fully utilize the ideas and concepts presented to minimize maintenance cost and risk levels associated with machinery ownership.

Robert X. Perez and Andy P. Conkey

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1

Troubleshooting for Fun and Profit

Process machines are critical to the profitability of processes. Safe, efficient and reliable machines are required to maintain dependable manufacturing processes that can create saleable, on-spec product on time, and at the desired production rate. As the wards of process machinery, we wish to keep our equipment in serviceable condition.

One of the most challenging aspects of a machinery professional or operator's job is deciding whether an operating machine should be shut down due to a perceived problem or be allowed to keep operating and at what level of operation. If he or she wrongly recommends a repair be conducted, the remaining useful machine life is wasted, but if he or she is right, they can save the organization from severe consequences, such as product releases, fires, costly secondary machine damage, etc. This economic balancing act is at the heart of all machinery assessments.

The primary purpose of this guide is to help operators and machinery professionals troubleshoot machines that are in a process service and operating at design process conditions. The reader may ask: What is the difference between field troubleshooting and other analysis methods such as a root cause analysis, failure analysis, and a root cause failure analysis?

Consider the following definitions:

Field troubleshooting is a process of determining the cause of an apparent machine problem, i.e., symptom, while it is still operating at actual process conditions. Troubleshooting efforts tend to focus on a specific machine or subsystem, using a proven body of historical knowledge. The body of knowledge may be in the form of troubleshooting tables and matrices or manufacturer's information. Keep in mind that process machinery can only truly be tested and evaluated in service and under full load, i.e., *in-situ*. Very few testing facilities are available that can test a pump or compressor at full process loads and with actual process fluids. Field troubleshooting evaluates the mechanical integrity of a machine in process service in order to determine if symptoms are the result of an actual machine fault or a process-related problem.

Here are examples of troubleshooting opportunities:

Example #1: Pump flow has fallen well below its rated level.

Example #2: Compressor thrust bearing is running 20 °F hotter than it was last month.

Root cause analysis (RCA) is a broad analysis of a system made up of multiple components or subsystems or an organization made up of multiple processes. These complex systems may not have any historical failure information to reference and are not well understood. The overall complexity may require that the overall system be broken down and analyzed separately. Here are two examples of RCA opportunities:

Example #1: The finished product from a process unit went out of spec.

Example #2: Plant XYZ safety incidents for the month of May have doubled when compared to last year's total.

One distinction between RCA approaches and troubleshooting is that RCAs tend to address larger problems that often require a team approach, while troubleshooting can normally be conducted by a single individual. As a general rule, maintenance and operations personnel normally participate more in troubleshooting activities than in root cause analysis activities due to the very nature of their jobs.

Failure analysis is the process of collecting and analyzing physical data to determine the cause of a failure. Physical causes of failure include corrosion, bearing fatigue, shaft fatigue, etc. Failure analyses can only be conducted after a component failure. A failure is defined as a condition when a component's operating state falls outside its intended design range and is no longer able to safely, or efficiently, perform its intended duty.

Root cause failure analysis (RCFA) methodology attempts to solve complex problems by attempting to identify and correct their root causes, as opposed to simply addressing their symptoms. The RCFA methodology allows an organization to dig deeper into a failure or series of failures in order to uncover latent issues.

To further clarify the differences between these analysis approaches, we recommend the following line of questioning:

1. The field troubleshooter must first ask: Do I fully understand the machine or subsystem that needs to be analyzed? If the complexity is beyond the troubleshooter's abilities, he or she should get help. At this point, management may decide to conduct an RCA analysis.
2. If the field troubleshooter decides to tackle the problem at hand, he or she should then ask: "Are the observed symptoms caused by a failing machine, a correctable fault, or by undesirable process conditions?" If it is a process-related problem, changes can be made before permanent machine damage occurs. If a fault is deemed to be correctable, then adjustments or minor repairs can be made in order to quickly

restore the machine to serviceable conditions.

If the machine fails, either a failure analysis or root cause failure analysis must be performed, depending on the extent and cost of the failure. The failure analyst asks different types of questions depending on the level of detail desired:

1. The failure analyst asks the question: "What is the physical mechanism, or sequence of events, that caused a given component to fail?" If the failure mechanism is clearly understood, perhaps design or procedural changes may be implemented to avert future failures.
2. The root cause failure analyst asks the question: "Are there hidden factors, such as unknown design, repair, operational, and other organizational issues, contributing to the observed machine problems?" If there are latent factors suspected but unidentified, perhaps an inter-disciplinary team can identify key factor or factors and address them to avert future failures.

All these approaches do have some common elements in their respective processes, and the information identified in one can be utilized in the other approaches. These are not necessarily competing activities, but are mutually supportive activities.

Figure 1.1 shows a simple decision tree that can be used to address machinery field problems. (Note: The RCA option is not considered in this

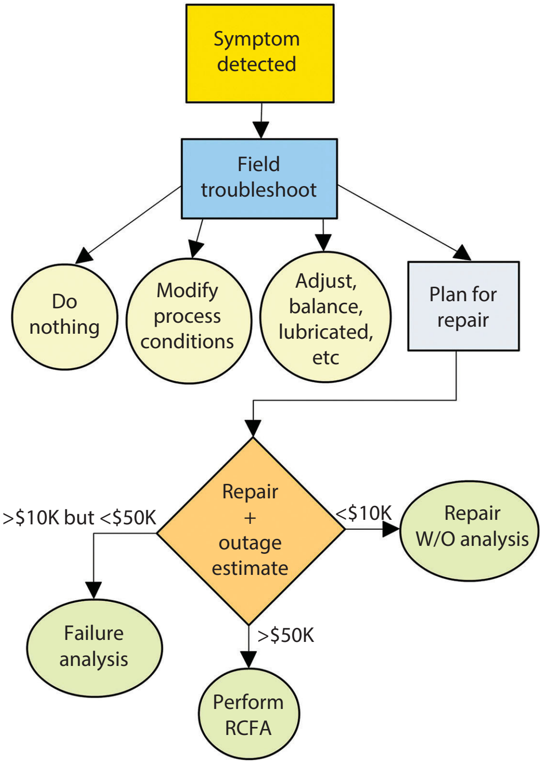

Figure 1.1 Troubleshooting Decision Tree.
Note: The dollar amounts shown here are based on the experiences of the authors. Each site may have its own trigger levels for repair costs. It goes without saying that these trigger levels need to be periodically modified for inflation.

chart because we have assumed the problem is confined to a specific machine and is within the troubleshooter's level of ability.) The troubleshooter begins at the top of the tree when a symptom is first detected. At this point, the troubleshooter assesses the situation and then picks one of the possible path forwards:

1. Do nothing
2. Modify process conditions
3. Adjust machine, i.e., balance, align, or lubricate machine as required
4. Plan to repair

If a repair is deemed necessary, the maintenance organization should then estimate the repair and outage costs. If the total cost (parts and labor) of the failure is less than $10,000, then a repair should be performed without any additional type of analysis. If the total cost of repair is estimated to be greater than $10,000 but less than $50,000, a failure analyses should be conducted on the failed parts in order to understand the nature of the failure. Finally, if the total cost of failure is greater than $50,000, then a root cause failure analysis is justified and should be executed.

The reader should note that the decision tree presented here is only one of many possible tools that can be used to address machinery field problems. Each organization can and should develop its own customized decision tree to satisfy its needs. For example, the cost breakpoints used in this example can be customized to satisfy your organization's process and management goals.

The decision tree in Figure 1.1 clearly illustrates that all machine decisions usually begin with some sort of field troubleshooting or assessment effort. Field troubleshooting can therefore be considered a type of "gatekeeping" step for deciding which machines need to be repaired. If performed diligently and correctly, field troubleshooting can eliminate unnecessary machinery repairs and improve the overall site profitability and operating efficiency.

In the remainder of this book, we will concentrate on explaining a novel field troubleshooting method to those on the front lines and in the position to gather key performance and operating data. By acting quickly, perhaps the underlying problem can be identified, corrected, and the machine may be returned to normal operation in a timely manner. The reader should always keep in mind that field troubleshooting may be the first step in a series of analysis steps if machine conditions continue to deteriorate. This could also be the introduction to the two other analysis methods previously mentioned.

1.1 Why Troubleshoot?

Why should organizations care about field troubleshooting? You might ask: “Isn’t that why we have a maintenance department, so they can repair machines that are acting up?” The problem is that not all machines that act up have failed; they may simply be reacting to some external change. Distinguishing between a machine that is just acting up versus one that has failed or is failing is the goal of a troubleshooter.

Let’s consider this simple example: A pump bypass line was inadvertently left open after a start-up. This condition leads to a low forward flow condition. If the pump is overhauled, the same result will be seen, resulting in wasted maintenance dollars and frustration. If a diligent operator would have found the open bypass valve while troubleshooting, it would have been a very rewarding discovery. The subsequent accolades from management would have boosted the operator's ego and spurred others to seek future troubleshooting opportunities.

While troubleshooting can be very rewarding and even fun at times, the main reason to consistently utilize a troubleshooting methodology is to add value to the organization. It has been demonstrated that a successful troubleshooting program can reduce machinery repair cost up to 20%. The savings come from:

- Keeping equipment in service that are serviceable and eliminating needless repairs
- Recommending required adjustments, such as balancing, before permanent damage occurs
- Uncovering latent plant issues, such as fouling, flow blockage, etc.
- Judiciously delaying repairs in order to properly plan work and get critical spare parts in stock before serious internal damage occurs

In a nutshell, troubleshooting allows maintenance and operating departments to better manage plant resources by maximizing the run lengths of machines, while avoiding major risks and consequences.

To realize the full benefits of field troubleshooting, all participants must possess adequate machinery experience and knowledge, be properly trained, and approach field problems wholeheartedly and with an open mind. What does being open-minded mean? An open mind means all participants have:

- No preconceived idea to what the problems or solutions are
- No hidden agendas
- Willing to listen to everyone's input

Participants with preconceived ideas are often doomed to failure because they are blinded to vital clues as to what's really going on. Their nearsightedness will result in a big waste of time and resources. Furthermore, troubleshooting participants with hidden agendas are not being fair or honest to their organizations. Those that believe they are unable to investigate a problem faithfully, fairly, and with an open mind should let someone else in the organization investigate the problem.

1.2 Traits of a Successful Troubleshooter

We probably all know someone that is especially skilled at getting to the root of a problem. Instead of simply changing parts out or "shooting from the hip," the skilled troubleshooter, weighs all the available field information and judiciously selects the optimal path forward. The correct decision may mean a simple adjustment, and sometimes a full-blown repair is in order. More often than not, successful troubleshooters identify and solve problems—they just don't change parts! That is, they target the problem, not the symptom.

Questions that arise in critiquing the success of a diligent troubleshooter are:

- What are the attributes that make a good troubleshooter?
- Does experience make a good troubleshooter?
- Does machine knowledge make a good troubleshooter?

It has been said that discovery comes to the prepared mind. We would like to build on this adage. We propose that for a troubleshooter to be successful they must have:

1. A prepared mind
2. An open mind
3. A flexible mind
4. Confidence in problem solving

Prepared mind: The successful troubleshooter regularly studies to develop a working knowledge of machinery technology. It is impossible to troubleshoot machines without having a firm grasp on their inner workings as well as an understanding of their function. Self-study, seminars, trade magazines, webinars, online forums, and mentors can all help you master complex process machinery.

Open mind: The open-minded troubleshooter only follows actual clues that are uncovered during an investigation and ignores hunches or theories that are baseless. Such troubleshooters try not to have preconceived ideas when approaching a problem for the first time. They don't assume that a machine is always going to fail a certain way or that all operators don't understand machinery. Fact-driven investigations tend to be more successful than investigations fueled by preconceived notions.

There was a machinery engineer who would always jump to conclusions. This particular engineer loved to play the blame game. He would either blame the operators or the last mechanics that repaired the machine. This close-minded approach to troubleshooting rarely bears fruit. This particular machinery engineer never realized his full potential as a troubleshooter. Everyone soon realized his troubleshooting abilities were limited by his close-mindedness. Eventually no one trusted him to solve the more challenging problems in the plant.

Flexible mind: In days past, it was easier for individuals to become conversant in many facets of plant operations. Today, we all tend to become specialized as we progress through our careers.

Try not to focus only on your area of expertise. (When you have a hammer, everything looks like a nail.) We should view our processes holistically, i.e., composed of numerous elements that interact with one another. Ask others for their opinion. They may provide a different view of the problem that could be vital to finding the true cause of the problem.

There was a time when technological changes in systems were usually gradual and not too radical. In contrast, today we are exposed to a dizzying barrage of incremental advances in manufacturing, materials, controls, and so forth. We are forced to either make a conscious effort to keep abreast of the new technological advances and understand how these advances affect our business or fall behind the knowledge curve. Those who make the effort to stay current in pertinent technologies will reap the rewards, i.e., better pay, advancements, and the enjoyment of a job done well. Those who fall behind due to conscious decision or indifference will eventually get left behind and replaced.

Years ago, a chess tournament director stated that he noticed that the better chess players, that is, the players that did the best in chess tournaments, seemed to use more clock than the others. Chess players that use “more clock” are taking more time to think about their moves. This suggests that those chess players that thought more about their moves probably discovered better moves than their opponents, which led to wins. Similarly, troubleshooters that think longer and deeper about the problem at hand have a better chance at uncovering the true nature of the problem.

Confidence in your abilities: With study, practice, and the occasional success comes confidence. Troubleshooters should keep score on their successes. It doesn't matter how much analysis is done or how many plausible theories you generate; if the problem is not solved, you have failed. Be honest about your successes and failures. With failure comes humility and new insights. With success comes recognition and confidence.

There is no perfect troubleshooter. Every engineer, technical specialist, operator, etc., has shortcomings. We have to hope that by learning a little more every day we can become capable problem solvers and more efficient troubleshooters. It's the challenge of the next problem that should keep us all studying.

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2

An Insight in Design: Machines and Their Components Serve a Function

Machines are put into service to serve a function. That is, they are there to do something, or perform an action. The majority of the machines installed in processing facilities are there to alter the energy of a fluid in the process stream. This is done by either pushing a fluid (liquid or gas) through the piping or by altering the thermodynamic properties of the fluid for a downstream process. The balance of the machinery in process facilities is there to provide power, such as motors, steam turbines and gas turbines.

A well-behaved process machine safely and efficiently converts some type of input energy into fluid energy at the proper flow and pressure that is required by the process. Degraded or malfunctioning process machines waste energy by converting some of the power into vibration, heat, and noise (see Figure 2.1). Fluid movers can waste additional power by converting input power into pressure pulsations and unwanted internal leakage. Heat, vibration, noise, pulsation, and leakage are sensible, or measureable, signs of inefficiency or distress that provide clues to the overall health of machines. Although all machines will exhibit these losses to some degree, it is the condition of excessive losses that would raise concern and merit a troubleshooter's skill to assess the situation.

Machines are systems that are composed of multiple elements that work together to perform

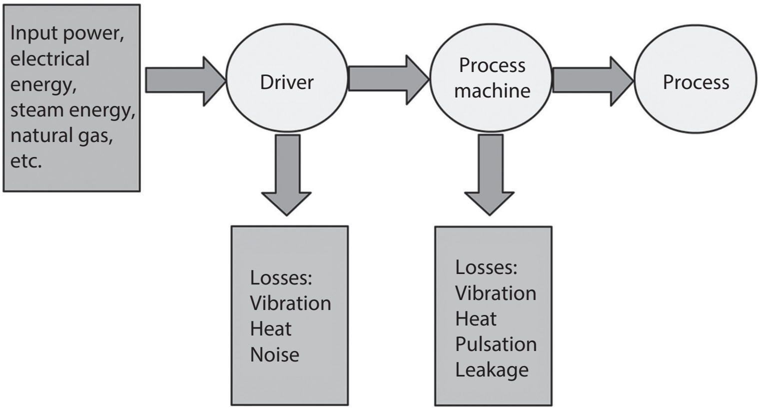

Figure 2.1 Machine energy losses.

a specific function. The manner in which these elements interact dictate how well the machine can perform its intended function. In troubleshooting a system it is necessary to be able to understand all the roles of all the working elements that make up the system so that they can be properly accounted for.

A list of the primary mechanical system elements are as follows:

a. Input energy source – The primary energy source (electrical, steam, or fluid energy) used to power a machine.
b. Primary energy converter (commonly referred to as a driver) – The primary element that is used to convert electrical, steam, or fluid power into rotational or linear power.
c. Output energy – The output energy of the machine that is transmitted via a shaft or other type of mechanical linkage, which is what a machine is intended to do.
d. Moving elements – Any internal element that moves relative to the housing or another part (shafts, cranks, pistons) in order to capture, create, or transfer mechanical energy.

e. Bearings – Elements that support rotating or moving machine parts. Bearings provide support, reduce friction, and provide protection from internal rubbing.
f. Seals – Critical elements that prevent/ minimize the migration of the fluids into the atmosphere or prevent leakage between machine sections. Internal seals can be used to increase fluid pumping efficiency.
g. Conduits – A means of transmitting fluid, steam, or electrical energy from one point in a process to another point in the process, i.e., piping, electrical lines, hydraulic tubing, hoses, etc.
h. Housing – A machine subsystem specially designed to protect moving parts, such as bearings, seals, etc., from the process medium.
i. Foundation – Any rigid structure designed to support a machine and connect it to the ground.
j. Performance monitoring subsystems – Sensor and associated monitoring systems used to measure and display critical machinery condition parameters, such as vibration, temperatures, shaft positions, pressures, etc.

k. Interfaces – Any point of interest where any of the items listed above interact with each other. Example: Process piping typically connects to the machine casing through a flange. The point where the pipe and machine nozzle meet is one type of interface. Improper alignment between a machine nozzle and the pipe can create an over-stress condition on the pipe as well as on the machine casing, which, if not corrected, can lead to machine problems and in some cases to machine failures. A leaky flange can be a good indication of poor connection between the components. Other examples of interfaces are bearings, seals, impellers, pistons, etc.

The primary function of a centrifugal pump is to add energy to a fluid so that it can either reach its next destination, or to change the state of the fluid for a particular process such as going through a boiler in a steam cycle. To change the state, namely the pressure, the components of the pump need to act and conduct their respective tasks successfully. Bottom line, the pump and the various components that make up the pumping system provide a function that essentially describes an action. That is, they are expected to *do something*. If a part/component/system cannot satisfactorily perform its intended function, then the performance of the system will be in jeopardy, or be deemed to have "failed". Knowing the functions of the various components that make up a system can facilitate the troubleshooting process.

One element in design is to address what functions a design, or system, is to perform. Functions are action items that are described using a verb. Performance criteria can then be established from these functions. Think about a pump as to what it is to do. A pump is needed to increase the pressure of the process stream. The function of the pump is to *increase pressure*. A performance criterion could be that it needs to increase the pressure by 100 psi. Additional parameters, such as fluid density, flow rate, temperature, could be defined as well.

To further the discussion on functions, we'll take a look at the primary components one would find in a pump and some common functions and how they relate to those components. First, some of the primary components of a pump are

- Impeller
- Shaft
- Housing
- Bearings
- Seals

Table 2.1 Common functions or actions.

Increase	Stop	Protect	Guide
Decrease	Start	Contain	Align
Alter	Accelerate	Restrain	Transmit
Transition	Decelerate	Prevent	Connect

Next, a table of common functions is presented.

Table 2.1 is not a complete list but it does provide an idea of how to identify or state functions. It is important to note that some components may actually facilitate more than one function.

Table 2.2 breaks down the key components of the pump and applies these functions.

Understanding the role that the different elements play in a machine and how their malfunction can lead to machine performance issues is essential in the troubleshooting process. As an example, consider the critical elements inside a centrifugal pump: The pump impeller (see Figure 2.2) is the primary component that changes the energy state of the fluid. If the impeller is not properly mounted onto the shaft (an interface) then the vanes on the impeller won't efficiently transfer energy to the fluid. If the impeller is cocked on the shaft this can also introduce force imbalances that can create vibrations and even cavitation.

Table 2.2 Functions of some components in a pump.

Component	**Function**	**Description**	**Loss of Function**
Pump	**Change** energy state of the fluid	The pressure of the fluid is increased. Velocity changes are related to outlet piping size.	Reduced pressure.
Impeller	**Transfer** shaft energy to fluid	Configuration of the vanes on the impeller is such that rotational motion of the impeller increases the energy state of the fluid.	Vane dimensions change.
Shaft	**Support** the impeller (if not integral)	Proper installation to make sure that impeller stays put and not only that torque is transferred, but impeller loads are transferred too.	Improper fit can result in vibrations, wear, impacts.

	Align the impeller	Proper placement on the shaft will insure that proper gaps are maintained to minimize losses	Improper alignment can result in improper gaps and loss of performance, cavitation, force imbalance loads.
	Transfer work from power source (coupling inferred)	A pump will be driven by a primary power source and the power will be transferred through a coupling.	Coupling issues can result in vibrations, heat formation, excessive shaft loads.
	Resist/counter interaction loads	As the fluid interacts with the impeller, various loads will be acting on the impeller. The shaft needs to be able to resist these loads without deflecting out of specs.	Too much deflection of the shaft can result in gap clearances to change, wear/rubbing issues, etc.

(*Continued*)

Table 2.1 Cont.

Component	Function	Description	Loss of Function
Housing	**Contain** fluid	Keeping all of the process fluid with the housing is important from a safety, environmental, and efficiency standpoint.	Leakage
	Divert flow	Fluid needs to be guided through the pump to minimize losses and to allow it to enter and exit efficiently.	Recirculation of fluid due to bad cut-waters, improper gaps.
	Support bearings	Need to insure that the bearings are properly supported.	A loose bearing or a too tight bearing will ultimate result in undesirable loads on the bearings, vibrations, and possible heating.

	<u>Anchor</u> to base/ platform	Eventually, all the loads need to be transferred to ground. Proper bolting loads are important.	Loose foot will allow pump to move.
	<u>Connect</u> to inlet and outlet piping	Transfer of the fluid into and out of the pump needs to be done so that minimal strain is transferred across the flanges.	
Bearings	**<u>Support</u>** shaft		
	<u>Reduce</u> rotational friction		
Seals	**<u>Prevent</u>** leakage of fluid		

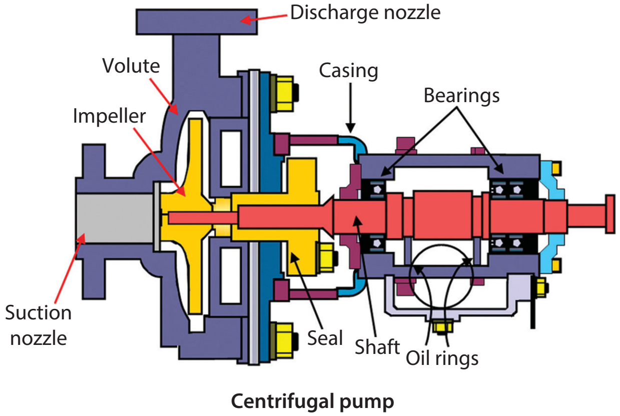

Figure 2.2 Centrifugal pump internal components.

The shaft provides multiple functions. The shaft provides support, alignment, and a means to transfer energy from the coupling to the impeller. The bearings provide support to the shaft. The pump housing provides a means to protect the parts, contain the fluid, and support the internal parts. The pump designer designs all the components to work in synergy so that the whole machine operates reliably and within required performance specifications.

2.1 An Overview of the Design Process

Designers of process machinery hope to create economical designs that can perform specific functions in process environments, such as pumping liquids or compressing gases, hopefully, for years between overhauls. They start by using various fluid performance prediction tools, test stand data, or past designs to obtain a fluid-end design that will deliver acceptable performance. The fluid-end design must be capable of providing the required flows and pressures with minimal losses and with low vibration and pulsation levels.

The transfer of fluid energy typically requires a number of multiple moving parts to interact. Multiple internal moving parts result in various loads applied to the rotating and stationary parts. These parts must be analyzed to ensure they won't fail under expected operating conditions. In addition, any secondary stationary elements subjected to operating loads, such as stationary braces or bolts, must be analyzed as well. The loads that are generated on an element can push (compress), pull, bend, and twist on the part. These loads can be static (do not vary over time) and others are dynamic (vary over time). Dynamic loads can be impacts-type loading (very short duration), cyclical (vary periodically over time), or transient such as those that occur when a machine starts up. It is possible to have a combination of static and dynamic loads as well, that is, a part is subjected to a static load, but also has a time varying load superimposed on it. An example of a combination-type load would be the bolts securing a flange. The bolts are statically loaded to maintain a seal. However, suppose there is a pulsation in the line resulting in a cyclic dynamic load along the pipe. Pressure pulsations will act at every piping elbow, resulting in dynamic shaking forces, which can shake the piping both laterally and axially. Consequently, the bolts holding the flanges in place will be subjected to both the initial static load plus the dynamic load.

Once the loads on the components are known, the designer then selects the various materials for the various machine components. This can be tricky as not only loading, but environment (internal and external), and Codes and Standards need to be addressed as well. Selecting the optimum material properties is vital to ensure overall success of the design. Material properties include modulus of elasticity, yield strength, fatigue limit, ductility, hardness, reactivity, and so forth. Figure 2.3 shows a general line of thought and areas of emphasis in the design of an element. The designer starts at the far left of Figure 2.3 by selecting the type of applied load expected, then proceeds to strengths analysis, then to material and geometry, and finally determines the potential failure criterion that can be expected if design loads are exceeded. Parts are designed so that if excessive loading was to occur, the part would fail in a particular way. That is, you might design the part to fail through excessive deformation as opposed to separating into multiple pieces.

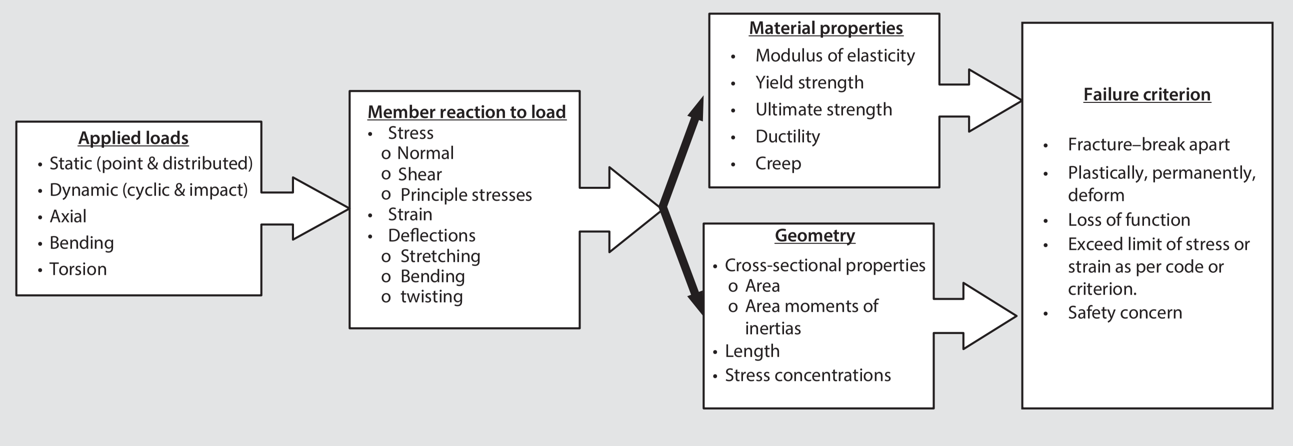

Figure 2.3 Mechanics of Elements Information (need to modify to include shear).

While developing the overall mechanical design, the designer must envision possible loadings on all the internal components in order to ensure that they are not overstressed. The designer also needs to consider the identified loads for all anticipated conditions and environmental factors, such as operating temperatures, corrosive or erosive fluid components, off-design operation, and so forth. The designer may need to go through several iterations as he or she analyzes the various machine elements. This is especially so as new insight is gained on the design at each iteration. Tweaking might involve, strengthening some highly stressed components or redesigning internal seals to improve efficiency. Eventually an overall design emerges that can be manufactured and then tested. To be deemed a successful design, it must be able to provide high-efficiency performance while also providing a long service life under real-world conditions.

2.2 Complex Machine Element Environments

To summarize, every component in a machine serves a specific function and has been designed with this function in mind. It is the designer's job to ensure that every component is composed of the right material, with the required material properties, and possesses the required strength. We could expect that any given machine design will gradually be perfected as design modifications are introduced to improve reliability.

However, in the real world, there are rarely simple textbook loading conditions acting on machine components. In addition to stresses due to mechanical loads and fluid forces, machine elements can experience unanticipated external loads, corrosion, erosion, fretting, thermal stresses, material degradation, transportation issues, installation issues, foundation issues, and so forth, which can all lead to premature failures. The troubleshooter must be mindful of all the various failure modes that could be present in the machine under investigation. The interplay of all the effects previously listed can lead to an infinite number of failure possibilities.

An experienced designer makes allowances for unforeseen loading and environmental conditions by employing a number of safeguards such as safety factors to highly stressed components, using upgraded metallurgy and materials, and applying coating to key areas of a machine. If a machine has been designed to meet well-defined operating parameters and the designer has properly accounted for mild variances in the operating parameters, then the machine and its components should rarely fail in service.

Troubleshooting Rotating Machinery: Including Centrifugal Pumps and Compressors, Reciprocating Pumps and Compressors, Fans, Steam Turbines, Electric Motors, and More.
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3

Machinery Design Issues and Failure Modes

The Pareto Principle, also known as the 80–20 rule, states that, for many events, roughly 80% of the observed effects come from 20% of the causes. The Pareto Principle tends to apply to machines in that roughly 80% of all site machinery failures tend to be caused by only 20% of the population, commonly called bad actors. We can also go on to state that of all the countless failure modes that can possibly occur in machinery, only a very small number results in 80% or more of all machine failures. This small percentage that account for the actual observed failures are called common failures modes.

If properly designed, major load-bearing and power transmission machine components, such as shafts, housings, couplings, rarely fail due to nominal operating loads and conditions and survive a few overloading events. It is the components at interface locations (see Chapter 2) that are more likely to fail. Interface components such as seals, bearings, impellers, pistons, and wear rings, to name a few, due to their work demand, have the greatest tendency to be subjected to wear, rub, distortion, fouling, fatigue, and erosion, or they can become misaligned. These insidious internal effects, usually related to environmental factors, assembly or operating issues, or poor maintenance practices, make interface components the problematic machinery components.

It is these interface components that tend to cause maintenance organizations the most grief. If we study the statistical nature of a site's interface component failures and their causes, we find that certain failure modes and failure causes occur more frequently than the rest. It behooves maintenance organizations to devote more time to eliminate these common failure modes and causes through improved maintenance and design practices.

A **common failure mode** is any machinery component failure that is typically encountered during the life of a given class of machine, such as bearings, seals, or packing. These failure modes may simply be the result of normal wear or occur prematurely due to manufacturing flaws, poor operating conditions, or improper maintenance. For example, normal tire wear and brake shoe wear can be considered common failure modes for an automobile. If a tire fails at a normal time interval, it was probably maintained according to the manufacture's guidelines; however, if a tire fails at a significantly shorter interval than expected, it probably found a nail in the road or was not maintained. A simple indicator of a component's reliability is its lifetime compared to the average life of a population of similar components in similar applications.

Common causes of failure or distress are frequently encountered design, installation, and operating issues that lead to machine failures or shortened serviceable lifetimes. For example, we know that imbalance, misalignment, loose bearing fits, plugged oil orifices, off-design operation, etc., tend to lead to failures or shortened component lifetimes. Let's consider a centrifugal pump with an unfavorable hydraulic design that results in a narrow operating range. Experience tells us that a pump of this design will be sensitive to a substantial change in flow conditions, thereby making it susceptible to flow-related vibration issues and related bearing failures. Vibration caused by off design operation is a common cause of hydraulic instability that results in high vibration.

When troubleshooting, it is helpful to know the common design issues, operating problems, and associated failure modes for different classes of equipment. Here are two examples of common causes of distress related to centrifugal pumps design issues:

1. Tight vane tip clearance that can lead to vane pass vibration
2. High suction specific speed that can lead to flow instabilities and vibration at off-design conditions

Common failure modes: Bearing and seals failures

Common operating problems:

1. Low flow or high flow operation can result in flow instabilities and low related vibration
2. Cavitation due to insufficient suction head can result in noise, vibration, and erosion

Table 3.1 shows some relations of design or operation issues and the resulting condition, apparent symptom, and common failure mode for a centrifugal pump.

Design/Operation	**Condition**	**Symptom**	**Failure Mode**
Design issue: Tight impeller vane tip clearance	Excessive vibration and noise issues	High vane pass vibration frequencies	Bearings and Seals
Design issue: High suction specific speed impeller	Flow instabilities occurring away from the design flow	Increased pressure pulsations and vibration levels	Bearings and Seals
Operational issue: Continuous operation at low or high flows	Flow instabilities	Increased pressure pulsations and vibration levels	Bearings, Seals, Shaft, etc.
Operational issue: Operating with a low suction head	Cavitation	Noise and Vibration levels	Failure of impeller due to erosion

Common failure modes tend to signify the location of "pressure points," that is, spots within the machine that push the limits of a given component design.

The ultimate goal of all machinery designers is to provide end users with efficient, reliable, and safe machines capable of operating over an expected range of design conditions. However, achieving this goal requires cooperation from maintenance and operating personnel. Proven standards, procedures, and safeguards must be employed by end users in order to realize long serviceable machine lifetimes.

Here is a quick overview of some safeguards and their sources that end users can adopt to keep their machinery operating at nominal stress levels:

1. Machinery design standards—There are many industrial design standards, such as API, ANSI, etc., that when used can ensure proven, robust machines are procured.
2. Machinery installation standards—Once a machine is purchased, it must be installed properly to ensure it is not overstressed due to piping loads resulting from poorly aligned flanges and fixtures.

In addition, steady, non-turbulent flow into and out of the fluid mover is desired to minimize bearing loads, shaft deflection, and seal stresses.

3. Maintenance best practices—Alignment and balancing standards ensure machines are repaired properly and reinstalled into the process.
4. Preventative monitoring and predictive maintenance best practices—Lubrication, vibration collections, periodic inspections, can help detect potential problems before they can lead to catastrophic failures.
5. Operating limits—To prevent operating a machine as it was not intended to operate, an operating facility may set machinery operating limits that may include flow and temperature and power limits. Integral control systems can be utilized to help regulate flow conditions based on operating points.
6. Periodic inspections—It is wise to periodically inspect process machinery. Periodic inspection can detect early symptoms of machine problems. These symptoms may include, high vibration, increasing temperatures, loss of flow, unusual noises, pressure pulsations, etc.

3.1 Common Failure Modes

Regardless of the lengths we go to purchase reliable designs, install, monitor, and repair them properly, and maintain proven procedures, machines will still fail in a variety of ways. Some failure modes are common, similar to medical conditions such as the common cold, while other failure modes are rarely encountered. For example, bearing and seal failures are probably the most common failure modes you will encounter, while impeller and shaft failures are rarely encountered.

Some failure modes can be considered primary and others are secondary in nature. A primary failure mode is an initial internal condition that can lead to subsequent catastrophic failure. For example, a plugged suction strainer can be considered a primary failure mode. By itself, a plugged strainer is not catastrophic, but can eventually lead to cavitation (secondary effect) and eventually a bearing failure (secondary failure) due to low-flow conditions.

Some other common machine failure modes include:

- Pluggage (usually a primary failure mode)
- Erosive Wear (usually a primary failure mode)

- Fatigue (primary or secondary failure mode)
- Bearing failure (primary or secondary failure mode)
- Rubbing (primary or secondary failure mode)

By understanding the nature of these common failure modes, we can readily recognize them in the field and attempt to either prevent their recurrence or minimize the extent of secondary damage they can cause if gone undetected. Here we will discuss these failure modes in some detail and provide actual field photos of each type.

3.1.1 Pluggage

Pluggage occurs due to the gradual build-up of solids in the flow path of the process piping or machine component. Symptoms of pluggage include the loss of flow or pressure and can sometimes lead to flow-related vibration. Figure 3.1 shows some representative photos of pluggage that resulted in failures.

3.1.2 Erosive Wear

Erosive wear occurs whenever an erosive fluid removes material from the component whether it

(**a**) Plugged suction screen on compressor inlet piping

(**b**) Plugged flue nozzles from a gas turbine

(**c**) Pump impeller clogged with salt crystals

(**d**) Pump impeller clogged with trash

(**e**) Suction screen for vertical pump clogged with trash

(**f**) Debris from (e) that clogged strainer

Figure 3.1 Real examples of pluggage.

is a piece of piping or a pump. Erosive fluid typically results from an abrasive component within the process fluid that causes removal of material much like sand paper. Symptoms can include vibrations due to imbalance, flow-related vibrations, loss of flow or pressure, or the loss of overall efficiency. Figure 3.2 contains a few representative photos of damage resulting from erosive wear.

3.1.3 Fatigue

Fatigue occurs whenever a material is subjected to cyclical loading and unloading for an extended period of time and the resulting stress levels are below some limiting design threshold. That is, the dynamic loading exceeds a certain threshold level and microscopic cracks will begin to form

(**a**) Impeller worn out due to erosion (**b**) Impeller worn out due to erosion (**c**) Hole in vertical pump bowl due to erosion

(**d**) Hole in vertical pump bowl due to erosion (**e**) Impeller worn out due to erosion (**f**) Expander wheel eroded due to liquids in the inlet gas

Figure 3.2 Examples of erosive wear failures.

at stress risers, or concentrators. Fatigue can happen over time, or very rapidly. Fatigue failure that occurs over many cycles usually has two distinct stages. The first stage is a propagation of the crack over a number of cycles and is evident by beach marks. Eventually, the crack reaches a critical size and the component fails rapidly. Causal factors such as high vibration, pressure pulsation levels, and unsteady flows are often to blame. Recall, a high static load with a cyclic load on top can result in fatigue failure too. Figure 3.3 contains a few representative fatigue photos.

3.1.4 Compressor Blade Fatigue Example

The leading edge of a centrifugal compressor blade failed (Figure 3.4) due to fatigue, which lead

(**a**) Shaft fatigue occurred due to fretting

(**b**) Pipe clamp bolt fatigued due to high shaking forces

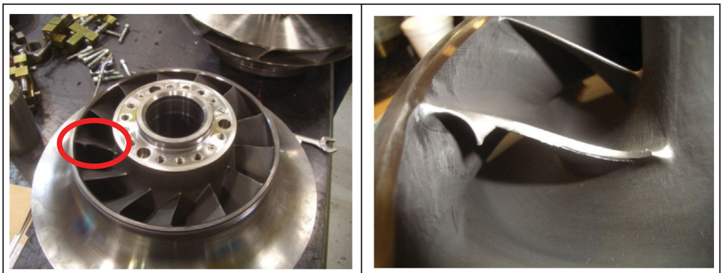
(**c**) Pipe clamp bolt fatigued due to high shaking forces

(**d**) Blade fatigue (arrow point to crack initiation point

(**e**) Axial compressor blade fatigues due to blade flutter

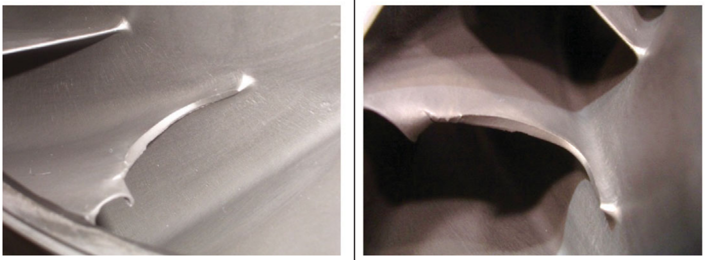
(**f**) Engine connecting rod bolt fatigued due to faulty bolt design

Figure 3.3 Fatigue failures.



(**a**) Overall impeller

(**b**) Close up of region of failure



(**d**) Closer view of failed blade. Curled portion is where rapid failure occurred

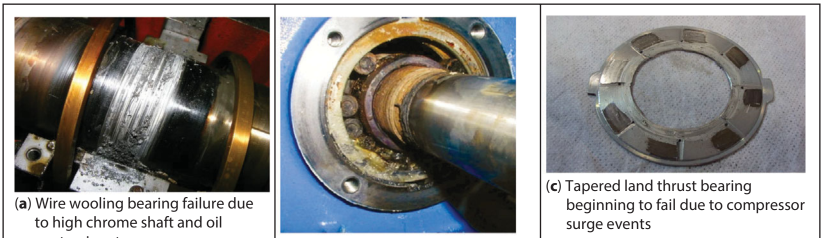
(**e**) Alternate angle of failed blade

Figure 3.4 Example of a fatigue failure on a compressor wheel.

to a rapid increase in high 1x vibration as a result of the imbalance of the impeller increasing. The manufacturer concluded that the combination of a thin casting thickness at the leading edge of the blade and vane pass pulsations led to a resonant condition at the blade. A resonant condition requires that the components natural frequency (dictated by geometry, material property, and mass, all design issues) coincided with an excitation (pulsation due to vane pass).

3.1.5 Bearing Failure

Bearings are mini-systems that require proper design, proper installation, and proper maintenance for successful operation. Although the operation of bearings is essentially simplistic, they can fail for many reasons. Failure could arise from poor lubrication, overloading, misapplication, and fabrication defects. Normally, bearings display symptoms of distress before they fail. Symptoms of a failing bearing include higher vibration levels and rising bearing or oil sump temperatures. One troublesome issue once a bearing exhibits symptoms of failure is that predicting when the bearing will fail is usually not possible. Figure 3.5 contains a few representation examples of bearing failures.



(**a**) Wire wooling bearing failure due to high chrome shaft and oil contaminants

(**b**) Cylindrical roller bearing failure due to improper application

(**c**) Tapered land thrust bearing beginning to fail due to compressor surge events

(**d**) Main bearing from reciprocating engine beginning to fail after grout had failed

(**e**) Radial tilting pad bearing completely destroyed due to loss of a blade

(**f**) Tiling pad thrust bearing has begun to fail

Figure 3.5 Bearing failure examples.

3.1.6 Rubbing

Rubbing occurs whenever a rotating component contacts a stationary component inside a machine. Rubbing is usually a secondary failure mode resulting from the loss of clearance between internal components after a bearing failure. Excessive shaft deflection from vibrations or thermal growth can lead to rubbing too. Symptoms related to rubbing normally include high vibration levels and noise. Figure 3.6 contains a few examples of rubbing failures.

3.1.7 Unique Failure Modes

Every piece of equipment has its own unique design issues and challenges in operation and

(**a**) Electric motor rubbed stator due to bearing failure

(**b**) Electric motor rotor rubbed stator due to a bearing failure

(**c**) Axial air compressor blade fatigues due to tip rubbing

(**d**) Scuff marks on cylinder wall from piston after it overheats

(**e**) Expander wheel on the right shows sign of rubbing due to excessive axial movement (new wheel on left)

(**f**) Thrust collar displays heavy rubbing after thrust pads fail

Figure 3.6 Failure resulting from rubbing examples.

each has its own unique failure modes. It is therefore recommended that you talk to the original equipment manufacturer about known design issues, operating problems, and failure modes before their machines are installed in the field.

New designs typically present greater challenges to machinery and operating professionals as they are unknown in their response to process or environment changes. If machines are a completely new design, designers may have to rely on computer modeling tools (CFD, FEA, etc.) to determine the critical locations where stress, temperature, heat transfer, etc. may reach recommended limits. This is a challenge as computational models are actually quite restrictive in accounting for all variances that might be encountered. It may later be determined that design assumptions were incorrect or that process conditions were wrong.

If a new design fails to perform reliably, you should work with the original equipment manufacturer to determine the nature of the problem. Determining why a machine element has failed is no longer a troubleshooting effort. At this point, you will need to gather field data and perform failure analyses on failed parts in order to identify the root cause of the problem. The ultimate problem resolution may require a combination of field data gathering and failure analyses, field testing, and analytical modeling.

Troubleshooting Rotating Machinery: Including Centrifugal Pumps and Compressors,
Reciprocating Pumps and Compressors, Fans, Steam Turbines, Electric Motors, and More.
Robert X. Perez and Andrew P. Conkey.
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4

Machinery in Process Services – The Big Picture

What is the sound of one hand clapping? This thought-provoking koan is used to challenge students engaged in the practice of Zen. (Note: A koan is a paradox used to train Zen Buddhist

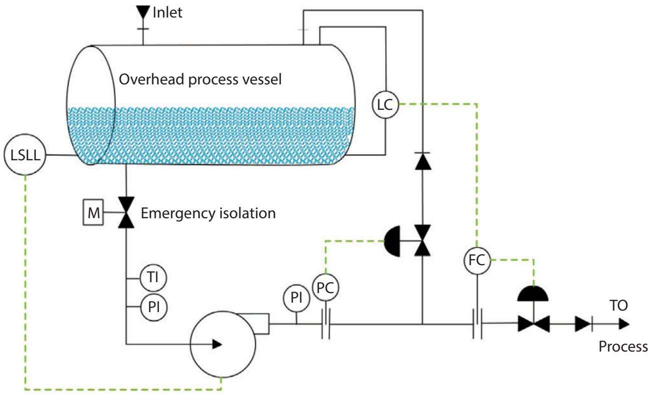

Figure 4.1 Centrifugal pumping system.

monks to abandon ultimate dependence on reason and to force them into gaining sudden intuitive enlightenment.) While this question seems out of place here, it applies to process machinery very well.

I ask the reader to answer this question: Can a centrifugal pump operate within expected parameters without a complete system (see Figure 4.1)?

The answer is clearly no. Without a suction vessel to hold liquid and suction piping to get the liquid to the pump's suction, the pump could never function properly. Without a properly sized discharge line and flow control valve, the pump could not deliver the liquid into the process. Just as a single hand cannot clap, the components in this pumping system cannot function independently. They must all function together to meet the process needs they were designed to satisfy as part of the system as a whole.

If one element of this pumping system is malfunctioning, the whole system will suffer. Here are some possible pumping system issues that can lead to serious consequences:

- Suction strainer is partially plugged
- Discharge piping has some unexpected blockage
- Suction or discharge piping is undersized or oversized
- Spillback valve is leaking back to the pump suction
- Vessel suction level is too low
- Pump driver is under sized
- Foundation is too flimsy
- Piping resonance is present due to lack of supports
- Oil coolers are undersized
- Relief valves is leaking
- Vibration sensors are out of calibration

Even though any of these non-pump issues will usually lead to major problems, it would be no surprise that the resulting symptoms would be reported as "pump problems."

Similarly, here are some issues with systems that could lead to undesirable symptoms in other machine classes:

- Low suction pressure on a reciprocating compressor will increase the overall compression ratio and lead to high discharge temperatures
- Low gas density could cause centrifugal compressor flow and overall pressure rise to both run below design levels
- Scaling or a flow blockage in an oil cooler would cause rolling bearing temperatures to rise
- Process changes could cause an induced draft (ID) fan to foul prematurely.

To successfully assess and troubleshoot process machinery, owner/operators must take a holistic view (see Figure 4.2) of machines and the systems they are associated with.

A holistic view of a machine system means understanding the following elements:

- <u>Actual process conditions</u>: such as process pressures, temperatures, fluid densities, fluid compositions, and flow rates.

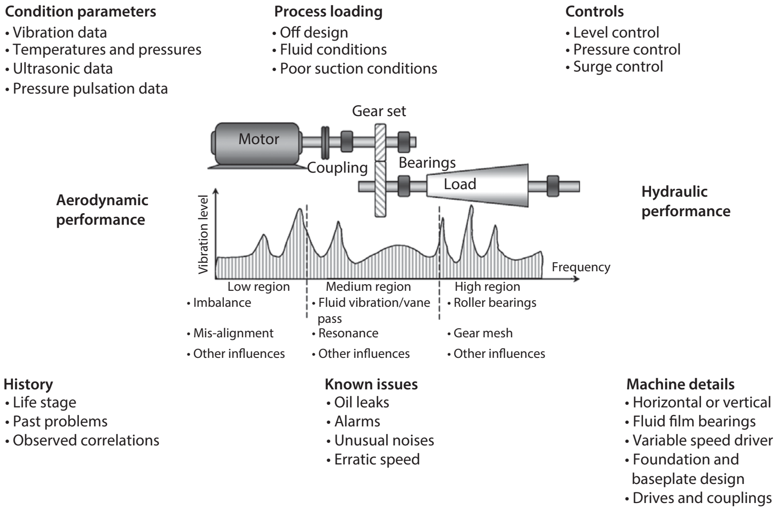

Figure 4.2 Holistic view of machinery.

- Control schemes: level control, flow control, pressure control, temperature, or other?
- Machine construction details: bearing design, lubrication system details, seal design, etc.
- Machine history: installation date, last service, and last upgrade.
- Known issues: such as leaks, alarms, noise, and other activities.
- Current overall mechanical condition of the machine: vibration, bearing temperatures, etc.

A holistic view allows machinery professionals to fully understand how the machinery systems are designed to function and where potential problems could possibly be lurking.

In the "olden days," a machinery professional would take a little bit of data and then make the call. The "new paradigm" requires that the machine evaluator:

- View the installed machine as a system
- Talk to the operators, mechanics, control specialist, etc.
- Collect the right data
- Understand what the data is saying
- Know the risks involved

Item two on the list, talking with people, especially those involved with the day-to-day upkeep of the machine is important in that you want people to be comfortable talking with you when a situation does arise.

The purpose of this guide is to teach field personnel how to think and react differently when they address perceived machine problems. A troubleshooter should always seek to answer these questions:

- Is it the machine?
  - Is there a flaw in its overall design?
  - Is there an issue with how the machine is being operated or applied?

- Is it an overall system issue, such as the machine is oversized or undersized for the actual requirements?
- Is it a process issue?
- Is it a subsystem issue, such as improperly sized oil supply skid, undersized control valve, etc.?
- Is it an installation issue, such as poor grout job, lack of support stiffness, misalignment, etc.?
- Is the problem external to the machine, such as broken anchor bolt, broken grout, support resonance, etc.?

Question	Description
Is it the machine?	Design flaw or assembly issue
Is it the overall system?	Actual operation condition compared to design specifications
Is it the process?	Any variation in the process conditions, such as fluid properties, pressure, or temperatures
Is it a subsystem?	Lubrication systems malfunction or control issue
Is it the installation?	Foundation, grout, or misalignment problem
Is it a secondary element to the machine?	Loose or improperly installed non-functional connector, such as piping or bolt.

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5

Causes Versus Symptoms

In the field, our senses are usually flooded with all types of stimuli, such as sounds of running machines, smells of production and lubrication fluids, vibration, and sights of discolored oil or dancing pressure gauges. At times, this symphony of sensory inputs can be overwhelming.

However, with experience, we come to depend on our senses to assure us that things are normal and to warn us of impending equipment problems. We learn that certain sensory inputs may be symptoms that something may be amiss with a given machine. Certain symptoms may be telling us a machine is failing, has already failed, or is in distress due to an external factor. With practice, we associate certain symptoms with specific causes. However, sometimes we need to do a little detective work to uncover the cause of the symptom.

It is crucial for troubleshooters to understand the difference between causes and symptoms (or effects) in order to effectively investigate the true nature of a machinery problem. Here are some illustrative examples of causes and their symptoms:

1. A pump vibrates because its impeller is out of balance due to fouling. What is the cause and what is the symptom?
2. A steam turbine experiences a high thrust bearing temperature due to internal fouling. What is the cause and what is the symptom?

To explain the difference between a cause and a symptom, we must first understand causality:

Causality is the relationship between an event (the cause) and a second event (the effect), where the second event is understood to be the consequence of the first event. Consider a series of falling dominos (see above figure); every subsequent domino falls as a consequence of the previous fallen domino. Similar to this domino analogy, machinery events can be viewed as a series of related events. Here is how a machinery event can be mapped

Machine Event ➔ Machine Effect/Symptom

That is, a machine event will result in the machine displaying some noticeable behavior. The mapping is such that the event is at the tail of the string, and the effect is at the head. Another way to think of this is that an *action* occurred that *resulted* in a change. On the flip side, reading the diagram from right to left, you can read it as "Something happened, but *why* did it happen?"

Stem broke → *Apple Fell*

Stem broke ← *Apple Fell*

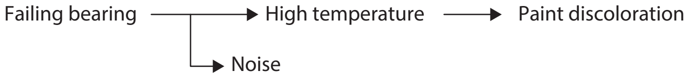
Note, in the discussion, the term *symptom* and *effect* may both be used. When the term symptom is seen, effect is implied, unless otherwise stated.

Finally, it should be noted that the arrow is also a way of defining points in time.

A machine expert knows from experience that a given machine event will subsequently lead to a related machine effect. History has shown that there is a set of known cause and effect relationships for various machine classes.

The ability to draw on specialized knowledge and experience allows a seasoned machinery specialist to troubleshoot efficaciously. Just like a chess grandmaster who is trained to pare a multitude of possible chess moves down to a manageable number of promising ones, an experienced troubleshooter learns to only consider possible causes that are likely for a given class of machine. The technique of paring down possible causes down to the "likely few" causes can save time and money.

A simple example of a machine cause and effect relationship is a failing roller bearing that leads to high bearing temperature and noise. It makes sense to state that the initiating event was the failing bearing and that the second and third events to occur were high temperatures and noise (see cause and effect diagram below). It doesn't make sense to say that the high temperature and noise causes the bearing to fail because these events occur later in time than the bearing defect.



Again, the initial cause in the event chain is at the tail of the time arrow and the next event, effect or symptom, is at the arrow's head, which occurs later.

Returning to the examples at the beginning of this section, we can now answer these questions:

1. A pump vibrates because its impeller is out of balance due to fouling. What is the cause and what is the symptom?

   Impeller fouling is the cause of this machine malady and vibration is the symptom of the malady.

   Impeller fouling → Vibration

2. A steam turbine experiences a high thrust bearing temperature due to internal fouling. What is the cause and what is the symptom?

   Internal fouling is the cause of the machine malady and the high bearing temperature is the symptom of the malady.

   Internal fouling → Rise in bearing temperature

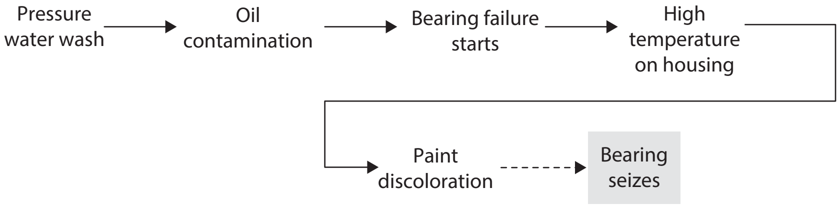
One of the first steps in troubleshooting is identifying your symptoms/effects. Because it is usually difficult or impossible to detect the machine malady directly, we must look to external effects or symptoms that point to latent machine problems. When troubleshooting machines, we are normally on the lookout for telltale symptoms, such as high temperature, vibration, noise, pulsation, etc. These are common effects of some underlying machine faults. A second challenge here is that the source of these telltales could be more than one possibility, hence, the need to ferret out information.

5.1 Causal Chains

In real machines, there can be multiple events that take place between the initial fault, or defect, and the final failure event. Consider the following

> An operator uses a high-pressure water hose to clean off dirt, oil, and grime from a centrifugal pump. The operator unwittingly gets water into the bearing housings, which contaminates and eventually degrades the lubricating oil. The degradation of the oil results in poor bearing lubrication. The excessive heat developed takes the next route out, and

> that is through the housing and paint. Oil contamination eventually causes the bearing to fail. If the bearing failure is not detected, the bearing will overheat and fail catastrophically (see causal chain below).



Note that the last arrow in the causal diagram is dashed. It is important to distinguish that the bearing failed, but it was not due to paint discoloration. The diagram is a mapping of when events occur. If desired, the length of the arrow connecting events could be related to the time when each event was observed or occurred.

The role of the troubleshooter may really depend on when they are brought in. If they were brought in when oil contamination was discovered versus the tail end at the physical failure, the approach and information available may be quite different.

Taking the approach from when the failure finally occurred, the task of the troubleshooter is to determine the source of failure, and the pump is sent to the shop. During the pump's repair, the most obvious indication of the mechanical failure would be the damaged bearing, so it could be called the physical root cause of the failure (see causal chain explanation below). But if we stopped our investigation there we would never understand the true root cause of the bearing damage. By moving further to the left, i.e., back in time, on the causal chain, we can peer deeper into the chain of events and identify pressure water washing as the latent root cause, i.e., hidden, root cause. Simply by looking at the bearing during disassembly, it may not be obvious why the bearing failed. It would take some detective work to discover that the bearing failed due to water ingress as a result of water washing.

High bearing temperature and paint discoloration fall to the right, i.e., later in time, of the physical root cause. High temperature and paint discoloration associated with high temperatures are called symptoms because they are perceptible signs of distress (see causal chain below) that are a consequence of an internal machine defect. On the flip side, that is, going from right to left, it may not be so clean. That is, if paint discoloration is observed, the question posed might be "What could cause the paint to experience discoloration?" Is it heat, chemical, environment, or some other cause? But as more information is gained, sources of the discoloration can be eliminated.

Pressure Wash (Latent root cause) ➔ Oil Contamination (Intermediate event) ➔ Bearing starts to fail (Physical root cause) ➔ High Temp (First symptom) ➔ Paint Discoloration (Second symptom) ➔ Bearing seizure

To uncover latent root causes, first, discover the physical root cause of the failure and then ask yourself: "*What factor or factors could have led to this damage?*" For example, let's say that the physical cause of a fan outage was a bearing failure due to high vibration. The primary question might be "Why were there high vibrations?" To address this, we can ask the following questions:

1. Why did the bearing fail (physical root cause)?
   The bearing failed due to high vibration.
2. Why did the system experience high vibrations?
   The high vibration was the result of fouling of the fan.
3. What caused the fouling?
   The fouling was caused by abnormal process conditions.

4. What caused the abnormal process conditions?
   The upset was caused by abnormally high process temperatures due to a bad thermocouple.

We could conclude that a bad control temperature value was the root cause of the fan bearing failure. One way to avoid this type of failure in the future would be to install multiple thermocouples that would allow the control system to continue operating with a failed thermocouple. Or, have an alarm when the temperature at the thermocouple is outside an expected range.

To maximize machinery safety and reliability, we recommend these causal chain guidelines be followed:

1. **It is best to begin the causal chain as early as possible.** In the example above, it would behoove the machine owner to detect either oil contamination using oil analysis methods or bearing failure using vibration analysis methods as early as possible before bearing degradation symptoms are noted.
2. **The most cost-effective means of preventing a failure, or a future occurrence, is eliminating the latent root cause.** In the first example, the latent

root cause is pressure washing. A procedural change is required to make sure operators are instructed to avoid pressure washing machines as well as to avoid sensitive areas of machines.

3. **To avoid costly secondary damage, employ proven analysis methods to detect machine faults in the earliest stages of failure.** In the first example, we can use oil analysis and vibration analysis methods to detect problems in the primary state.
4. **Always strive to uncover the latent root cause of unwanted events.** The latent root cause of a problem is the causal factor that, if properly addressed, will prevent a recurrence of the problem. Addressing possible causes that are not root causes will either have no effect or merely mask the real problem.

5.2 Summary

In this section, we have briefly covered the differences between causes and symptoms and how multiple machine failure events can make up causal chains. All machinery professionals should have a solid working knowledge of the event types that can make up machine causal chains, i.e., latent root causes, physical root causes, intermediate events, symptoms, etc. Understanding machinery causal chains and the risks they represent will help you better manage your machines and machine management processes.

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6

Approach Field Troubleshooting Like a Reputable News Reporter

Reputable news reporters are trained to get all the facts on a given subject or event before writing or reporting a story. Facts are the basic building blocks of all investigations. Without facts we are simply guessing about what may or may not have happened.

An accepted means of getting all the pertinent information is by asking the questions that we will refer to as the Five Qs (5Qs). The Five Qs methodology is widely employed by news reporters, journalists, and researchers. These investigators have found that a story or investigation should be initiated by asking the following probing questions:

- What?
- Who?
- When?
- Where?
- Why?

Only when these questions are accurately answered can the investigator be assured that he or she has all the pieces to the puzzle required to pen a clear and complete story.

When troubleshooting, we need to rearrange the questions in the following order:

1. What seems to be the problem? Or, what are the symptoms? What is your assessment of the problem?
2. Who knows the most about the problem?
3. When do, or did, the symptoms show up?
4. Where do the symptoms show up?
5. Why is the problem occurring?

Asking the 5Qs in this order saves you time and saves company resources by asking certain key questions early in the investigation. Before spending time on "why", the first four questions have to be addressed.

In the sections to follow, we will investigate the 5Qs in more detail in order to obtain a deeper understanding of what each question means, how to think about them, and how they can be helpful in drawing the right conclusions. Then, when all the basic facts are collected and understood, the investigator can proceed to uncover the true nature of the problem(s) involved and develop an action plan to correct the problem(s) at hand.

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7

The "What" Questions

As a troubleshooter, we must act like an impartial news reporter and get all the pertinent facts before trying to write a complete story. We need to ask who, what, when, where, and why? In our experience, we believe it is best to start with "what" questions. The "what" questions help to define the problem, describe it, and quantify it. A clear definition of the problem helps the troubleshooter focus on the pertinent issues at hand.

There are five "*What*" questions that need to be addressed. They are

- What is the perceived problem or what are the symptoms?
- What is your assessment of the problem?

- What is at stake?
- What is at risk?
- What additional information or data is needed?

Each of these queries will be addressed as follows.

7.1 What is the Problem or What Are the Symptoms?

The first question to ask is: What seems to be the problem or what are the symptoms?

To troubleshoot, you must first characterize the basic nature of the problem, that is, you must clearly determine what your symptoms are. Once the symptom or symptoms are identified, you

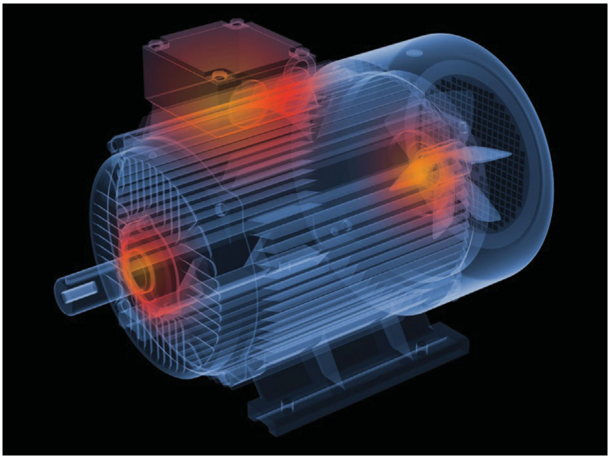


Figure 7.1 Overheating electric motor.

must next determine what potential causes can lead to your observed symptoms. Next, you need to methodically weed out each potential cause until only one remains. Recall the paint discoloration discussed in the previous section. This remaining potential cause will be the most likely root cause. (A root cause of a problem is the causal factor that, if properly addressed, will prevent a recurrence of the problem.) It is possible that you have several root causes. Addressing possible causes that are not the true root causes will either have no effect or merely mask the real problem.

Zeroing in on and clearly defining the symptoms allows you to focus only on the potential causes that could possibly lead to the observed symptoms.

For example, some of the most common complaints, or symptoms, from users of pumping systems are:

1. Flow too low
2. Flow too high
3. Unstable flow
4. Pressure too high
5. Pressure too low
6. Power too high
7. Power too low
8. High vibrations or noisy

By postulating various possible causes of these symptoms, the troubleshooter can quickly hone in on the likely cause of the problem. The symptom of "flow too low" may be caused by the wrong impeller, low speed, pluggage, etc. By knowing these potential causes, the investigator avoids spending time on non-related potential causes that do not affect flow.

7.2 What Is Your Assessment of the Problem?

The point of this question is to determine if the perceived problem is really a problem at all. There are many situations, such as detected vibration on a compressor bearing housing, that may be perceived as a problem, but when fully analyzed is not deemed a problem.

Consider this example: An operator places his or her hand on a bearing housing and deems it too hot. He returns later with an infrared temperature gun only to discover the temperature is 135 °F. Once the operator finds out that a temperature below 150 °F is fine, he can drop this concern and continue with his inspection round.

It is critical to make a proper assessment before continuing with the investigation. That is, you need to make sure that the data used is quantitative as opposed to qualitative. Too hot as per touch can be unreliable as opposed to a measuring instrument that is properly calibrated. If the assessment indicates there is no problem, then the issue should be dropped. Here are several other possible conclusions that could be drawn after machinery condition is collected and evaluated:

- Normal: If machine conditions are normal, no further action is required.
- Trending upward, but below the action level: If machine conditions are clearly deteriorating, but below the action level, trending is recommended.

- Trending upward, but above the action level: If machine conditions are clearly deteriorating and above the action level, a more aggressive monitoring plan is warranted, such as developing a repair plan and ensuring spare parts are available.
- Near or at the danger level: If machine conditions have reached the danger level, shutdown plans should be initiated.
- Above the danger level. If machine conditions are above the danger level, an immediate shutdown is recommended.

Figure 7.2 is an idealized plot of a machine's mechanical condition with respect to time.

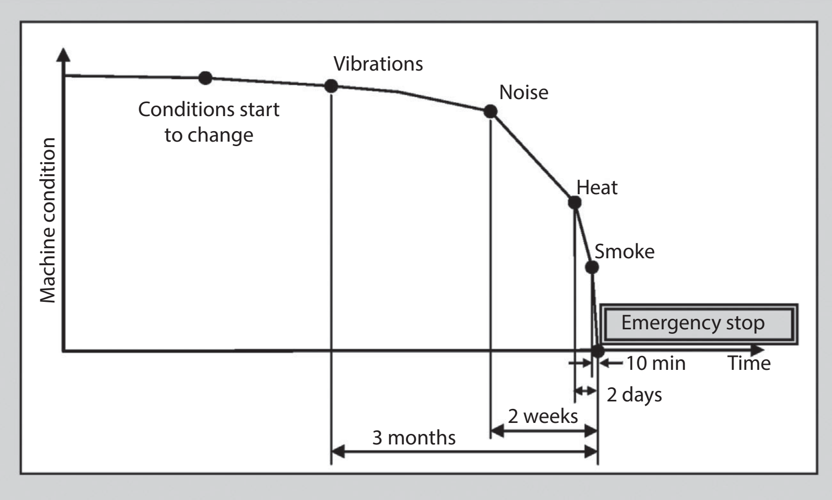


Figure 7.2 The risk of waiting too long.

It illustrates the consequences of waiting too long before taking action. First vibrations are noted, then noise, then heat, and then finally smoke. The best strategy is to properly monitor machines so that early clues to machine distress are found early, before serious damage occurs.

An important question is: How should a machine assessment be performed and what machine condition parameters should be evaluated? That's where the reference *Is My Machine OK?* (IMMO?) comes in. Its sole purpose is to provide those who deal with industrial process machines a handy resource for assessing the potential risk of failure and providing a solid basis for reliable and safe machinery operation. It was developed to be taken into the field by plant supervisors, maintenance personnel, and reliability professionals so that informed decisions about their equipment can be made. It covers the most commonly used machinery condition parameters, such as vibration, pulsations, temperature limits, lubrication, etc.

This reference is made up of three sections: 1) *Evaluating Process Machines*, which contains basic instruction and practical advice on evaluating the condition of machines, 2) *Equipment Specific Assessments*, which covers the evaluation

Table 7.1 Location of assessment guidelines inside "Is My Machine OK?

Equipment Type	**Location of Assessment Data**
Piping vibration	Chapter 11
Machinery vibration	Chapter 13
Pressure pulsations	Chapter 17
Pump performance	Chapter 8
Compressor performance	Chapter 19, page 198 and Chapter 16, page 173
Lubrication	Chapter 20
Bearing temperatures	Chapter 19

of centrifugal pumps, steam turbines, electric motors, and piping, and 3) *General Assessment Guidelines*, which contains field assessment methods, limits, and advice commonly employed to evaluate process machinery.

Table 7.1 is a cross-reference table that will help the reader find the relevant condition assessment tables in *Is My Machine OK?* The hope is that together, this troubleshooting guide and *Is My Machine OK?* will provide field personnel with an integrated methodology to assess and troubleshoot most commonly process machines.

7.3 What Is at Stake?

In other words, what is the potential consequence if the present condition gets worse and results in a machine failure? Some possible consequences are:

- Personal injury
- Environmental release
- Lengthy machine outage
- Production losses
- Costly secondary machine damage
- Loss of credibility
- Loss of goodwill
- Loss of customers

Consequences in industrial settings tend to fall into four main categories: 1) Safety related, 2) economic risk related to repair costs, 3) economic risk related to process losses, and 4) environmental risk related to loss of containment. Obviously not all of these consequences are equal. On a scale of 0 to 1,000,000, a serious injury or death would be given a rating of 1,000,000, while a major repair may only have a rating of 10,000. Every organization has their own way of rating or ranking consequences. (Table 7.1a on page 71 in Chapter 7 ("Risk Ranking Machinery Issues") of *Is My Machine OK?* provides some guidance on quantifying various types of consequences related to machinery failures.)

7.4 What Risk Is at Hand?

A more fundamental question to ask is: What risk am I taking by continuing to operate this machine? Risk is defined as the product of consequence times the probability of occurrence. The combination of the assessment results and the potential consequence is a measure of overall risk. The machinery analyst's job is to determine the probability of failure in some prescribed time interval, such as time to the next planned overhaul or time to the next unit outage. The analyst must determine if the probability of failure is unlikely, possible, likely, or almost certain.

After a field assessment is conducted, you can evaluate the level of risk represented for a given situation. For example, if the probability of failure is possible but the consequence of a failure is low, the level of risk is low. However, if the probability of failure is possible but the consequence of a failure is very high, then the current risk level is high. The calculation of risk can help you prioritize developing problems in order to properly assign resources to the problems representing the highest risk levels.

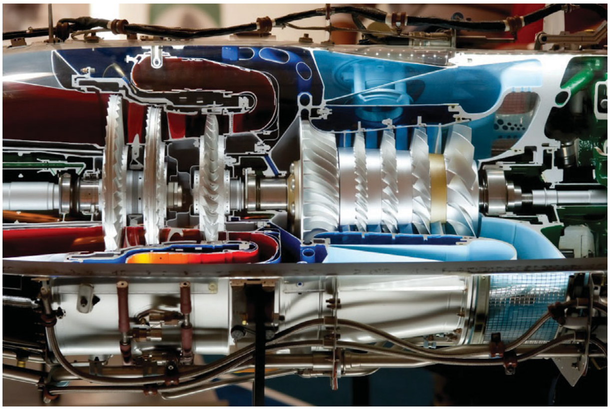
7.5 What Additional Information Is Required?

> The final "what" question is: What additional machine data do I need to collect? The answer to this question will be determined after performing an initial field audit of the machine. (Chapter 6 in IMMO? contains detailed advice on how to perform an audit.) For complex machines consider inviting a mechanic, machinery professional, or other specialist to walk around the machine to assess the situation. Two sets of eyes are always better than one.

Once you have an idea of where the problem areas are and you have interviewed the "key personnel" (refer to the "who" questions in Chapter 8), you are ready to create a detailed test plan addressing the following points:

- What data should be collected?
- What types of probes or sensors should be used?
- What types of events should be recorded, i.e., start-up, shutdown, low flow, etc.
- What analysis plots should be created?
- Who should be involved in the data analysis?
- What precautions are required to ensure the machine is not damaged during the testing?

Addressing Vibration Problems



If during the field audit phase of the investigation, vibration is found to be the predominate symptom, then a preliminary vibration analysis is recommended. A preliminary vibration analysis can save you time and money by helping the troubleshooter focus on the most probable causes and avoid possible cause that are unlikely. Vibration analysis is a methodology that uses vibration characteristics, such as frequency and phase content, to determine the potential cause(s) of vibration.

An advanced knowledge of vibration analysis is not required to troubleshoot machinery; however, some knowledge of this field is recommended. Chapters 14 and 15 briefly cover vibration analysis and rotordynamics for those interested in learning the basics of these technologies and how they can assist in the troubleshooting process. When in doubt, bring in a vibration or rotordynamic expert to help you collect, analyze and interpret the vibration data.

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8

Who Knows the Most About the Problem?

In this step of the troubleshooting process you need to ask yourself: Who knows the most about the problem? This question is a continuation of the data collection process. Regardless of how much reference material you have located on a given process machine or how much machine condition data you have collected, there are always additional valuable resources available to augment your overall knowledge of the process/machine system. As mentioned in Chapter 3 of this guide, it is important to maintain a holistic view of a machine and its system. This means learning as much as you can about:

- Machine construction details. Bearing design, lubrication system details, seal design, etc.
- Control schemes. Is the machine operating on level control, flow control, pressure control, etc.?
- Machine history
- Known issues, such as leaks, alarms, etc.

Learning about design and construction details can be as easy as studying the equipment manual for the machine in question. The project manuals probably contain drawings and specification with key mechanical details, such as bearing and seal designs, number of stages, etc., and design details, such as expected design flows, pressures, and temperatures, etc. However, the manual will not have a detailed history of the machine or describe any past issues and may not have any details of the current process control systems.

To maximize your chances of success, your analysis team needs to include

- Operations personnel
- Process engineers

- Mechanics
- Control professionals
- Original equipment manufacturers (OEM)

Operations personnel are the eyes, ears, and noses of a process organization. They have a close-up view of what their machines are doing and know what's normal and what's not, that is, they are more likely to observe symptoms of an ailing machine. They are also in a good position to recount the machine's history and the overall historical context of a given problem.

Process engineers know the most about the process and about what special operating conditions may be encountered. This includes current and future conditions.

Mechanics are great sources of technical information. They know how frequently a machine is failing and when it was last repaired. They can also provide an opinion on the overall design and if any design issues are present, such as flimsy shaft, a weak baseplate, poor seal design, and so forth. This is especially so if there is a constant need to continually repair the same component of the machine.

Control professionals are invaluable at explaining the control system and troubleshooting them if control problems are noted.

Original equipment manufacturers are the best resources for machine design details and finding out about known design issues. You should try to bring the OEMs in early on for complex problems and for critical machines.

Information is power in the sense that the more information you have, the more likely you are to be able to successfully resolve a problem. The name of the troubleshooting game is collecting as much data as possible to better understand what is really going on. Employing knowledgeable individuals with vested interests in the problem at hand increases your chances of gathering the right information to solve your problem in an expeditious and efficient manner.

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9

When Do the Symptoms Show Up?

"When" refers to the time when the problem has occurred or is occurring. "When" can be defined by 1) the time of day, 2) time relative to an event, 3) time relative to the present run time, or 4) time relative to the machine's lifetime. Let's define what is meant by these different views of time:

a. <u>Time of day</u> – This relationship is fairly easy to understand. If a machine event, such as high vibration or a high bearing temperature, is happening during the heat of the day or immediately after a cold front blows in, the problem may be temperature related.
b. <u>Time relative to an event</u> – If a machine event, such as high vibration or high bearing temperature, occurs at different times of the day, but coincides with a definitive process event, the machine is trying to tell you something. For example, if a pump shakes violently every time the tower level drops below a certain level, cavitation is probably occurring. Other relative timing events could be recent bearing replacement, oil change, process upset, machine adjustments, pressure washing, and so forth.
c. <u>Time relative to the machine's present runtime</u> – The present run time is the time since the last machine repair or overhaul. If a compressor is expected

to have a run time of six years and you are in the fifth year of a machine run, then you should expect some internal wear and degradation. Conversely, if the same compressor is in the first day of a fresh overhaul, any issues experienced are probably not due to internal wear.

d. Time relative to the machine's lifetime – This term describes the time from the first installation of a machine and the time the problem was encountered. For example: Let's say that a compressor was installed in 1995 and was last overhauled in 2008. This means it's been 17 years since the compressor was first commissioned. The distinction here, as opposed to c), is that not all the parts needed to be replaced at the last overhaul cycle. Therefore, there may be a number of components that are original and subject to deterioration.

Here is a set of examples illustrating how timing can be described: Assume there is a centrifugal compressor that has a thrust bearing temperature that is running 5 °F below the alarm limit. After talking to the operators you collect the following information:

a)	Time of day:	Bearing temperature levels fluctuate around 10 °F from day to night.
b)	Time relative to an event:	Bearing temperatures seemed to jump up to current levels after an apparent surge event that occurred the previous week.
c)	Time relative to the machine's present runtime:	The last compressor overhaul was performed two years ago. An average compressor run time is six years.
d)	Time relative to the machine's lifetime:	The compressor was installed in 2004 (current year is 2012), which means, the compressor has been in service about eight years.

9.1 "When" Questions to Ask

There are at least nine "when" questions to ask. The list is not in any order of priority:

1. Has this problem ever been seen before? If so, when was it last observed?
2. Has there been a recent repair to the machine under investigation?
3. Have there been any recent modifications to the machine or auxiliary systems?

4. Have there been any changes to the operating procedures?
5. Where are we with respect to the repair cycle? (Recent repair or near end of life.)
6. Was the change in condition sudden or gradual? If sudden, does it coincide with an event?
7. Has anything changed recently in the process?
8. Was the change gradual or intermittent?
9. Does there seem to be any correlation to the time of day, ambient temperature, load, process changes, or other events?

It could be beneficial not to restrict the number of people you ask about these various time events. One question might spark something in someone's memory that could lead to some additional useful information.

9.2 Ways to Display Time Related Data

There are times when a machine problem requires that large quantities of time-based information be collected, digested, and then analyzed. Two useful ways to display sizable sets of time-related data are timelines and data trends. These visual tools plot display information in a way that provides analysts a means of readily grasping pertinent historical information in order to formulate potential theories and definitively rule out unlikely scenarios.

In the following sections, timelines and trend plots, and how to interpret them in order to understand what's going on with your machine, are discussed. Timelines provide a mapping of discrete events in a particular time span, whereas trend plots provide a graphical means of displaying process or machine condition data.

9.3 Timelines

A simple, yet powerful, troubleshooting tool is the timeline. A timeline can provide the reviewer with a synopsis of a machine history. It can quickly show if the machine has been reliable, how long it has been in service, or if there have been changes to its design or operating conditions. Timelines can be depicted in either a graphical representation of events, as seen in Figure 9.1, or as a table of events as seen in Table 9.1. Both methods of data presentation allow the reader to quickly absorb key events that have taken place in a machine's past. A timeline can be used to describe a machine's entire operating lifetime or a few days before a problem is detected. The graphical timeline in Figure 9.1

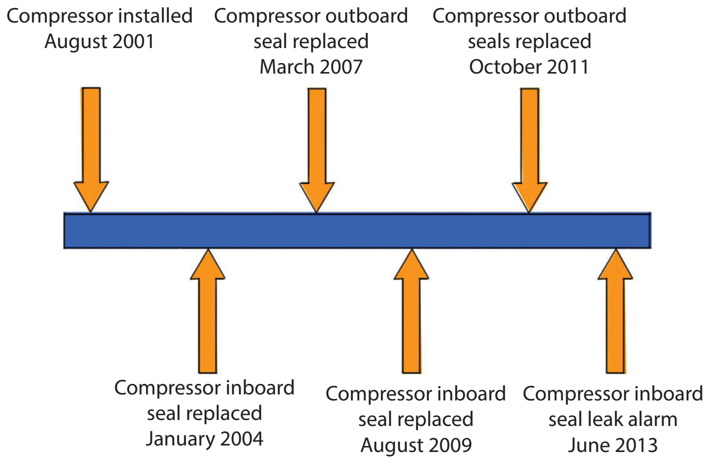

Figure 9.1 Graphical timeline.

shows that a compressor has experienced a number of seal failures. The current seal leak alarm is probably an indication that a seal has failed again.

As an example, let's review the tabular timeline in Table 9.1 that was developed after a steam turbine was not able to bring a centrifugal pump up to rated speed.

The details in this tabular timeline provide the reader with some key details: First it can be seen that the turbine has been in service for about 12 years, which suggests it was probably designed and installed properly. Next, it can be seen there have been several component failures in its history, but none that are out of the ordinary, or unexpected. Most significantly, it can be seen that the governor was replaced during the last steam turbine overhaul. At this point, the analyst

Table 9.1 Steam turbine timeline.

Date	Details	Comments
April, 2002	Steam turbine installed	
May, 2010	Steam turbine overhauled	Turbine ran eight years from the last overhaul
June, 2012	Outboard packing replaced	Packing lasted two years.
June, 2013	Inboard packing replaced	Packing lasted three years.
November, 2013	Inboard bearing replaced	Failure was due to water in bearing housing
March, 2014	Steam turbine overhauled: After the overhaul, the governor was replaced	After the installation of the rebuilt steam turbine, they weren't able to get the pump up to rated speed

should probably focus on a possible problem with the steam turbine overhaul or a governor issue. (We should probably defer any blame on the centrifugal pump as this time.) The most prudent move would be to focus on the governor and determine if it is functioning properly. If the governor checks out to be functioning properly, then consider the turbine overhaul with suspicion.

The next example will consider the tabular timeline in Table 9.2 that summarizes an electric

Table 9.2 Electric motor timeline.

Date	**Details**	**Comments**
February, 2000	250 HP electric motor installed and commissioned	The motor drives a single stage centrifugal pump.
June, 2005	Electric motor overhauled	Motor ran over five years from the last overhaul. Vibration were low after rebuild.
June, 2010	Electric motor overhauled	Motor ran five years from the last overhaul. Vibration were low after rebuild.
June, 2013	Electric motor bearing failure	Bearing failed due to lube oil contamination.
November, 2013	Inboard bearing replaced	Failure was due to water in bearing housing.
March, 2014	Motor is tripping on high amps	During unit outage, the centrifugal pump impeller was changed out to a larger diameter in order to achieve more flow.

motor that is continually shutting down due to high amps. This timeline shows that the motor was very reliable from the time it was installed in February 2000 until March 2014. During this time, there were no recorded occurrences of over-amping. The data in the table suggests that the over-amping is related to the centrifugal pump modifications done in March 2014.

These two tabular examples illustrate how timelines can be used to capture and display a series of discrete machinery events. However, if the available historical data is in the form of a continuous or periodic data stream, trend plots are probably a better choice for data presentation and analysis.

9.4 Trend Plots

There are five trend types to keep in mind when asking the "when" questions:

- constant amplitude type data trends,
- step change type data trends,
- upward or downward type data trends,
- correlation type, and
- erratic data trends

These types of trends are covered in more detail in Chapter 5 of *Is My Machine OK?* Here we will briefly illustrate what these data trend look like and discuss what they are trying to tell you.

A data series is a collection of related values. The data may represent machine load, machine vibration, bearing temperature, a process flow, or any other variable of interest. Most data collected is relative to time as digital acquisition systems (DAQs) are programmed to monitor at set time intervals. A time series or trend is when a data series is plotted or analyzed with respect to time. Trend plots are popular because they are easy to create and interpret. They can be used to see what is happening to a machine or process variable over time and allow for possible prediction of what might happen in the future. The example trends in Figure 9.2 show the satisfaction rating of two product brands that are plotted with respect to time. We can make a few observations: 1) The satisfaction ratings of both brands are constantly improving and 2) Brand B is faring slightly better in rating trials.

Figure 9.3 shows two additional trend plot examples. One plot is that of a gradually increasing value and the other shows a step change in a measured value. Trend plots are useful because they provide visual representations of the measured parameter over time, which can aid in the troubleshooting process. For example, if a step change occurred at the same time in a change in

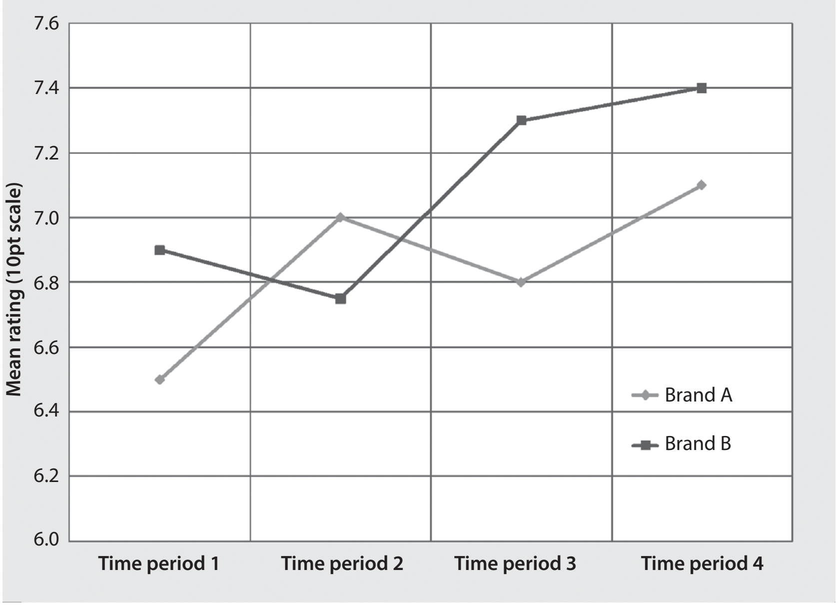

Figure 9.2 Trend plots.

the process, there may be a correlation between the two events that should be investigated. A gradually increasing trend plot may be an indication of either a deteriorating internal or external component.

The key to analyzing trends is to review machine data in a time interval that frames the time of interest. Take for example, the data in Figure 9.3. The time span of 20 months with a one-month interval between data points is adequate to show the upward trends and the step change in the seventh month of the plot. If the span is too short or collected points are too far apart, critical

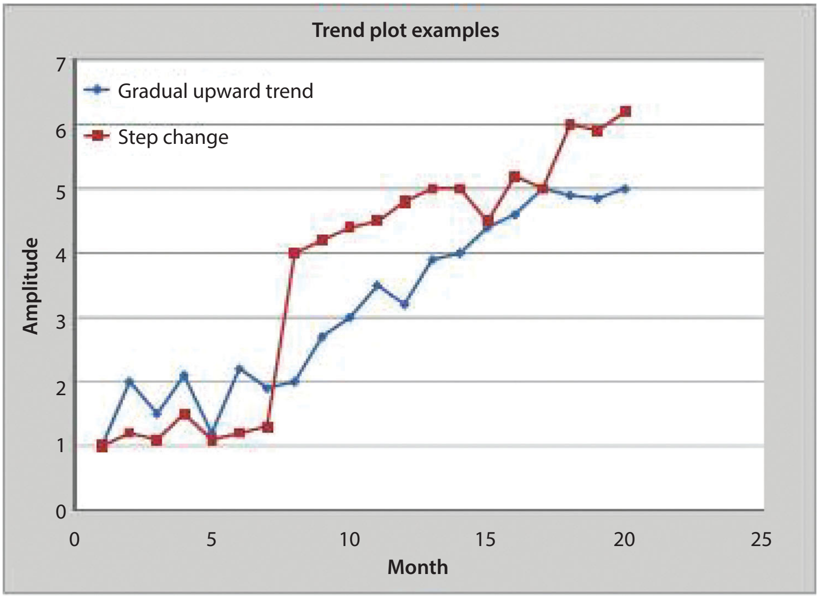

Figure 9.3 Gradual increase vs. a stepped response.

data could be lost or erroneous results could be observed. It is recommended that a wide time interval be reviewed first so that the time of interest can be determined. Also, if a wide range of data points are available, it could be better to plot the points on a larger interval than on the actual one (daily data collected, but plot on a weekly trend as an example). This could help in observing the trend without being distracted by daily variances in operations. Once critical events are identified, the time interval can be tightened, or reduced, in order to glean details of an event or events.

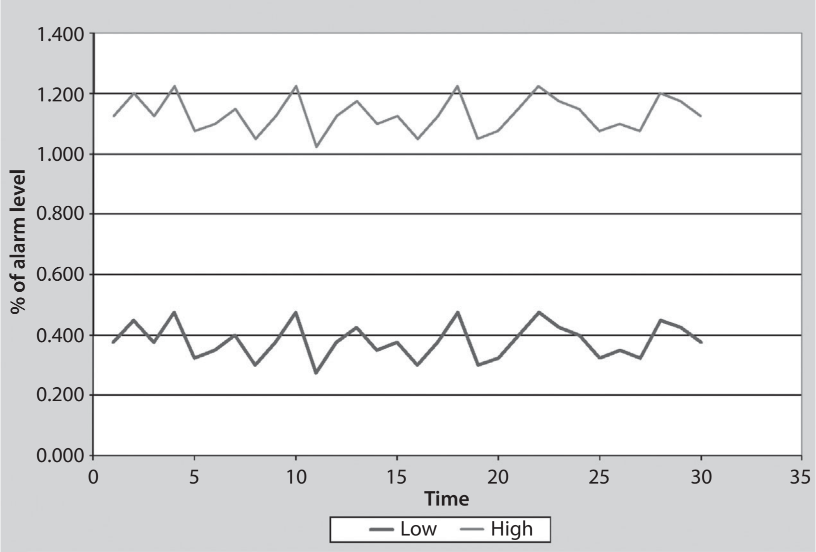

Figure 9.4 Average constant amplitude trends.

9.5 Constant Amplitude Trends

A constant value plot can be observed in Figure 9.4. Although there is a fluctuation in the data the plot does indicate that nothing is changing relative to a mean or average value. This could be good or bad. If amplitudes are always low relative to an alarm level, that's good, but if amplitudes have been high relative to an alarm level from day one, the trend may mean that you are probably dealing with a design issue.

9.6 Step Changes

As discussed for Figure 9.3, a step change plot is telling you there has been a sudden change inside

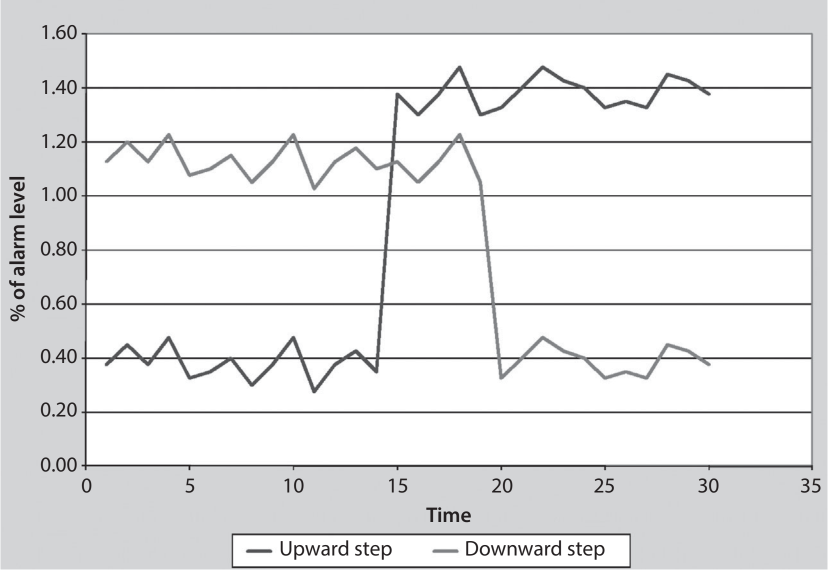

Figure 9.5 Trends with step changes.

the machine or in the process. Step changes, as seen in Figure 9.5, can be a jump up, or a jump down. Trending other factors, such as process, to the trend in question can provide insight. As an example, if there has been no observed change in the process, this may be an indication of sudden damage inside the machine.

9.7 Gradual Versus Rapidly Changing Trends

An upward or downward trend plot as seen in Figure 9.6 is telling you that something is changing either in the machine or due to a process effect. The key to understanding the trend is determining

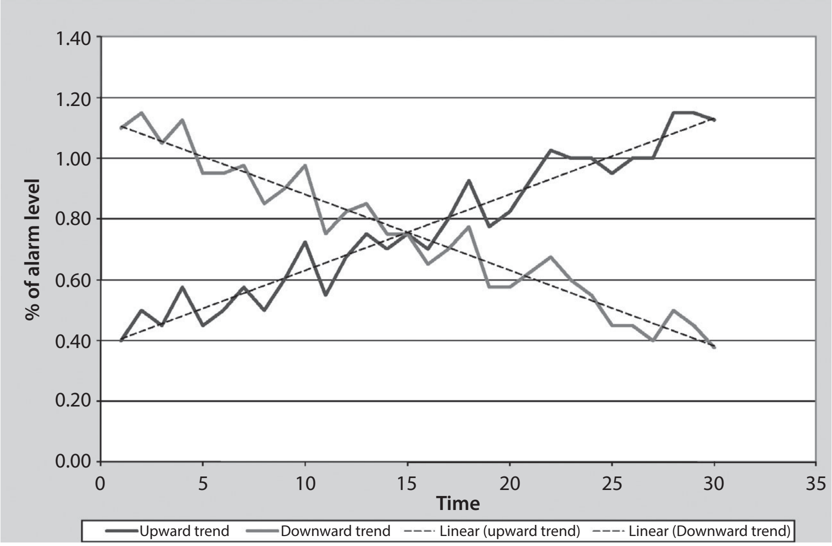

Figure 9.6 Upward and downward trends.

1) when the change in slope occurred and 2) what the rate of change is relative to the average life of the machine. A change in slope close to a process event may be telling you the process is somehow involved in the change in condition. However, if the slope is gradual and at the end of a machine run, the trend may be signaling that the machine is simply at the end of its serviceable life.

Another trend plot possibility is a trend indicating a rapidly changing machine parameter. You can see in Figure 7.2 that as a machine's condition deteriorates, the time interval between different stages of degradation tends to decrease with each subsequent stage of condition. For example, if the time between high vibration and a high bearing temperature was two weeks, then the time between the high bearing temperature and indication of smoke will be two days, and so on. One way to evaluate the potential for a catastrophic failure is to calculate the rate of change of the condition parameter in question. For example, if the vibration level on a machine doubles in 24 hours, then we can say that there has been a 100% change in the parameter in a day, which should be considered a rapid increase. In contrast, a 100% change in a month should be considered a much more gradual rate of change in machine condition.

Takeaway: A rapid change in a machine parameter, such as vibration, bearing temperatures, rotor or rod position, etc., should always be cause for concern because it may signal an impending catastrophic machine failure. If critical condition parameters are changing at the rate 10% to 20% per month or more slowly, then there is time to study the problem in more detail and develop a plan of attack. However, if machine condition parameters are changing at a rate of 10% to 20% per day or more rapidly, then there is little time to react. It is time to bring the machine down for repair, immediately.

9.8 Correlations

Figure 9.7 shows a trend plot of ambient temperature, gas turbine power, and thrust bearing

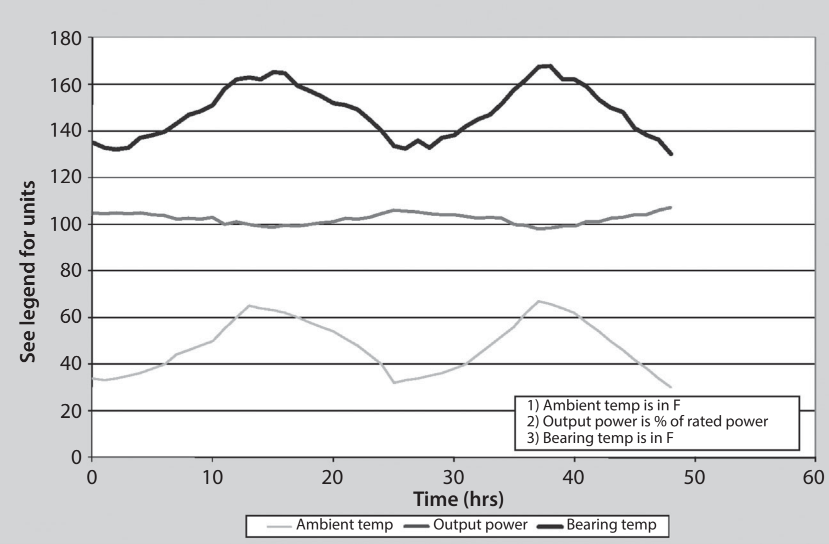

Figure 9.7 There seems to be a correlation between these machine readings.

temperature. By inspection, it can be seen that these values are interrelated. If you plotted the thrust bearing temperature versus the ambient temperature you would get a linear plot similar to Figure 9.8. This plot shows that there is a strong correlation between the ambient temperature and the bearing temperature. Correlation plots are useful to determine what factors have the greatest impact on the machine parameters of interest.

9.9 Speed-Related Issues

Two types of correlations that are important to always keep in mind are 1) vibration changes

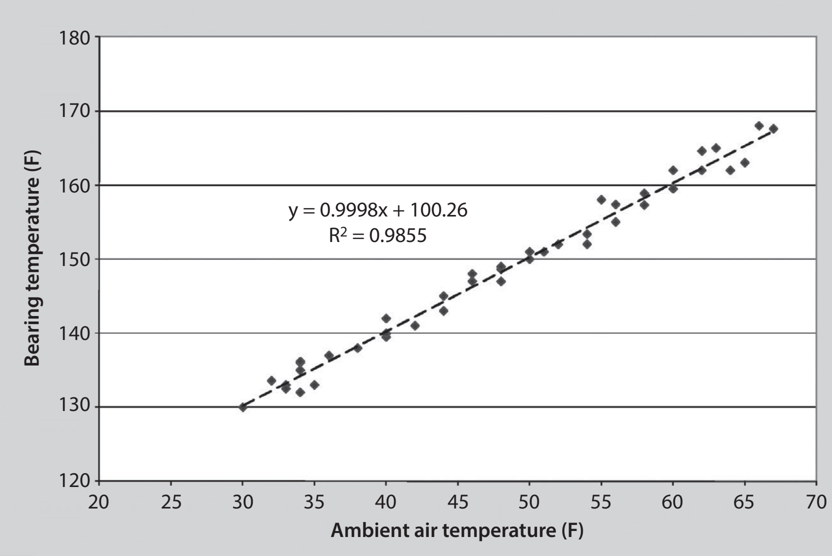

Figure 9.8 Correlation plot shows a strong correlation between the ambient air temperature and the bearing temperature.

related to machine speed and 2) pressure pulsation changes related to machine speed. Sudden increases in vibration or pulsation levels are indications of critical speeds or resonance. This topic is covered in detail in Chapter 18 of *Is My Machine OK?*

One way to readily identify a resonance is to first record the raw vibration data at a given location, over the speed range of interest and then plot the associated vibration spectra over the recorded speed range. (In this example, piping vibration on a reciprocating compressor is analyzed.) This composite plot, as shown in Figure 9.9, is called a

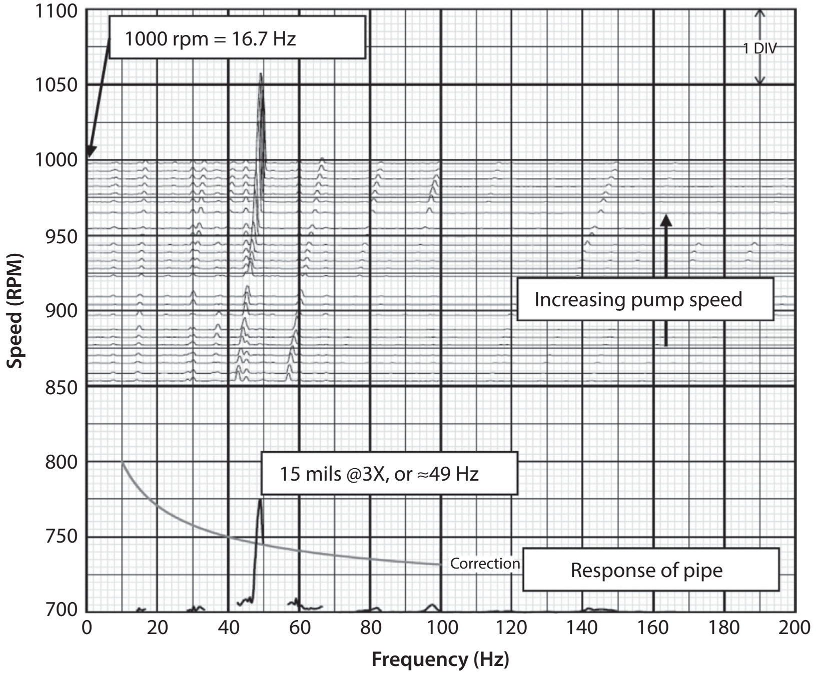

Figure 9.9 Speed raster.

speed raster (or waterfall). This speed raster shown at the top of the figure represents the machine sweep speed range from 850 to 1000 rpm. The plots at the very bottom of the figure represent 1x, 2x, 3x, etc., slices of the waterfall. It's easy to see by inspection that the 3x piping vibration components exceed the "correction" criteria as it peaks at 15 mils. From the speed raster, you can determine the peak 3x amplitude appears at about 1000 rpm compressor speed.

Figure 9.10 shows how to determine if the problem is vibration or pulsation related. Here both

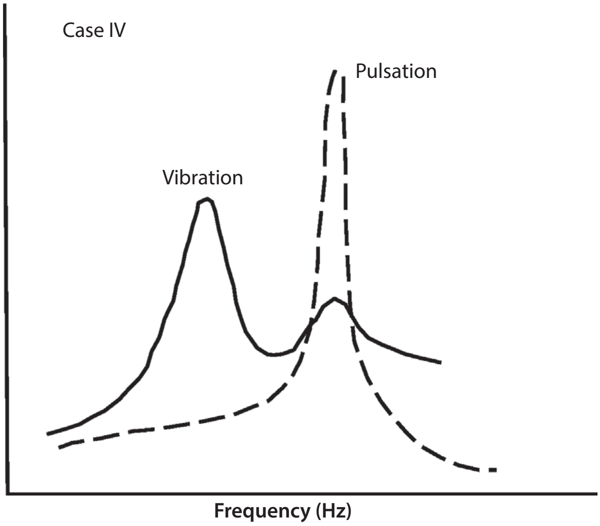

Figure 9.10 Plotting vibration and pulsation data together to differentiate between vibration and pulsation resonances.

vibration and pressure pulsation data are plotted together versus machine speed. The plot clearly shows the location of the vibration resonance and pulsation resonance. Keep in mind that pulsation data should be taken under full load conditions, i.e., full pressure and rated flow conditions.

9.10 Erratic Amplitude

Erratic amplitude plots (Figure 9.11) are more difficult to interpret, but can also be useful. Erratic amplitude plots suggest there is no

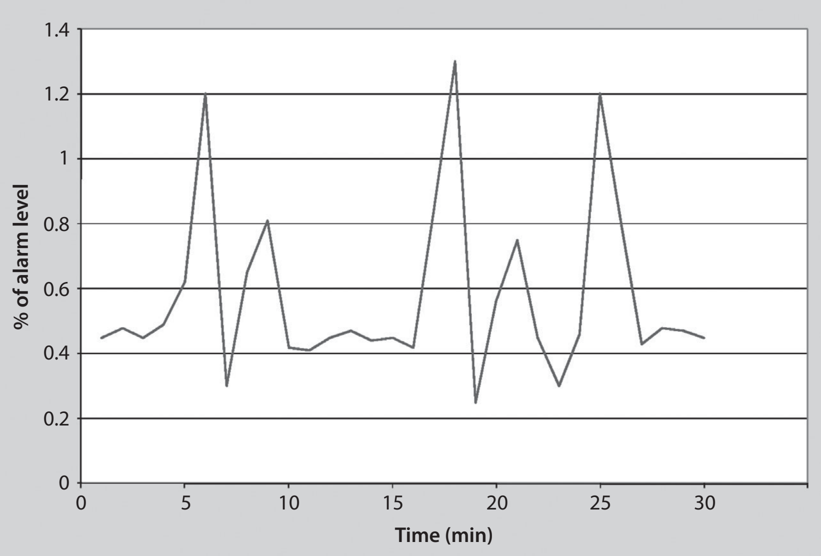

Figure 9.11 Erratic data.

clear coincidence between the value of interest and any process events. Additional testing may be required to verify if the trend is truly erratic or not.

Now that we have covered "when" questions, here are some examples of how "when" questions can help uncover possible causes of machinery problems:

a. High vibration after repair—This may be caused by an improper assembly. Additional analysis can either confirm or refute this theory.

b. Low flow after repair—This may be caused by the installation of the wrong impeller. A performance assessment can either confirm or refute this theory.
c. Gradual increase in bearing temps—One possible cause could be oil cooler fouling. Performing an exchanger performance evaluation could determine if this is a likely cause of higher temperatures.
d. Sudden increase in motor amps—A sudden increase in gas density will certainly lead to higher motor amps. A gas analysis can help confirm or refute this theory.
e. Knocking disappears under load—This effect is sometimes called a "load knock." When the rod load is low, the rod and crosshead can move freely from one end of a bushing clearance to the other, thus causing a knock. Conversely, when there is a sufficient rod load, the rod and crosshead is locked into one position and knocking sounds disappear.
f. Motor vibration that appears only under a load—There are various electrical and

magnetic problems that only show up under a significant current load.

After you have completed this portion of the investigation, you should have a fairly good idea of when the problem appeared or is recurring. You can now proceed to the "where" questions.

Troubleshooting Rotating Machinery: Including Centrifugal Pumps and Compressors,
Reciprocating Pumps and Compressors, Fans, Steam Turbines, Electric Motors, and More.
Robert X. Perez and Andrew P. Conkey.
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10

Where Do the Symptoms Show Up?

The location of the problem can provide important insights into the nature of the problem. To zero in on the problem, here are some key questions to ask:

- Is the problem occurring on the driver, driven equipment, gear box, etc.? The answer to this question will identify what machine type that is acting up and help direct you to the proper troubleshooting guide.
- What part of the machine is affected?
  - Is the entire machine affected?

  - Is the problem isolated to particular bearing?
  - Is the problem concentrated in one area of the machine or baseplate?
- Are multiple machines affected? The answer to this question will determine if it is a machine issue or a system issue. If multiple machines are affected, there is probably some type of system problem involved. For example, a common plugged suction strainer will affect all pumps connected to it. However, if only one machine is affected, it is probably a machine problem.

10.1 Locating a Machine-Train Problem

Let's consider the pump train in Figure 10.1, where we have an electric motor driving a centrifugal pump. Commonly used conventions for machine locations are shown. Bearing locations here are defined as: 1) pump drive end bearing, 2) pump opposite drive end bearing, 3) motor drive end bearing, and 4) motor opposite drive end bearing. (The drive end locations are those closest to the drive coupling.) These positions are broken down further into vertical, horizontal, and axial positions. The baseplate positions can be similarly defined as follows: 1) northwest

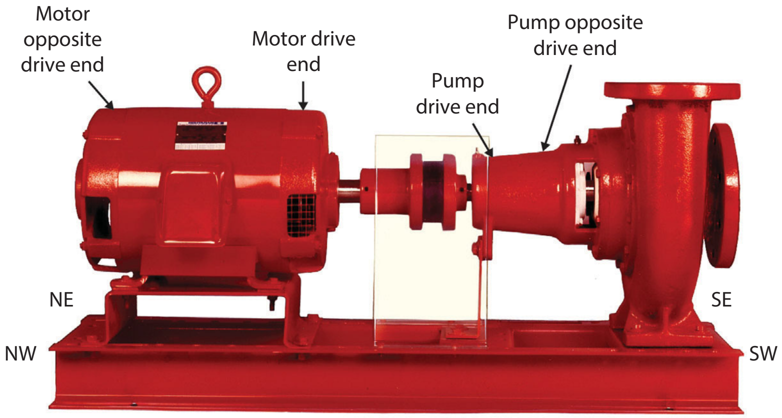

Figure 10.1 Identifying vibration measurement locations.

corner, 2) northeast corner, 3) southwest corner, and 4) southeast corner. Additional baseplate positions can be defined as needed.

Reciprocating compressors have their own unique method of identifying locations of interest. For example, every gas compression cylinder with a piston and piston rod that is connected to the compressor crankshaft is called a throw. It is common to define the throw closest to the flywheel as the #1 throw. The next throw is the #2 throw and so on until all the throws are numbered. Furthermore, it is also important to identify the compressor valves on each given throw. Figure 10.2 illustrates how compressor valves are commonly identified. You can use these two naming conventions to identify a specific valve on a compressor as follows:

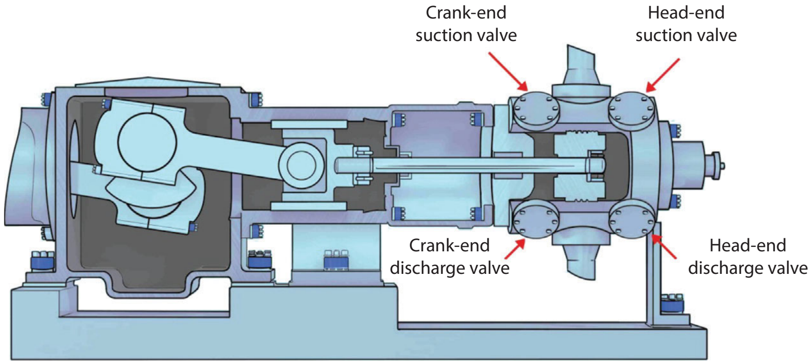

Figure 10.2 Reciprocating compressor location notations.

The crank-end suction valve on throw #3 is running hot. Since there are typically multiple valves on each end of a cylinder, a further refinement of the valve location may be necessary to pinpoint the location of the problem, such as the north or south suction valve, or right or left (facing the crank case) suction valve on the throw #3 is running hot.

Horizontal, vertical, and axial vibration data can be collected on a reciprocating compressor's crankcase when required to conduct detailed assessments and analyses. Location identifiers such as flywheel end, driven end, opposite of flywheel, opposite of driver end can be used to pinpoint a specific machine location. "Horizontal crankcase position at the flywheel end" is an example of a crankcase location description.

Here are some examples of what the location of a given symptom may be telling you.

1. High vibration levels at inboard location of machines may be telling you that misalignment is present.
2. High vertical vibration level relative to horizontal vibration level on a machine may be indicating you have a grout issue or a broken hold-down bolt. Gathering baseplate vibration data across the entire baseplate to generate mode shape of the entire baseplate will help determine if it's a localized issue or if the entire baseplate needs repair or modification.
3. A large difference between and vertical vibration level relative to horizontal vibration level on a machine may indicate you have a resonance or critical speed of some kind. A ratio vertical to horizontal vibration levels of 4 to 1 or greater (or 0.25 to 1 or less depending on the orientation of the resonance or critical) is a good indication of a resonance or critical speed. (See Chapter 18 in *Is My Machine OK?* for additional insight into this topic.)
4. Another cause of high vertical vibration could be inadequate vertical support

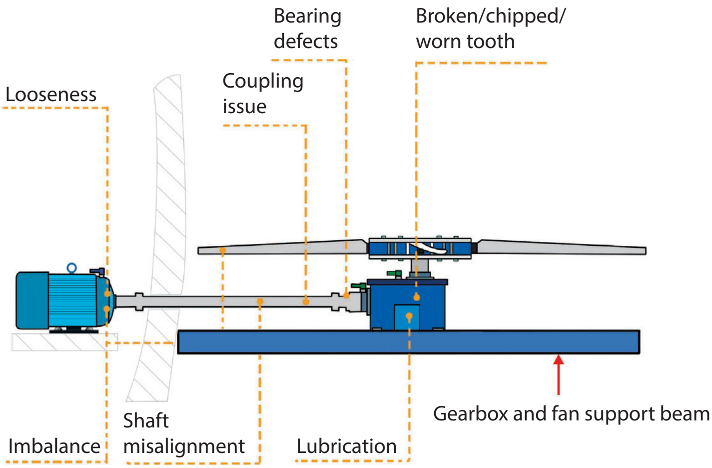

Figure 10.3 Cooling fan support structure.

stiffness, as suggested in Figure 10.3. A lack of stiffness in the support member under the motor and fan could be result in high vertical, as well as horizontal, vibration levels throughout the motor/fan train. A modal analysis of the entire structure would be required confirm or refute this supposition.

5. High temperatures on all bearings in a given machine may be telling you there's a common lubrication problem of some kind—perhaps the oil properties have degraded due to contamination or the oil cooling system is no longer able to provide the oil flow required. However, only a single hot bearing in a machine may signal that either there is a design issue,

that there has been a load change or that the bearing is failing. For example, a sudden increase in the thrust bearing temperature, with all the radial bearing temperatures remaining normal, usually means either that the thrust bearing is failing or that the rotor overall thrust loading has changed. Look for recent changes in the operating conditions to explain possible thrust bearing temperatures jumps. Rotor fouling can also create higher than normal thrust loads and therefore higher than normal thrust bearing temperatures.

6. A high temperature on the discharge of a reciprocation compressor may be an indication of a high compressor ratio or internal problem. The way to distinguish between these two possibilities is to first calculate the theoretical discharge temperature (refer to Chapter 19 of IMMO?) and compare your calculated valve to that observed. If there's a large discrepancy, you can look for hot valves covers. A localized high temperature on a compressor valve is a good indication of a bad or failing valve. (Note: A hot valve may also be an indication of a bad valve seat or gasket.)

10.2 Troubleshooting Problems Involving Multiple Machine-Trains

Here is an example of a situation involving multiple process machines installations. Let's assume there are two pumps in the same application. One is the main pump and the other is the spare pump. They are both taking suction from a process tower with a full level of fluid. Both pumps were installed five years ago and have provided reliable service since their commissioning. Suddenly, the main pump begins to lose flow, so flow is switched to the spare, which seems to provide adequate flow.

The fact that the spare pump is able to provide normal flow suggests that we are dealing with a problem that is specific to the main pump or its piping system. We can also conclude that we are not dealing with a pump design problem, since that spare pump is able to provide the rated flow. These facts lead us to investigate the main pump and its piping system. Possible problems that could suddenly affect the main pump and its piping are:

1. Closed or partially closed discharge valve in the main pump
2. Plugged suction piping on the main pump

3. Plugged discharge pump on the main pump
4. Worn-out main pump

Conversely, if we had found that neither pump was able to pump rated flow, we would have to consider possible causes that could affect both pumps, such as an open spillback line, low tower level, etc.

Here is another example of a problem involving multiple machine trains: Let's assume there are three identical cooling water pumps, driven by steam turbines, and they have all provided reliable service for years. Now you find that only two of the steam turbines are able to bring the pumps up to full speed and rated flow conditions; the third pump is unable to reach rated speed or provide rated flow. These observations point to the real possibility that we are dealing with a pump-train specific issue. In this case, it would be prudent to check the following items on the steam turbine first before proceeding any further:

1. Check the governor speed setting
2. Ensure that the proper number of hand valves are open
3. Ensure that the inlet steam valve to the turbine is fully open

4. Ensure that the governor is functioning properly
5. Check to see if the inlet steam strainer is plugged

If the cause of the problem has not been uncovered at this point, you then must consider internal steam turbine issues and then pump issues.

Take away: When machine trains in identical services are all acting up in a similar manner, investigate causal factors that are common to all of them. However, if only one machine train in a group is acting up, look to issues that are unique to the problematic unit.

10.3 Multiple Versus Single Machine Train Examples

Here are two realistic examples that demonstrate the differences between possible causes of multiple machine trains exhibiting the same symptoms and the possible causes of only a single machine train exhibiting a symptom. (Note: There are many more possible causes that could lead to a low-flow condition in centrifugal compressors and pumps. Only a few potential causes are shown in these examples for illustration purposes.)

Centrifugal Compressor Example (see Table 10.1): The table below shows a comparison of what to consider when dealing with several centrifugal compressors in the same service that are providing less than the expected flow, versus what to consider when dealing with a single centrifugal compressor that is providing less than the expected flow.

Centrifugal Pump Example (see Table 10.2): The table below shows a comparison of what to consider when dealing with several centrifugal pumps in the same service that are providing less than the expected flow, versus what to consider when dealing with a single centrifugal pump that is providing less than the expected flow.

Table 10.1 Centrifugal compressor example.

Symptom	Possible Causes if Symptom is Common to Multiple Machine Trains	Possible Causes if Symptom Only Shows up on a Single Machine
Low Flow on a Centrifugal Compressor	1. Design issue common to all compressors	1. Worn internal clearances
	2. Molecular weight of gas lower than design	2. Driver issue
	3. Low suction pressure	3. Plugged suction strainer
	4. High discharge pressure	4. Wrong impeller(s)
	5. Suction temperature higher than design	5. Wrong speed set point

Table 10.2 Centrifugal pump example.

Symptom	Possible Causes if Symptom is Common to Multiple Machine Trains	Possible Causes if Symptom Only Shows up on a Single Machine
Low flow on a Centrifugal Pump	1. Design issue common to all pumps	1. Worn internal clearances
	2. Specific gravity of pumped fluid is too low	2. Driver issue
	3. Low suction pressure	3. Plugged suction strainer
	4. Tower level too low	4. Wrong impeller(s)
	5. High discharge pressure	5. Wrong speed set point

10.4 Analyzing Noises, Pings, and Knocks

Indications such as mechanical vibration and high temperature are typically localized effects that are relative easy to pinpoint and analyze. For example, normally radial vibration occurs in the plane where significant shaft deflection is occurring and high temperature effects are not transmitted very far from the heat source. In contrast, anyone who has dealt with machinery noises and knocks can attest to the fact that their analysis can be confounding. This is due to the fact that machinery sounds and noises can be transmitted throughout the machine and amplified by machine elements. A problem located at one end of a machine or line may seem to originate at the opposite end of a machine or line due to sound energy transmission. For this reason, it is best not to use sound as the sole means of analyzing a machine.

Here are some common examples of noise issues:

1. Knocking of a reciprocating compressor
2. Noisy rolling element bearing
3. Rattling due to a loose rotating element on a rotor
4. Banging due to a loose flapper in a check valve
5. Leaking relief valve

Each of these issues is unique and requires a different strategy to correctly identify them in the field. For example, let's consider the analysis of knocking on a reciprocating compressor. Isolating the source of the knock is challenging for even experienced analysts because knocking sounds can be transmitted throughout the compressor frame and throws. An analyst may approach this type of problem by using vibration analysis in conjunction with sound to determine when the knock occurs relative to the crank's rotation. The relative phase timing of when the knock occurs relative to events occurring during the combustion or combustion cycle can help pinpoint the source of the knock.

There are several technologies that can assist you in analyzing machine noises:

1. Vibration analysis, which can help identify characteristic frequencies of the vibration and shed light on the cause of the noise.
2. Ultrasonic analysis, which can be helpful in zeroing in on the source of the noise. An electronic process called "heterodyning", which is built in to some ultrasonic instruments, can translate ultrasounds sensed by the instrument into audible sounds that the user can hear and recognize through headphones.
3. Stethoscope, which is a low-tech means of zeroing in on the source of the noise.

In summary, we have to be careful not to be fooled by machine noise. Its actual source and nature can be masked by many complex factors. Use the presence of noise as a starting point and then use other analysis tools to determine what is really going on. To uncover the true nature of the noise, you may need to use another 5Q line of investigation, such as: When is the noise most noticeable? With practice you will improve your ability to decipher machinery noises.

10.5 Seeing the Light at the End of the Tunnel

At this point you should now have a fairly good idea of where the problem is occurring. This means you have completed the first four Qs and are now ready to proceed to the final step in the troubleshooting process. Carefully study and discuss what you have learned so far with the other group members before proceeding to the next chapter.

Troubleshooting Rotating Machinery: Including Centrifugal Pumps and Compressors, Reciprocating Pumps and Compressors, Fans, Steam Turbines, Electric Motors, and More.
Robert X. Perez and Andrew P. Conkey.
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11

Why Is the Problem Occurring?

We have found that the causes of machine problems are quite often elementary in nature, such as low flow being caused by an open bypass or plugged suction strainer or motor overamping resulting from a compressor's inlet gas being heavier than the design value. For this reason, we recommend that, at the outset of an investigation, the troubleshooter assume the root cause of a machine problem is straightforward and easily corrected. At this point all that is required to identify the nature and cause of the problems is basic machine information, such as pressures, temperatures, overall vibration, amp loading, etc., and logic.

If the solution to the machinery problem has not been found quickly, it suggests the problem is probably complex or unique. Once you have evaluated all the common potential root causes and found they do not apply to your observation, you should then move on to the more esoteric potential root causes. This situation calls for more advanced methods to approach the problem. At this point the troubleshooter must ensure that all those participating in the troubleshooting process understand the problem by developing a precise problem statement. Here are some examples of detailed problem statements:

Example #1:

The outboard bearing on the Main Feed Pump is running at high temperature (>210 °F). The operator reported this issue was first detected early this week. The temperature seems to be constant and does not vary with load to time of day.

Example #2:

High vibration levels are seen on all Hydrogen Recycle Compressor when the speed reaches 12000 rpm. This is a new compressor that was installed last month. The vibration levels are very sensitive to load and speed.

11.1 Fitting the Pieces Together

Once you can write a clear problem statement similar to the ones above, you probably already have a good idea of what the problem is because you know what the symptoms are, when they occurred or are recurring, and where the problem seems to be showing up. The next step is putting all the pieces together in order to see what possible cause is the most plausible.

The best method that we have found to confirm or refute potential causes is the cause mapping method. (Notes: 1.The fault tree method, which is similar to cause mapping, can also be used by the reader if he or she wishes to. 2. Visit http://www.thinkreliability.com/ for more information about cause mapping.) Cause mapping is a visual method of displaying the failure or problem under investigation along with all the potential causes of this failure or problem (see Figure 11.1). In one view,

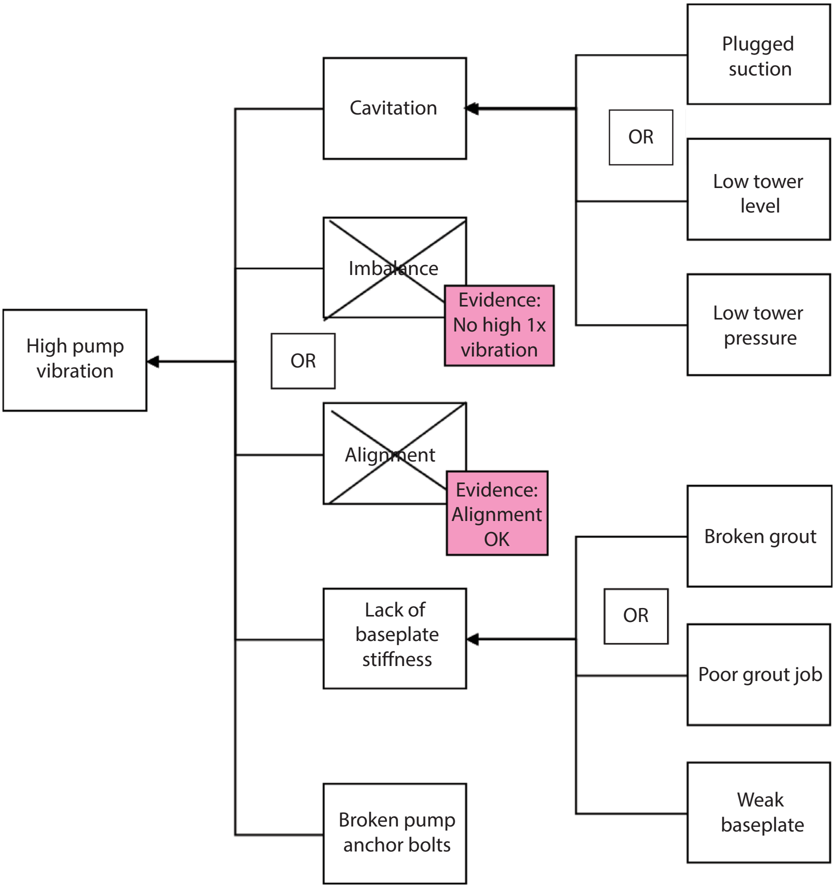

Figure 11.1 Cause map example.

the reader can see how all the potential causes are related to the failure or problem at hand.

Let's study this cause map example in some detail. Cause maps are read from left to right. The box at the far left ("High Pump Vibration") represents the final step in the causal chain.*

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* Readers will notice that all the cause maps in this book have arrows that face toward the left. This is because cause map arrows face in the direction of time

Here, the boxes at the far right of this example represent all the potential first steps in possible causal chains that could lead to a "High Pump Vibration" event. Every path from right to left is a possible chain of events. Let's follow the chain of events at the top of the cause map. Going from right to left, we would read the chain as follows: A plugged suction could lead to cavitation which in turn could lead to high pump vibration. This causal map could be continued to the right by asking: What could lead to a plugged suction and so forth? For simplicity, we choose to stop the cause map at this point.

One advantage of a cause map is the ability to pare down the causal tree by testing the various causal chains against the information collected. For example, one of the causal chains read as follows: Alignment leads to pump vibration. If the alignment is found to be within specifications, you can cross this possibility out and go to the next possibility. If the vibration spectra from the pump do not show any predominant running speed components, i.e., any 1x vibration peak, you can cross out that possibility of mass imbalance being present and go to the next causal chain. Eventually

---

progression, meaning that the final event [later in time] is found at the far left and all potential initiating events [earlier in time] are found on the far right.

you will be left with one causal chain remaining. This causal chain is the most probable cause.

11.2 Reciprocating Compressor Example

Let's consider a cause map for determining the cause of a high discharge temperature on

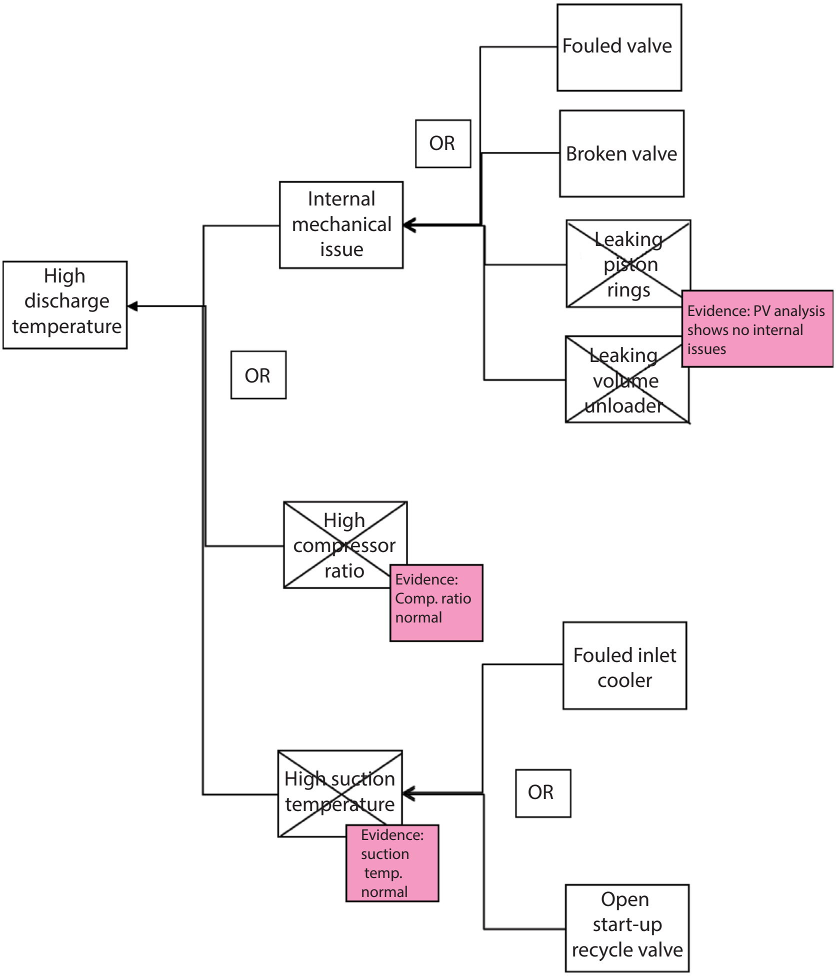


Figure 11.2 Reciprocating compressor fault tree.

a reciprocation compressor (see Figure 11.2). For the sake of simplicity, we can start from the bottom up. If we find that the suction temperature is normal, we can move up to the next possibility. Next, if we find that the compression ratio is normal, we can move up to the next possibility. There are four remaining possibilities in the cause map:

1. Fouled valve(s)
2. Broken valve(s)
3. Leaking piston rings
4. Leaking volume unloader

If a compressor performance analysis indicates there are no internal problems, we can turn our attention to the valves. Using an infrared temperature gun, all valve cap temperatures should be checked. Any valve caps running significantly higher than the rest of the cylinder indicate the probable location of bad valves. This is a good example of how the location of a problem can provide vital information concerning the nature of the problem.

11.3 Troubleshooting Matrices

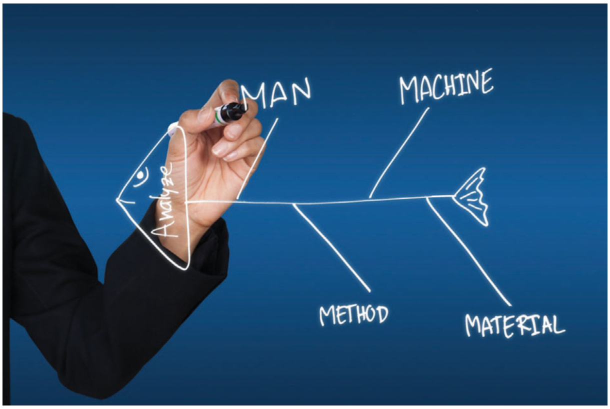
To save time, we have gathered basic troubleshooting matrices and tables for common process machine types in Appendix B. There is also a special matrix that covers hot bearing issues. Appendix B has troubleshooting guides for:

1. Centrifugal Pumps
2. Centrifugal Compressors
3. Reciprocating Compressors
4. Reciprocating Pumps
5. Fans
6. Steam Turbines
7. Electric Motors
8. Hot Bearing Issues

Consider Appendix B as a starting point for troubleshooting. You should use whatever resources at your disposal to identify all the possible causes that should be considered. The original equipment manufacturer, equipment manuals, in-house experts, and consultants are all potential information sources that can be used to augment the basic matrices and tables in Appendix B.

11.4 Assessing Machine with Multiple Symptoms

In the real world, we rarely see straightforward, "textbook"-quality machine issues. Instead, there are complications that can often cloud the true nature of a machinery problem. A less than ideal foundation, poor piping flow conditions, piping strain, etc., can all result in complex secondary effects that can produce a set of symptoms that can be difficult to analyze.



Machinery troubleshooting becomes even more complicated when dealing with multiple symptoms that seem to be unrelated. One example of this situation would be a machine that is vibrating and has high bearing temperatures. Is the vibration problem causing a bearing issue or is the high bearing temperature issue causing the high vibration? How does a troubleshooter attack this situation?

There are two possibilities:

1. The symptoms are completely unrelated.
2. The symptoms are interrelated.

Here is a general approach that can help you make sense of a multisymptom situation:

Start by postulating a machine situation that could lead to all of the observed symptoms. If a plausible machine condition can be found that can explain all the observed system, then proceed with your analysis based on your hypothesis. If no conceivable machine condition can be found to explain all the systems, assume you are dealing with multiple maladies. If you suspect multiple issues, address the most pressing issue first. For example, if there is a temperature falling in the danger region, but vibration is at a marginal level, go after the temperature issue first. Once one machine malady is identified and corrected, you can then proceed with the next most pressing issues, and so on.

Troubleshooting Rotating Machinery: Including Centrifugal Pumps and Compressors, Reciprocating Pumps and Compressors, Fans, Steam Turbines, Electric Motors, and More.
Robert X. Perez and Andrew P. Conkey.
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12

Analyze, Test, Act, and Confirm (Repeat as Needed)

Complex troubleshooting is often an iterative process, which requires the investigator to follow a number of promising paths and leads before a final solution is found. Various approaches, analysis methods, and field trials may be required before the problem is properly identified and clearly understood. There may be false starts and blind alleys encountered along the way before the actual physical root cause is found and properly addressed.

Figure 12.1 depicts how a troubleshooter must hone in on the true cause of a problem. First, he is faced with considering the entire "universe" of possible causes. Using an iterative process,

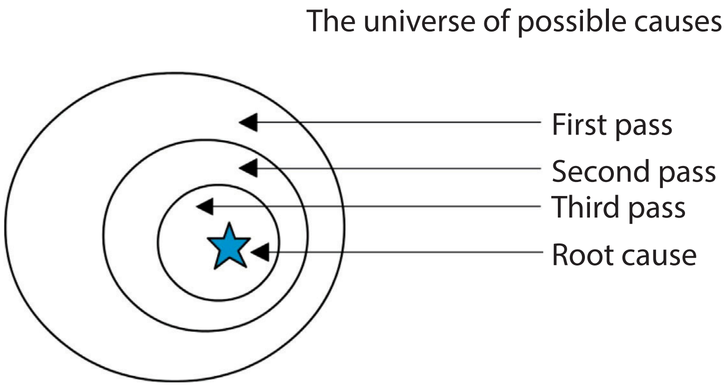

Figure 12.1 Zeroing in on the true nature of the problem.

the investigator slowly and deliberately zeros in on the cause of the problem. Gradually, through persistence and investigation skills, the list of viable causes shrinks until the physical root cause is identified.

Remember to always start your investigation by checking those factors that are the easiest to verify first. You may quickly discover the problem is simple in nature. For example, a low-flow issue might be due to operating the pump at the wrong speed, having a pump rotor turning in the wrong direction, or having a plugged suction strainer. Once the obvious things are ruled out, you can consider more complex possibilities, such as a pluggage in the suction vessel or discharge piping.

Consider this example: First you determine the problem is probably related to the steam turbine that is driving a centrifugal compressor (first pass). This revelation allows you to ignore the rest of the compressor train at this time. Next, your initial field analysis reveals you have a vibration problem (second pass). This observation allows you to concentrate on only those potential causes that could be related to vibration. Then, you determine the problem is centered around the opposite drive end (ODE) bearing housing (third pass). This discovery allows you to concentrate your analysis efforts further, allowing you to perform detailed vibration survey. Eventually a vibration mode shape analysis on the steam turbine reveals a lack of stiffness due to broken grout under the ODE bearing housing (Physical Root Cause).

This example illustrates that problems are rarely solved during the first pass. There may be times you get lucky and hit on the root cause on your first stab; but typically it is the methodical, persistent troubleshooter that discovers the true root cause of a complex problem. There have been instances noted by one of the authors in which it has taken years and multiple occurrences of the problem to fully understand what is really going on.

12.1 The Iterative Path to the Final Solution

After you have systematically analyzed all the data and observations, you should have a good idea about what is going on and what the most probable cause of the problem is. At this point your options are to:

a. Accept that you have uncovered the most probable cause and act on that knowledge or
b. Develop new theories that can be tested under field conditions in order to increase the probability of success. The more plausible causal chains that are postulated the better your chances of success. (Go to Appendix B to review troubleshooting matrices for common process machines. These matrices may be useful for developing a list of plausible root causes.)
c. When applicable, use analytical models, such as rotordynamic or computational fluid dynamic modeling to validate theories.
d. If you are not confident that the root cause has been found, you should go back to the “what” questions to redefine the issue and decide if additional data or

testing is required. For example, let's say you are analyzing a hot journal bearing and found that oil flow has little effect on the bearing temperature. You discovered that varying the oil supply pressure by 5 psi only changed the bearing temperature by 1 or 2 degrees. You also found that the supply oil temperature is normal. Using this new information you can redefine the problem as follows: *There is a hot inboard radial bearing on the Main Charge Pump. The oil supply temperature to the bearing is normal. We found that varying the oil supply pressure had very little effect on the bearing temperature. We will now look to see of the bearing temperature increase correlates with any recent process event.* The troubleshooter can continue on this action loop until the problem is resolved.

Once you have decided to act, here are your choices:

- Make no immediate operating changes or maintenance adjustments but continue to monitor the machine's condition: Choose to either continue to monitor the machine based on the present inspection schedule, or increase monitoring intervals and/or points. Look for signs of deterioration and act accordingly.

- Test and assess: 1) Vary operating condition speed, flow, pressures, suction level, etc. and observe how machine responds. 2) Check for off-design machine operation due to off-design process conditions, open bypasses, restrictions, control issues, etc. Correct any simple problems such as open bypass lines, low suction levels, and off-design conditions as you find them. If the problem can be resolved with simple field adjustments, then you are done.
- If you determine that you are dealing with a <u>system issue</u> that cannot be corrected on-line, you will need to shut down. Here are few examples of issues that need to remedied off-line:
  a. Clearing line blockages
  b. Repairing leaking valves
  c. Replacing or adjusting troublesome control valves
  d. Cleaning fouled coolers
- If you determine that you are dealing with a <u>machine issue</u>, here are your options:
  a. Switch to spare, if available

b. Plan a shutdown for balancing, alignment, oil change out, piping modifications, regrouting, etc.
c. Plan a shutdown for repair (i.e., full machine overhaul if needed). Reduce stresses if possible while waiting for repair by reducing process induced loads
d. Shutdown immediately for balancing, alignment, oil change out, piping modifications, regrouting, etc.
e. Shutdown immediately for repair

Together with maintenance and operations, discuss the findings and options; then, arrive at a consensus decision.

The final step in the troubleshooting process is to confirm that your actions have indeed solved the problem. It's always a good idea to gather some data after the "solution" has been implemented to send out to management and all those that were affected by the problem. This step ensures that the problem is indeed solved and garnishes valuable publicity for you and your team's efforts. As word gets out that you have a successful track record in solving machinery problems, you will be asked to get involved in more problems in the future.

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13

Real-World Examples

In the next few pages are some examples of real-world machinery problems that were solved by systematically gathering and analyzing field data and employing the methods covered in this book. A variety of examples, ranging from simple to complex are included here to illustrate the 5Qs troubleshooting methodology can be applied universally to all types of machinery problems.

13.1 Case Study #1

Title: Water pump won't pump: 1800 rpm motor accidentally replaces 3600 rpm motor

1. What seems to be the problem or what are the symptoms?
   A centrifugal pump in water service won't deliver enough flow to satisfy the current production needs.
2. What is your assessment of the problem?
   If pump flow isn't increased, cooling water flow to the plant could be interrupted or curtailed. Due to the high potential impact of reduced water flow, solving this problem is considered vital to the health of the plant.
3. What additional machine data do I need to collect?
   A field audit did not reveal any vibration issues, open bypasses, partially closed valves, etc. Pump performance seems to be the only problem experienced.

4. Who knows the most about the problem?
   By talking to the operators, it was discovered that the pump motor had been replaced recently. The mechanics confirmed that the electric motor driver had been replaced with a surplus motor from another unit.
5. When do the symptoms show up?
   The low flow was only experienced after the electric motor was replaced. Operations never experienced a flow problem with the old motor.
6. Where do the symptoms show up?
   The problem is only seen on this pump. All other pumps in the area have normal flows.
7. Why is the problem occurring?
   The predominant theory is that the wrong motor was recently installed.
8. Analyze, Test, Act, and Confirm
   A speed check confirmed that the pump and motor are turning at 1800 rpm instead of the rated 3600 rpm. In their haste to install a new motor, the electricians failed to notice the replacement motor was designed for 1800 rpm.

13.1.1 Closing Comments

This case study indicates the importance of checking all equipment specifications whenever replacements are selected. Rated speed, pressure and flow ratings, metallurgy, etc., must all be checked and double checked before selecting and installing replacement units in the field.

13.2 Case Study #2

Title: In-line centrifugal pump bowl exhibits cavitation-like symptoms.

1. What seems to be the problem or what are the symptoms?
   Vibration levels on a 20-horsepower in-line centrifugal pump were found to be significantly higher than recent

values. We were asked to investigate the problem.

2. What is your assessment of the problem?
   The highest vibration level observed was 0.62 ips (rms) on the pump. From the table below, we can gather that 0.62 ips (rms) falls in the "damage occurs" range. The vibration spectra from the highest vibration reading shows broad banded frequency content, which is indicative of cavitation.

3. What additional machine data do I need to collect?
   After a field audit, it was decided to also check pump suction conditions to see if suction pressures or liquid levels had changed.

4. Who knows the most about the problem?
   The operators were interviewed first. They confirmed that this is a recent issue. During the interview it was determined that the variable speed drive was adjusted recently to get more flow from the pump. For this reason, the electricians were interviewed to better understand what was going on.

Table 13.1 ISO Evaluation standard (1).
Note: This vibration evaluation standard is intended for machines operating with rotational speeds between 600 and 12,000 RPM. The standard only applies to overall (unfiltered) casing vibration readings in the frequency range of 10 to 1,000 Hz.

SI Units		**English Units**		**Machines <15 Kw (20 HP)**	**Machines between 15 and 75 KW (20 to 100 HP)**	**Machines >75 Kw (100 HP)**	**Steam turbines, gas turbines, generators, etc.**
mm/sec rms	**mm/sec zero-peak**	**in/sec rms**	**in/sec zero-peak**				
0.28	0.40	0.01	0.02	Newly Commissioned Machinery	Newly Commissioned Machinery	Newly Commissioned Machinery	Newly Commissioned Machinery
0.45	0.64	0.02	0.03	Newly Commissioned Machinery	Newly Commissioned Machinery	Newly Commissioned Machinery	Newly Commissioned Machinery
0.71	1.00	0.03	0.04	Newly Commissioned Machinery	Newly Commissioned Machinery	Newly Commissioned Machinery	Newly Commissioned Machinery

1.12	1.58	0.04	0.06	Unrestricted Operation	Newly Commissioned Machinery	Newly Commissioned Machinery	Newly Commissioned Machinery
1.8	2.55	0.07	0.10	Unrestricted Operation	Unrestricted Operation	Newly Commissioned Machinery	Newly Commissioned Machinery
2.8	3.96	0.11	0.16	Restricted Operation	Unrestricted Operation	Unrestricted Operation	Newly Commissioned Machinery
4.5	6.36	0.18	0.25	Restricted Operation	Restricted Operation	Unrestricted Operation	Unrestricted Operation
7.1	10.04	0.28	0.40	Damage Occurs	Restricted Operation	Restricted Operation	Unrestricted Operation
11.2	15.84	0.44	0.62	Damage Occurs	Damage Occurs	Restricted Operation	Restricted Operation
18	25.46	0.71	1.00	Damage Occurs	Damage Occurs	Damage Occurs	Restricted Operation
28	39.60	1.10	1.56	Damage Occurs	Damage Occurs	Damage Occurs	Damage Occurs
45	63.65	1.77	2.51	Damage Occurs	Damage Occurs	Damage Occurs	Damage Occurs
71	100.42	2.80	3.95	Damage Occurs	Damage Occurs	Damage Occurs	Damage Occurs

5. When do the symptoms show up?
   The cavitation symptoms did not show up before the speed adjustment. Now they show up at all flows.
6. Where do the symptoms show up?
   High vibration levels and noise seem to be concentrated on the pump.
7. Why is the problem occurring?
   During the discussion with the electrical specialist, it was discovered that the pump speed was initially limited to 3000 rpm. The speed limit was incorporated to reduce the pump's net positive suction head required (NPSHR). During the pump selection, it was found that the only way for the pump to properly function was to limit pump speed. Under the reduced speed conditions, there was adequate suction head for the pump to operate properly, thereby reducing the likelihood of cavitation occurring under normal operating conditions. However, to increase production rates, the pump speed was increased to its maximum speed of 3600 rpm. At this higher speed, cavitation was inevitable due to the higher NPSHR requirement.

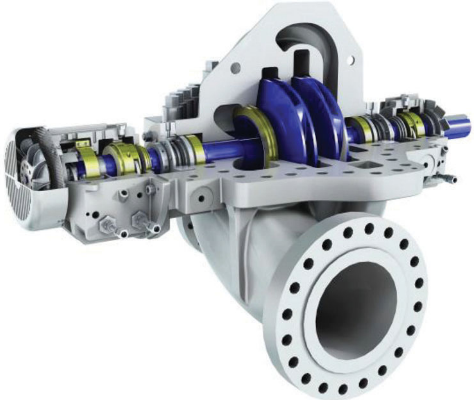
8. Analyze, Test, Act, and Confirm
   As a test, we decided to reduce the pump speed back to 3000 rpm. As expected, pump vibration and noise levels dropped back to normal levels.

13.2.1 Closing Comments

This case study illustrates the importance of communication between different site organizational groups. A discussion between operations, maintenance, and engineering could have averted this problem. Major programming changes to critical machinery should be discussed by everyone affected before being implemented.

13.3 Case Study #3

Title: A newly installed centrifugal pump has never been able to boost pipeline flow as expected.



1. What seems to be the problem or what are the symptoms?

   Operating personnel found that a 3-stage, 125 HP, motor-driven, centrifugal pump in pipeline service was not able to generate any significant increase in pipeline flow whenever it was placed in service. The electric motor is rated at 3560 rpm and is driven with a variable frequency drive (VFD).

   This surplus pump was removed from another facility and installed in this location in order to boost flow in the pipeline. The hope was that this pump would produce a pressure rise in the pipeline and therefore increase the total flow through the pipeline. At the rated flow and speed, the pump was expected to generate about 150 psi of pressure rise. However, when the pump was commissioned and brought up to rated speed, operators never saw any significant increase in flow or pressure rise across the pump. One of the operators noted that pressure rise across the pump could be increased from about 15 psi to slightly over 50 psi by pinching the pump's discharge valve. Operations confirmed that station valves were all in their proper positions when the pump was placed in service.

2. What is your assessment of the problem?
   There appeared little risk to the equipment or operating personnel. Vibrating and sound levels are low when the pump is running. The only risk was economic risk due to a loss of revenue due to the lack of pressure boost.

3. What's at stake?
   Since this pump is only one of several pumps on the pipeline, Operations was still able to deliver product with the remaining pumps. However, without realizing an increase in flow with this pump, there was an incremental loss of pipeline flow and a corresponding incremental loss of revenue. We rated the economic loss of this situation at a "medium" level, i.e., about $1,000 per day loss of lost revenue. The need to recover the additional incremental flow was significant enough to get a team of one engineer, a control specialist, two operators, a maintenance superintendent, and an operations supervisor on-site to troubleshoot the pump.

4. What additional machine data do I need to collect?

   Initially, it was thought that the problem could be caused by either the pump turning in the wrong direction or that the VFD (variable frequency drive) was not properly calibrated. We decided that we needed to take a vibration meter, speed tachometer and a set of pressure gauges out to the site in order to check pump performance. A complete set of manufacturer's pump performance data was also taken to the field for comparison with the field-collected data. We felt that we also needed to check the rotation of the pump before performing a field performance test, just in case this was a factor in this problem.

5. Who knows the most about the problem?

   We decided we needed someone to verify that the VFD was functioning properly, so we asked an instrument tech to monitor the output frequency from the drive during our testing. The instrument tech set up a laptop to record the output frequency to the motor, pump pressures, and motor amps during the testing.

The operators were quizzed about when the problem was first noted. They confirmed that the pumps had never worked properly from day one.

The operators rechecked all the valve positions before the field test to ensure they were in the proper position.

Note: Field personnel also reported that the pump suction screen had plugged up several times since the pump's installation due to large quantities of pipeline scale. However at the time of testing, the pump screen differential pressure was very low (<5 psi).

6. When do the symptoms show up?
   Operators confirmed that the pump was never able to generate the rated pressure differential (150 psi). At the rated speed, the pump differential is about 15 psi.

7. Where do the symptoms show up?
   The problem was only showing up at this pump. All the pumps on the pipeline seemed to be unaffected by this issue. This observation seemed to rule

out the fluid properties being a source of the problem.

8. Why is the problem occurring?

   There were several possible causes considered:

   a. The pump was turning the wrong direction
   b. The motor VFD was not calibrated properly and therefore not running at the correct speed
   c. The motor was an 1780 rpm motor instead of a 3560 rom motor
   d. Centrifugal pump rotor was plugged or fouled due to ingestion pipeline scale
   e. There is some flow bypassing occurring that has not been identified

9. Analyze, Test, Act, and Confirm

   The direction of rotation was checked first and was found to be correct. The motor rated speed was confirmed to be 3560 rpm as expected. Then, the pump speed was checked with a speed tachometer and was verified to be correct. We found that the pump was turning at 3560 rpm with an input supply frequency of 60 Hz. At 3560 rpm, the pump differential was found to be only 15 psi, but yet the motor was discovered to be drawing rated amps. The high amp load seemed to suggest that the pump was moving a substantial amount of liquid.

At this point, we began to think that perhaps the pump rotor may be fouled. However, one team member began to suspect that perhaps the pump station recycle line was open or partially open, allowing product to recycle around the station. This condition would explain the low differential pressure across the pump and the high amps. (A high pump flow caused by the extra recycle flow would cause the pump to run-out to the end of the performance curve. At the end of the curve the pump differential would be well below the rated pump differential pressure.)

Before we pulled the pump case for inspection, we decided to inspect the station bypass motor valve and eventually discovered it was not properly assembled. When the motor valve indicator showed it was closed, it was really 85% open, allowing recycling. Once the motor valve was properly adjusted, the pump was able to generate the rated differential pressure and appeared to be operating normally.

13.3.1 Closing Comments

This centrifugal pump case study illustrates the importance of intuition, field observations and inspections. One of the troubleshooting team members had a feeling that there was something wrong with the station bypass motor valve. He realized that due to its construction that he couldn't visually confirm it was closed. On a hunch, he asked that a valve representative visit the site and confirm the valve setting. The valve representative confirmed that the way the motor valve had been assembled it was 85% open when the valve indicator showed it was closed. Takeaway: Always confirm "closed" valves are really closed. Not all valve position indicators tell you the truth.

13.4 Case Study #4

Title: 5000 HP Electric Motor has a critical speed problem

1. What seems to be the problem or what are the symptoms?
   Immediately after the start-up of a 5000 hp, 3600 rpm electric motor, vibration levels climb to over 6 mils (pk-to-pk) on one end of the motor.
2. What is your assessment of the problem?
   By studying the vibration severity chart in Figure 13.1, we can see that 6+ mils at 3600 rpm falls into the "monitor closely" range.
3. What's at stake?
   This motor is part of a highly critical power train. It supplies extra horsepower for the axial air blower that

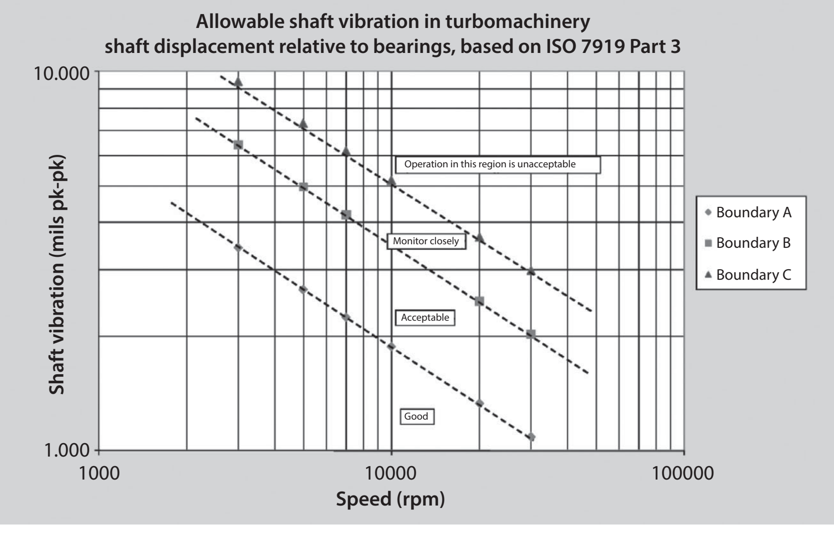


Figure 13.1 ISO 7919 Part 3 vibration guidelines.

sends compressed air into a de-coking vessel. Without the motor, the process unit would be down, resulting in an economic penalty of over $250,000 per day. Furthermore, if the motor fails catastrophically, there could be costly secondary damage to the driven equipment. There is a potential process outage of everywhere from 5 days to 30 days, depending on the overall damage.

4. What additional machine data do I need to collect?

   A field audit was performed to understand the overall condition of the electric motor and power train. No other field issues were discovered other than the motor vibration.

   The investigation team decided to collect start-up and shutdown data on the electric motor off of all the existing motor proximity probes. Additionally, accelerometers would also be installed on the motor casing to determine if any structural resonances were present. Once all the data was collected, Bode plots would be generated to determine if there were any critical speeds near the operating speed.

5. Who knows the most about the problem?
   The operators, mechanics, and process engineers were interviewed to better understand the problem. When it was discovered that one of the motor couplings was redesigned during a recent modification to the power train, the project engineer and equipment manufacturer were also interviewed.

6. When do the symptoms show up?
   a. Everyone agreed that the high vibration levels began occurring after the coupling modification.
   b. The symptoms only occur at full speed conditions.
7. Where do the symptoms show up?
   The high vibration levels were only occurring on the end of the motor where the new coupling was installed.

8. Why is the problem occurring?
   All the findings seem to confirm that the new coupling dropped one of the motor's lateral critical speeds near the operating speed. The problem occurred after the change and on the end of the motor with the new coupling. The Bode plots confirmed there was a highly

tuned critical speed just below operating speed.

9. Analyze, Test, Act, and Confirm

   Rotordynamic modeling confirmed that the observed symptoms were the result of a critical speed problem. Once the root cause of the problem was determined, modeling was used to determine potential solutions. Of all the options, the best option seemed to be replacing the existing coupling with one of a lighter design. A design called a reduce moment coupling was chosen. The model indicated that the lighter coupling would move the critical speed sufficiently away from running speed to allow reliable operation.

   The new coupling did indeed correct the problem. The electric motor has been operating at acceptable vibration levels ever since.

13.5 Case Study #5

Title: A hydrogen recycle compressor in a hydrotreating unit can't generate sufficient recycle flow after plant start-up.

1. What seems to be the problem or what are the symptoms?
   After a process outage lasting about two weeks, operations started up a hydrogen recycle compressor in order to establish recycle flow. However, instead of a healthy 120 psi pressure rise across the compressor, only about 20 to 30 psi of pressure rise was being created by the compressor. The compressor is driven by an electric motor through a gear box, so once the motor is started the speed is constant. At the low differential pressure, there was not enough flow produced to satisfy the process requirements for start-up.
2. What is your assessment of the problem?
   The process unit that this compressor serviced was vital to the rest of the

refinery. There would be a major interruption to the rest of the refinery without this compressor.

3. What's at stake?

   The cost to the plant could be as high as $1,000,000 per day if the compressor wasn't available for service in the next 48 hours.

4. What additional machine data do I need to collect?

   A field audit did not uncover any additional mechanical problems. There were no signs of vibration, base plate issues, auxiliary problems, etc. Initially we decided to perform a performance assessment to determine if the compressor was performing properly.

5. Who knows the most about the problem?

   The mechanics were interviewed to determine if any work had been done on the compressors. No work had been done.

   The operators were interviewed to determine if process conditions were normal. One fact that arose while talking to the operators was the fact the pure hydrogen was being used for the unit start-up. In some similar recycle units, a combination of hydrogen and nitrogen was used to get the proper molecular weight of the gas.

6. When do the symptoms show up?
   Interviews revealed that the compressor was working properly before the process outage. Something seemed to change in the way the compressor was being operated at the time of start-up.
7. Where do the symptoms show up?
   The problem was showing up at the compressor at full speed. The lack of pressure rise across the compressor was the problem.
8. Why is the problem occurring?
   There were only two possible causes considered: Either the compressor was worn out or the start-up gas was too light to generate the proper compressor pressure rise.

   Since the compressor seemed to be operating fine before the outage, the possibility of the compressor being worn out was low. The most probable cause of the problem was that the start-up gas was too light.

9. Analyze, Test, Act, and Confirm

   Performance calculations showed that the compressor was performing properly. The problem was that the pure hydrogen gas available at start-up was too light. The design gas molecular weight was about 8, while pure hydrogen has a molecular weight of 2. A trace amount of hydrocarbons in the gas mixture during normal operating conditions has a major effect on the average molecular weight of the gas due to the relative lightness of hydrogen. Therefore, pure hydrogen will only create a differential pressure that's 25% of differential predicted with the normal process gas.

   When the start-up gas was later "spiked" with nitrogen to increase the average molecular weight of the gas, sufficient differential pressure was created to allow the unit to start up. These results confirmed that the root cause of the problem was that the start-up gas was too light.

13.5.1 Closing Comments

This case study illustrates the importance of gas density when dealing with centrifugal compressors. A change of gas properties of greater than 10% can have major effects on compressor performance. Potential differences between normal and start-up gas conditions should be addressed during the initial compressor design and selection phase.

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14

The "Hourglass" Approach to Troubleshooting

When approaching a new field troubleshooting problem, it is always helpful to visualize an approach with the shape of an hourglass (see Figure 14.1). During the initial phase, you should maintain a broad view of the problem, similar to the top of an hourglass. Avoid zeroing in on any one cause initially and consider all possibilities. Focusing on only one possible cause too early can derail the investigation and waste time and money.

Next, focus in on the root cause by gradually eliminating possible causes. Once the most likely cause is determined, it's time to act and confirm. During this time, you are in the neck of the

Figure 14.1 Hourglass approach.

- Funnel—pertinent data collection
- Focus—analysis, decide, act and confirm
- Think globally—Application of the findings

hourglass. All your resources at hand should be used to attack the problem in order to correct the malady in an expeditious manner. Once you have confirmed that the problem is solved, you are ready to move to the bottom of the hourglass.

World-class organizations take advantage of the learnings garnered from troubleshooting efforts by applying the findings across their organizations. The key question to ask yourself at the end of an investigation is: Can this learning (or learnings) be applied elsewhere in the organization? By thinking globally the organization can avoid a similar issue, by acting preemptively.

Here is a simple hourglass approach example:

Let's say you discover that the pump-to-motor misalignment led to high vibration levels on a hot oil pump. You eventually determined that the primary cause of the misalignment was vertical thermal growth that was not accounted for during the alignment process. If during the investigation, you discover that the mechanics had never been trained to account for thermal growth, you might want to recommend that hot alignment training with a focus on correcting for thermal growth be provided across the site.

Hourglass approach example #1:

250 HP solvent circulation pumps were found to be vibrating and extremely noisy under normal flow conditions. After several days of field testing, it was discovered that the pumps were grossly oversized for the application and that the pumps were prone to internal flow recirculation due to their hydraulic design. (Note: These pumps both had a suction specific speed number of over 17,000. Today, pump designers try to keep suction specific speed under 11,000.) It was also discovered that the common recirculation line originally installed to keep the pumps near their best efficiency flow was closed in order to reduce power costs. Pump vibration levels returned

to acceptable levels after the spillback line was returned to service.

This is a good example of a troubleshooting exercise that uncovered a hidden system problem. It was the combination of an oversized pump with a limited flow range and closed spillback line that caused severe vibration and pressure pulsations due to internal recirculation. A better understanding of the pump/system interactions allowed these pumps to remain in service.

Two key lessons were gleaned from this field study: 1) Keep centrifugal pump suction specific speed values below 11,000 and 2) If low pumping flows are expected, install a recirculation line to keep the pump close to its best efficiency point at all times. Following these two design guidelines has reduced the frequency of flow induced centrifugal pump vibration events on new installations considerably.

Hourglass approach example #2:

Numerous gas turbines of the same model were experiencing early failures. These gas turbines were forced to shut down due to either high vibration, loss of power, or high exhaust temperatures. One fact all these failures had in common was they all seemed to occur near the end of the manufacturer's recommended run length. During the disassembly of one of these failed gas turbines, a smoking gun was found: Staking pins that were designed to hold the first stage power recovery blades in place were found to be severely corroded. Further investigation revealed the pin metallurgy was inadequate for the actual conditions expected at the inlet of the first stage power wheel. Once a staking pin corroded significantly, the affected blade would move axially and start to rub against a stationary nozzle, causing high vibration levels before eventually failing catastrophically.

The following facts were uncovered from the investigation: 1) The problem was common to only one gas turbine model type, 2) the problem was time dependent, and 3) the initial failure mechanism was the corrosion of the staking pins holding the power recovery wheel blades in place. In order to reduce the frequency of this mode of failure, a new pin metallurgy was eventually selected. The remaining in-service gas turbines with old metallurgy were monitored by boroscoping on a quarterly basis until they could be upgraded with new pins. This preempted approach dramatically reduced the number of premature failures in the fleet due to pin corrosion.

14.1 Thinking and Acting Globally

Every machine problem, failure, or issue an organization experiences is an opportunity to learn something new about its machines and processes. We can capitalize on these experiences by thinking globally in order to apply our learnings across the organization. Here are a few ways to get the word out:

- Company-wide bulletins
- Modification of existing operating or maintenance procedures
- Modification of purchasing specifications
- Information sharing at in-house group meetings

Sharing your learnings throughout the company maximizes everyone's time and effort, while minimizing valuable resources. It is very rewarding to uncover and correct previously hidden issues that may be present in your plant before they can lead to dire consequences. Your management will greatly appreciate all the positive effects realized across the site due to your troubleshooting efforts.

Troubleshooting Rotating Machinery: Including Centrifugal Pumps and Compressors, Reciprocating Pumps and Compressors, Fans, Steam Turbines, Electric Motors, and More.
Robert X. Perez and Andrew P. Conkey.
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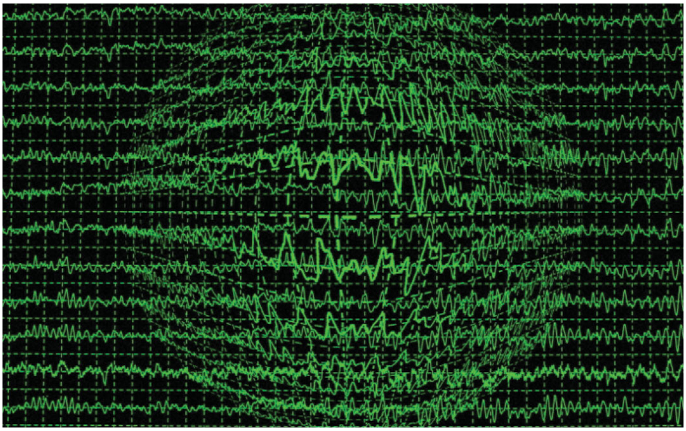
15

Vibration Analysis



If during the field audit phase of the investigation, it is discovered that vibration is the primary concern, then there is another "what" question to ask: What is or are predominant vibration frequency or frequencies seen in the vibration spectra? The frequencies found during the initial vibration analysis can provide important clues to the nature of the problem.

Vibration is the back and forth movement or oscillation of machines and their components. Most industrial devices are engineered to operate smoothly and avoid vibration, not produce it. Vibration in industrial equipment can be both a sign and a source of trouble, possibly indicating mechanical problems or internal deterioration. If not corrected, it can cause additional damage. In critical process machinery, a machine running with vibration levels close to zero is the ideal.

The following section presents a quick overview of vibration and its analysis for those unfamiliar with this technology.

15.1 Vibration Analysis Primer

The topic of vibration analysis is complicated and requires years of study and practice to master. However, there are numerous excellent reference materials available to newcomers who want to develop a working knowledge of vibration analysis. Here we will cover some basics concerning the process of vibration analysis. Some of the challenges associated with vibration analysis are determining why particular vibration characteristics are occurring.

One example of a well-studied machine problem causing vibration is shaft misalignment, which can arise due to manufacturing error, twisted or bent housing, excessive pipe strain, and so forth. The vibration signals generated by these forms of misalignment tend to have particular frequency characteristics. The waveforms generated by specific mechanical maladies makes vibration analysis an exercise in pattern recognition. For example, misalignment-type issues often create waveforms composed of two times the running frequency. Therefore, if we see a waveform with two times the running frequency component during the analysis process, we should suspect that misalignment is present.

Vibration analysis is the process of evaluating vibration data that have been collected and processed and then relating the findings to potential problems that may exist in the mechanical system under study. To be able to do this, it is necessary to understand some basic characteristics of vibrating systems. Vibrating systems can best be understood using four primary properties: mass, stiffness, damping, and the excitation source or sources.

Consider a passenger vehicle as an example of a dynamic system. The vehicle body has substantial mass and is supported by springs and dampers (tires can be included). Within the vehicle body is the engine, which is part of the mass of the vehicle itself and is connected to the car body via motor mounts, which also have stiffness and damping. When the vehicle is at rest and the engine is off, the system will not vibrate. However, when the engine is started, the loads generated by the engine cause the whole car to vibrate to some degree. That is, the engine acts as an exciter. The degree to which the car responds, or vibrates, can be controlled by controlling the speed of the engine. When the car is put in motion, different elements within the car tend to vibrate differently. The steering wheel will vibrate to some degree, the dash to another degree, and the console shifter vibrates in another way. You can discern the different responses of each part by your sense of feel. You can also compare the response as the engine speed changes. The road surface and wind loads also provide more excitation to the response of the vehicle.

This simple example describes how numerous factors that can excite the response of the car and elements within the car. The primary sensor in the vehicle is the driver, or even one of the passengers. The driver feels vibrations from the seat as well as the steering wheel. Drivers that are familiar with vehicles can often distinguish one vibration source from another and can react accordingly when the vibration changes. One example is the rumble divots that are along the shoulder of many US highways. These are designed so that when your vehicle passes over these you are subjected to a startling vibration that hopefully keeps you from driving off the road. Table 15.1 is a very simplified cause and effect relation of some excitations and a vehicle.

One other sensor set that is often relied upon within a vehicle is the human ear. Sound is just another means of detecting mechanical vibrations. Our ears are specialized frequency detectors that can discern subtle changes in mechanical vibration that lead to airborne vibrations. Sounds can play a critical role in assessing the behavior and condition of a vehicle.

Most process machines are similar as far as their basic designs. They all have casings, rotors, seals, bearings, and foundations. One example is an axial compressor. The compressor's primary function is to change the thermodynamic properties of a gas stream by accelerating it and then converting fluid kinetic energy into pressure energy in the diffuser sections of multiple stages. The compressor's rotor is supported by bearings, which are supported by bearing housings, which are ultimately supported

Table 15.1 Vehicle vibrations and driver sensing.

Vibration Experienced	**Sources**	**Severity/Action**
Steering wheel shimmies	Issue with front wheel or alignment of wheels	High (possible wheel or steering failure). Get wheels checked and repaired immediately.
Whole car shakes at idle	Engine is operating off peak operating point	Medium/Get tune up/check ignition sequence
Whole car rocks when driving down smooth road	Buffeting wind load	Low consequence. Adjust driving alertness level.
Car pitches and oscillates for more than 4 cycles when passing over a bump	Bad shocks-low damping in system	Low consequence. Vehicle operational, but not necessarily comfortable to ride. Schedule shock replacement.
A clacking noise from front tire area when making a 90° turn in a front wheel drive car	Damaged CV joint	High, failure of components not easily predictable plus consequences of failure is high. Immediate replacement required.

by a foundation. The compressor is driven by a power source, typically an electric motor or steam turbine. In addition, there are seals that keep the fluids from escaping the machine or moving between stages. Numerous static and dynamic forces continuously act on the rotor and seals. The dynamic forces, which are caused by imbalance, misalignment, pulsations, etc., lead to rotor vibration.

Vibrations collected from a machine are comprised of all the responses the machine is reacting to. It is common to measure vibration at or near the rotor support bearings (see Figure 15.1 below). The vibration collected is taken either at a set interval in time or continuously, if permanently mounted sensors are installed. The time required to collect the sample is dependent on

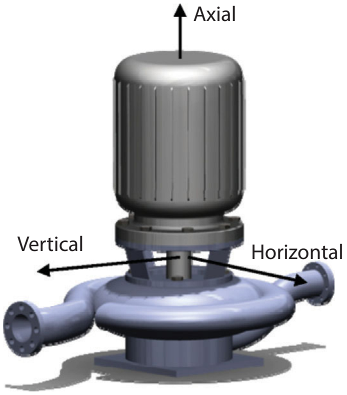


Figure 15.1 Vibration measurement positions for an inline pump.

the number of points to collect, the sampling rate and the number of averages required.

One fundamental plot generated for vibration analysis is called the time waveform and represents the total vibration experienced by the sensor at a given point (See waveform "A" below). Often the time waveform observed is not a simple sinusoidal wave but rather a more complex plot. Depending on the nature of the excitation source there can be some useful information here. However, the primary tool that is used to examine vibration responses is the "spectrum", which is a Fast Fourier Transform (FFT) of the time waveform. The spectrum is a frequency-domain representation of the raw vibration waveform (Figure 15.2).

The process of breaking up a raw vibration waveform into its frequency components is analogous to white light passing through an optical prism. The prism filters white light into its constituent components that make up the rainbow components red, orange, yellow, green, blue, indigo, and violet. Similarly, the figures (Figures 15.3 and 15.4) below illustrate how a complex machine vibration waveform can be transformed into the frequency domain that makes it easier to relate to the various machine characteristics.

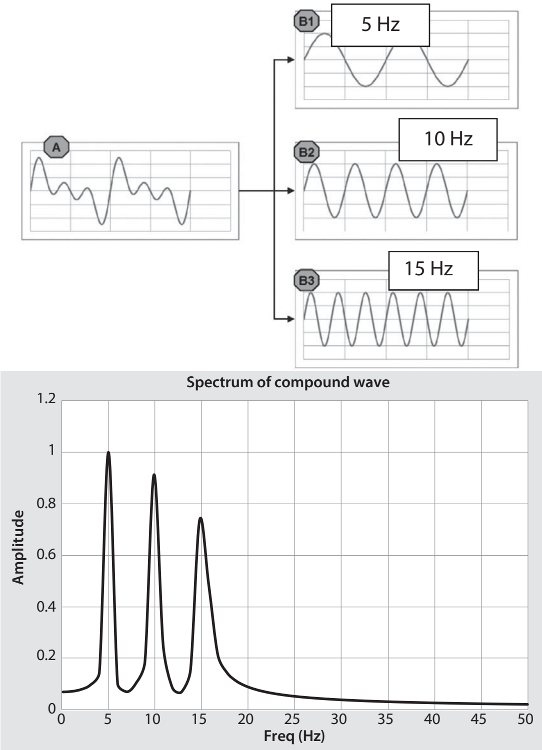


Figure 15.2 How the raw waveform can be transformed into pure sine waves and a corresponding spectrum.

A simple vibrating system can typically be described by the following expression:

$$m\ddot{R} + c\dot{R} + kR = \sum F_{ext}$$

Inertial effects + Damping effects
+ Stiffness effects = External Forces

The left-hand side of the equation is comprised of, from left to right, the product of the mass

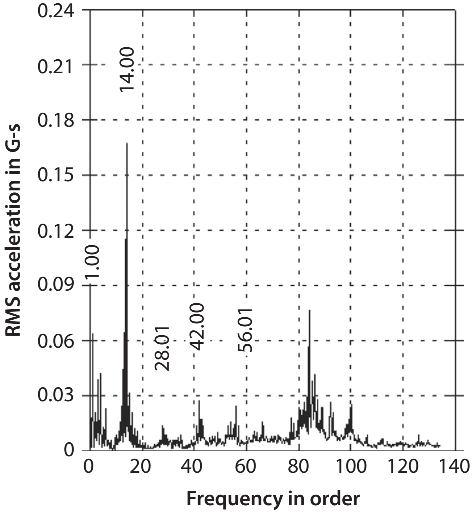


Figure 15.3 Typical vibration spectrum.

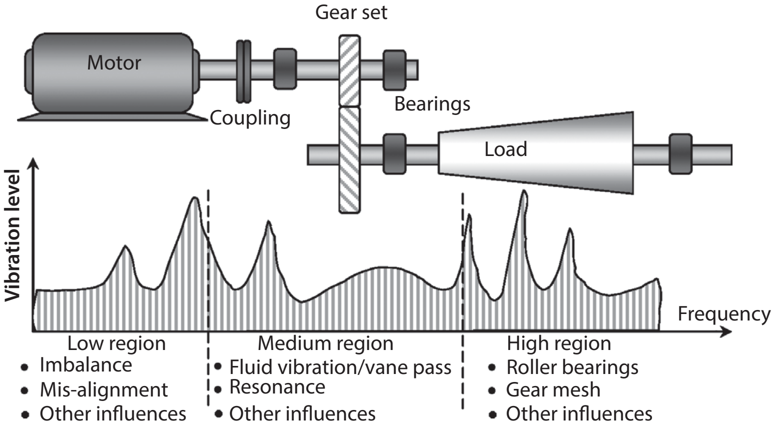


Figure 15.4 Spectrum for a complex machine.

and acceleration, then the product of the damping and velocity, and finally the product of the stiffness and displacement. Each of the product terms represents a measure of some type of force.

These are, from left to right, the resistance force of the accelerated mass, the force generated by a damping element, and the force resulting from the stiffness of the system. The right-hand side of the equation is the summation of all of the external forces that are acting on the system. What is pertinent here is that the right-hand side represents the external forces acting on the system and the left-hand side represents how the system will respond. For most process machinery, the excitation forces are related to the operating speed of the machine and often occur at some multiple (n) of the operating speed (X). As an example, a pump with six vanes operating at 1800 rpm, or 30 Hz, will have an excitation around 180 Hz ($n = 6$, $X = 30$, *and* $nX = 180$ *Hz*). Basically, any component that interacts, directly or indirectly, with the rotating element (bearings, seals, impeller vanes, etc.) can be a source of vibration excitation.

The quality of the data used for vibration analysis is dependent upon the type of sensor used, how the sensor is to be mounted, maximum excitation frequency expected, data sampling rate, and number of points collected. Before conducting a vibration analysis, the analyst should know the speed range, frequency range of interest, and the required frequency resolution. This information will allow the analyst to select the proper sensor, data-sampling rate, and frequency range

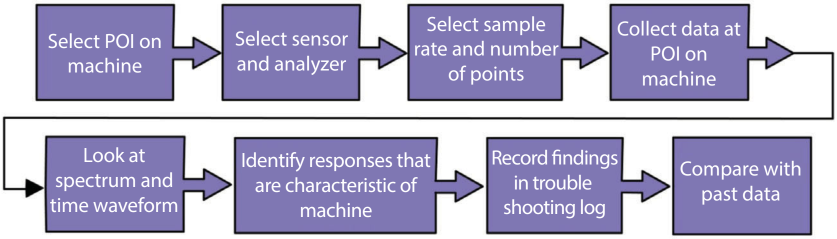


Figure 15.5 Data collection analysis scheme. POI: points of interest.

to ensure a proper analysis. Below is a data collection analysis technique (Figure 15.5) that can be employed for machinery vibration analysis.

The following example illustrates this technique:

Let's say you have vibration concerns on a two-pole electric induction motor. Your experience tells you it might be dealing with an electrical problem, which means the vibration will probably show up at some multiple of two times the line frequency or as a side band of the 1x, 2x, 3x, etc. components.

1. <u>Select points of interest (POI) on machine:</u> Because this motor doesn't have permanent sensors, we will need to install either a temporary uniaxial or tri-axial accelerometer on the bearing housings of the electric motor. This same sensor will need to be moved to all the points of interest to adequately assess the motor. Collect the vibration

points in the order that has been predetermined by your site's convention. A typical route order is as follows: motor outboard horizontal, motor outboard vertical, motor outboard axial, motor inboard horizontal, etc.

2. <u>Select sensor and sensor mounting:</u> We have determined that our magnetic base accelerometer and field analyzer can easily handle a frequency range of 1000 Hz. The two-pole motor operates at (nominally) 60 Hz. A frequency range of 1000 Hz allows you to cover 1000/(2 × 60) = 8.333 times the 2X line frequency of interest, which should be more than adequate.
3. <u>Set analyzer sample rate and number of points</u>: Let's assume that we expect electrical sidebands to appear around the 2x line vibration components. These sidebands will appear at about 2x line + 1.333 Hz and 2x line – 1.333 Hz. 3200 lines of resolution will provide 1000Hz/3200 lines or 0.3125 Hz/line which should be sufficient to detect the sidebands. (Here, we assumed that the slip frequency is (3600–3560)/60 = 0.666 hz, so 2x slip is 1.333 Hz.)

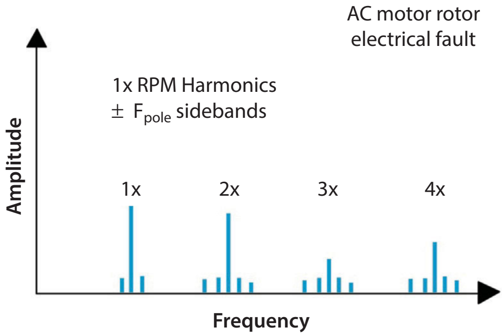


Figure 15.6 Electrical motor spectrum.

4. Collect data at point of interest on machine: Move sensor to all the identified points of interest and record the data.
5. Look at spectrum and time waveform: Figure 15.6 shows that all the mechanical components (1X, 2X, 3X, etc.) have sidebands.
6. Identify responses that are characteristic of machine: Sidebands in the spectra of induction electric motors are indications of bad rotor issues.
7. Record findings in troubleshooting log and then compare with past data: It could be an indication of a deteriorating motor if sidebands have not been seen on previous spectra. This might also be a signal to do a thermal scan of the motor and wiring to make sure that there are not any thermal issues too.

15.2 Identifying Machine Vibration Characteristics

Early in the investigation of the problem, it is important to know what the nature of the problem at hand is. Does it appear to be a flow-related problem, or process related? Does it appear to be a mechanical problem? Does it appear to be a problem internal or external to the machine? There is a plethora of things that could be causing the concern. So, how can the numerous possibilities be pared down to a manageable number? Vibration analysis is a powerful tool that can be used to sort through all the potential maladies and weed out those that are not likely. Narrowing down the potential machine issues saves time and money.

Vibration analysis methods allow the troubleshooter to match spectral peaks with known machine characteristics and internal problems. Knowing what frequency components correspond to given maladies is required to properly identify potential problems. For example, most vibration analysts know that 1*X* vibration corresponds to imbalance, 2*X vibrations* corresponds to misalignment, and the *nX* vibration corresponds to vane passing in a pump with *n* vanes. However, it is important to utilize the proper vibration analysis table for the machine type under investigation. For example, using an analysis table for electric motor with rolling element bearings may not contain all the potential vibration issue required to properly analyze a steam turbine with sleeve bearings. Table 15.2 shows a vibration analysis table for a machine with journal bearings.

Using Phase Data to Better Understand Running Speed (1x) Vibration.

If the vibration analysis reveals that the predominant shaking frequency on a machine is running speed vibration, i.e., 1x, then a phase angle analysis can be performed to better understand what is occurring. Vibration phase angle, usually denoted by the Greek symbol φ, is calculated from the time difference (or delay) between a reference mark or sensor signal and the peak or zero crossing point of the vibration signal of interest (see equation below). Phase provides the relative timing of a vibration signal relative to a time signal, similar to tuning a car engine with a timing light. Keep in mind the orientation of the vibration sensors as shown in Figure 15.7 when comparing their phase relationships of their output signals.

A phase angle of 0° means two vibration signals are exactly in phase, while a phase angle of 180° means two vibration signals are exactly out of phase (see Figure 15.8).

Table 15.2 Journal bearing problems.

Vibration Source	Exciting Frequency	Dominant Direction	Amplitude	Spectral Envelope Appearance	Comments
Oil Whip	0.38X to 0.48X	Vertical and horizontal	Unsteady, peak may pop in and out view	Sharp peak	Causes: 1) Oil is too cold 2) Lightly loaded bearing 3) Speed above design
Excessive Bearing Clearance	1X harmonics	Vertical and horizontal	Steady	1X will be the largest of the harmonic series	4X to 8X and/or 7X to 15X
Journal Bearing looseness, Rattling	0.5X, 1X	Vertical and horizontal	Erratic	0.5X harmonics	Check bearing crush is looseness if suspected
Journal Thrust Bearings, Kingsbury	1X; shoe rate of Kingsbury	Axial	Steady	1X harmonics; shoe rate harmonics for Kingsbury	Usually six shoes

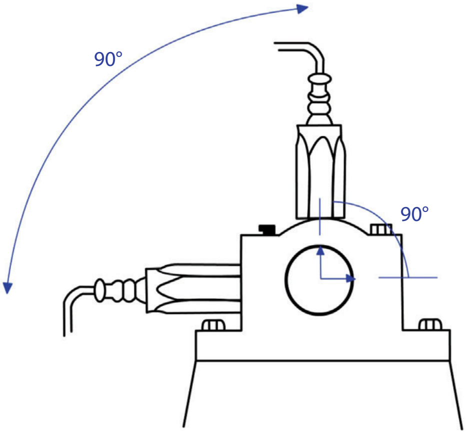


Figure 15.7 Vibration sensors oriented 90 degrees from one another.

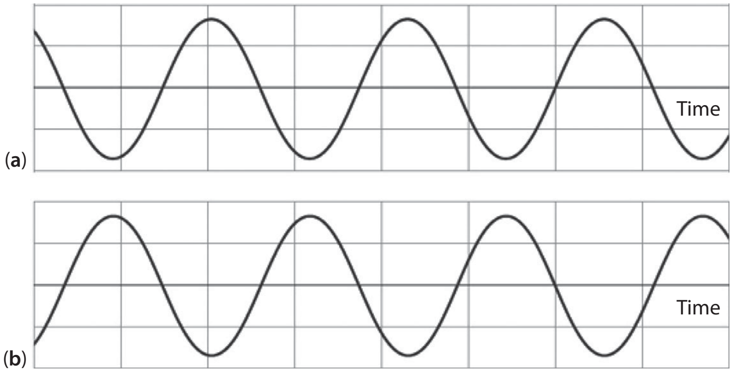


Figure 15.8 Sine waves a and b are 180° out of phase relative to one another.

$$Phase = \varphi = \cos^{-1}\left(2\pi f \Delta t_{delay}\right)$$

Any competent vibration analyst should be capable of making relative phase comparisons on a machine or structure in order to determine if you are dealing with a balance, alignment, eccentricity, bent shaft, soft foot, or looseness issue. A phase study might include points measured only on the machine bearings or it can include points over the entire machine from the foundation up to the bearings.

For additional vibration analysis advice for the various machine classes, refer to Chapters 14 and 15 in *Is My Machine OK?* Detailed analysis tables for Gear Problems, Rolling Element Bearing Problems, Pump Problems, and other elements and machine classes can be found in Chapter 14.

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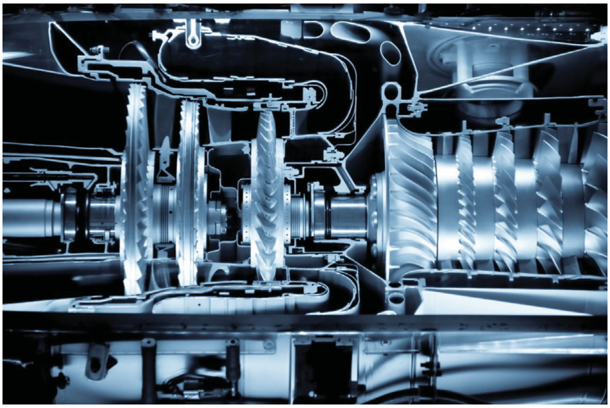
16

Applying the 5Qs to Rotordynamic Investigations



Those who routinely deal with machinery rotordynamic problems should find the following troubleshooting discussion helpful. The 5Qs (what, who, where, when, and why) method covered throughout this guide may also be applied to investigating *rotordynamic phenomena. Those readers who rarely encounter rotordynamic problems may choose to skip this chapter.*

16.1 Introduction

Rotordynamics is a specialized branch of applied mechanics concerned with the behavior and diagnosis of rotating systems, ranging from jet engines and steam turbines to auto engines and computer disk storage. At its most basic level, rotordynamics is concerned with one or more mechanical structures (rotors) rotating around a single axis that are supported by bearings and influenced by internal phenomena. The detailed study of rotordynamics demands accurate knowledge of the particular mechanical elements supporting the rotor, i.e., fluid film bearings and seals. If the rotordynamicist does his or her job correctly, the machinery train can provide reliable service throughout its lifetime.

16.1.1 Rotordynamics: A Brief Overview

The thickness of one or two sheets (0.001 to 0.003 inches) of paper can be the difference between safe, reliable operation and potentially catastrophic failures in world of rotating equipment. This is especially true in many high performance compressors, turbines, and other equipment, which operate with seals and journal bearings, and have very tight clearances between the blades or impellers and their housings, or shrouds. Rotor excursions, or displacements, of just a few thousandths of an inch ("mils" of vibration) inside large compressor can cause wiping of the seals, rubs that could potentially induce unstable vibration, impacting impellers or blades into the housing, and many other undesirable problems. So, how is it that the OEM has confidence that their equipment will run smoothly? Aside from shop testing it really starts with a rotordynamic analysis.

It is certain that any piece of equipment that has moving parts within it has undergone some form of dynamic modeling. One type of dynamic modeling that is applied to rotating equipment is rotordynamics. Rotordynamic modeling attempts to account for all of the influences (internal and external) that could be acting on a rotor system. The study of rotordynamics is very complicated and involves quite a bit of high-end theory and math. There are many good sources that delve into this area in more detail. Here we will explain how basic rotordynamic knowledge is useful in the troubleshooting process.

Consider a typical rotor train for an axial compressor. There may be a prime-mover in the form of an electric motor that supplies the power so the compressor can do its job. The electric motor is coupled to a gearbox so that the speed out of the motor can be increased. The gearbox itself has a gear set that operates on fluid film bearings. The output shaft from the gearbox is coupled to the compressor. The compressor itself has seals, journal bearings, thrust bearings, inlet piping, outlet piping, rotor blades, and stator blades. Each primary element (motor, coupling, gear box, coupling, and compressor) contributes to the overall dynamic response of the system. It is important to remember that vibrational energy will flow through the entire machine train directly (along the primary power train) or indirectly (through the housing). Each element will have resonant frequencies that could be of concern. Knowing how much of the system to include requires years of rotordynamic experience.

Previously a mathematical relation was shown that is a simplistic representation of any mechanical system that is subjected to an external excitation that will vibrate (Inertial effects + Damping effects + Stiffness effects = External Forces). The same relation is used for rotordynamics. Modeling rotating equipment is necessary to:

- Determine the response of the machine during steady-state operation
- Determine clearances at seals, blade tips, bearings during steady-state operation
- Determine peak response during start up and coast downs
- Determine response of machine if operating conditions change
- Check for the stability of the machine.

The list is not all-inclusive but provides a brief overview of the needs for modeling. It is worth noting that the concerns such as rotor flexing, of the machine during start-up, steady-state operation, and coast down are essentially the same. However, there is a difference between transient versus steady-state operation. If the machine speed is varying over time, many factors are also changing (bearing stiffness and damping, for example). However, if the speed is somewhat fixed, the process fluid properties can be varied to see how the unit will respond. In addition, the fluid properties of the journal bearings could be varied as well to see the level of impact that this could have on the behavior of the machine. The last item, stability check, is important for the machine to avoid vibrations that grow in an uncontrollable manner over time. Unstable vibration levels are typically associated with exciting a type of resonance of the rotor-bearing system. The challenge with this is that many machines do not have a single "critical speed", but have resonances that can vary with machine speed.

There are two types of rotordynamic analysis that should be conducted for all rotating equipment. The first type is called a "Lateral Critical Speed and Stability Analysis". This is an analysis that looks at the lateral motion, or motion perpendicular to the shaft centerline. This is necessary to see how clearances at bearings and seals are affected during operation, calculation of loads at bearings, also to see where the nodes (points of no motion) occur, and to check the stability of the machine. You wouldn't want to inadvertently place a proximity probe at a point where little to no motion occurs. The second type of analysis that is required is called a "Torsional Critical Speed Analysis". The torsional analysis is an investigation of the twisting behavior that can occur. This is primarily done to examine the response of the machine as the input torque is applied during start-up and steady-state conditions. Tremendously high torque loads and relative twisting motion along shaft elements and between elements can occur during start-ups and when operating at a torsional critical speed. A cumulative fatigue analysis can be conducted to predict the number of start-ups that the system could be subjected to over time, if stress levels above the endurance limit are encountered.

16.2 Using Rotordynamic Results for Troubleshooting

The results from a rotordynamic study can be useful in the troubleshooting process. The rotordynamic analysis typically provides expected performance, i.e., vibration levels, critical speeds, amplification factors (AF), etc., based on what was assumed in terms of geometry, seal type, bearing type, operating fluid condition, etc., at the time the unit was under design. Comparing the values between the rotordynamics model, the design plans, and what is actually seen in the field could help in addressing where things went awry.

Within the last ten years or so software for rotordynamic analyses have become very sophisticated in what can be accounted for in the model. Models typically can handle change in shaft dimensions including fillets, roller bearings as well as journal bearings, many different types of seals, fluid coupling forces due to interaction of the fluid between the blades and housing, the housing itself, couplings, and so forth. Although most top-rated rotordynamic codes are fairly comprehensive, it is important that the analyst has the necessary experience to use the software properly.

Once a rotordynamic model is created it can be a valuable tool to explore possibilities. A large axial compressor cannot just be taken in and out of service as needed. However, if there is an issue with a compressor, comprehensive data can be taken which can be crossed check with a model. If there is not good agreement between the model and field data, then the rotordynamic model can be adjusted to determine what element within the compressor might be the most likely source of the observed problems.

One example is a compressor for which the analysis predicted the operational speed was well above the first critical speed, but below the second critical. The required API separation margin was also suitable. But when the compressor was in service, there were unacceptably high levels of vibrations. The behavior looked like the 1st critical had shifted to a higher value, closer to running speed. What could cause this? Well, if the bearing span was decreased that would make the shaft stiffer, hence the 1st critical would increase. However, it is known that the bearing span is correct with the original specs. However, under the right conditions, seals can act like bearings and can change the critical speed of the rotor. So, the rotor model can be adjusted to see what influence a rigid seal would have on the rotor behavior.

Here are a few important field-to-model comparisons to examine when evaluating troublesome machines:

1. Do the field measured critical speeds match those predicted by the model? If the critical speed or speeds don't match the model, the problem may be caused by a) the installation of the wrong bearing or bearings, b) the use of the wrong oil, or c) fundamental errors in the rotordynamic model.
2. Do the measured amplification factors (AFs) match those predicted by the model? (Note: The amplification factor is a measure of the susceptibility of a rotor to vibrate when its rotational speed is equal to the rotor natural frequency. For imbalance type of excitation, the synchronous amplification factor is calculated by dividing the amplitude value at the resonant peak by the amplitude value at a speed well above resonance (as determined from a plot of synchronous response vs. rpm.)
   a. If the AFs are higher than those predicted, you should check the

    oil properties. Low viscosity values may be lead to poor damping performance.
  b. Bearing clearance can also affect damping properties and therefore affect the measured AF.

3. Are separation margins, i.e., the margins between the operating speeds and critical speeds expressed as a percentage, equal to or greater than those predicted by the model?
4. Are all vibration amplitudes less than or equal to those predicted by the model? High vibration levels that seem to be caused by imbalance can sometimes be corrected with a field balance.
5. High vibration levels, critical speed issues, high Qs, unusual vibration components should be reported to the original equipment manufacturer for their review.

Discrepancies between field observations and the rotordynamic model should be resolved by either: 1) revisiting the model to ensure its accuracy or 2) determining if cause is due to an underlying assembly or installation issue.

The math and numerical processing that goes on behind the scenes on most rotordynamic codes is involved and requires the solving of many second-order linear equations and other functions. Some of the expressions are calculated multiple times as their characteristics are dependent on the operating speed. In addition, not all the characteristics behave linearly and this can add a level of complexity to the solution.

The output data from a typical rotordynamic analysis can be daunting and many different plots can be generated. Typical plots that are generated are:

- Critical speed map: a diagram that depicts undamped critical speeds and various rotor mode shapes for range of bearing stiffnesses. The critical speed map is useful for predicting critical speeds and rotor mode shapes (see Figure 16.1) for a range of bearing stiffnesses.

Here's an example of how a critical speed map can be used to predict rotordynamic performance in the field. Let's ask the following question: Where can you expect the 2nd rotor mode (Figure 16.1) to exist if we have an intermediate bearing stiffness? We can expect the 2nd rotor mode to be present at 13,144 rpm and that the mode will be a pivotal mode, i.e., a rotor vibrational mode

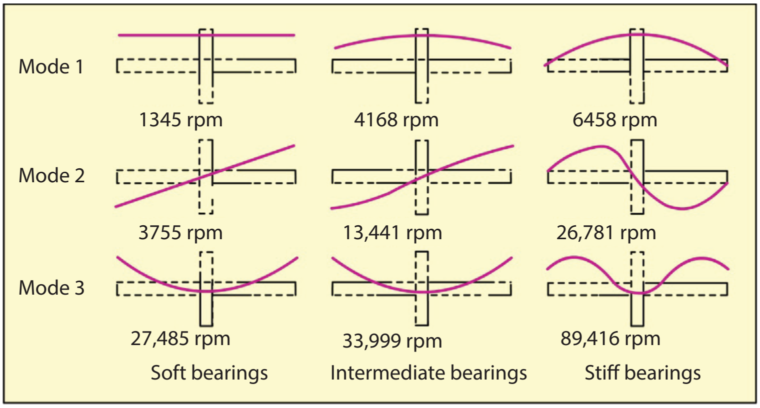


Figure 16.1 Rotor modes shapes versus bearing stiffness.

with a node in the center of the rotor and greater motion at the bearings. If we experience high vibration levels near 13,411 rpm, we can suspect that we have a critical speed problem. This suspicion would be further supported if the 1x vibration signals at the opposite ends of the rotor are 180 degrees out of phase.

- <u>Bode plot</u> (Response Plot): a plot that shows the amplitude and phase response of a point on the rotor relative to frequency. (see Figure 16.2 a & b.)
- <u>Mode shape</u>: a plot that shows how the rotor will displace for a given operating speed. These plots can also show forward or backward whirl (Figure 16.1). Mode

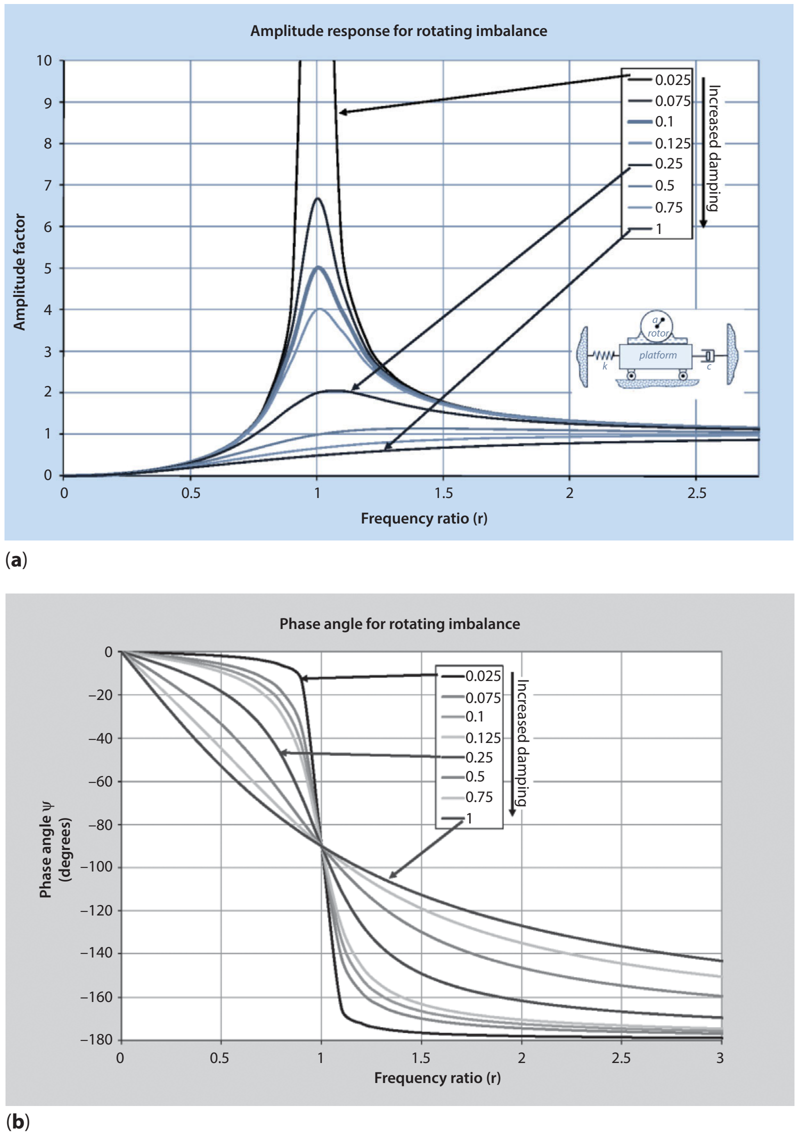


Figure 16.2 (a) Forced response plot (b) Forced response phase plot.

shape information can be useful when troubleshooting 1x vibration problems in the field. They tell you where on the rotor you should expect relative high and relative low vibration levels. For example, you may have a compressor that has a second critical mode shape that is strongly influenced by overhung weight of a coupling. The mode shape would show higher expected lateral vibration amplitudes at the coupling end of the rotor and lower expected amplitudes at the opposite end of the rotor.

- Orbit plot: a plot that shows the path that the center line of the shaft at a given point will take at a given speed (Figure 16.3).

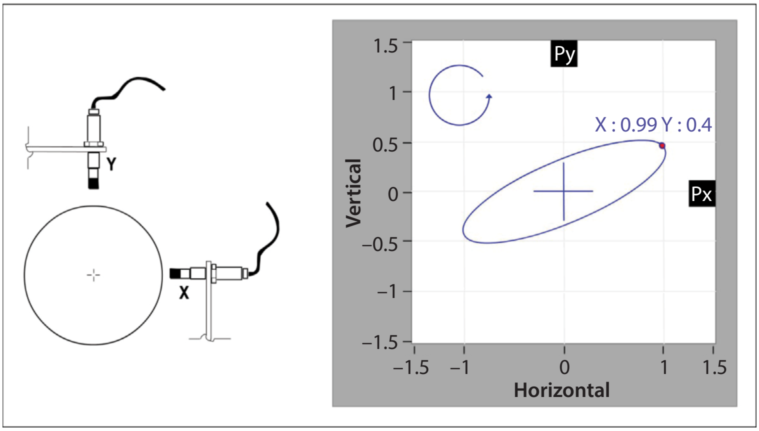


Figure 16.3 Orbit plot generated from two orthogonal proximity probe.

The orientation of the orbit can also be useful in the troubleshooting process. The orbits generated using the rotordynamic model at various speeds should be corroborated with field data to see if there is agreement in terms of their orientation, cusps, loops, etc. Normally, orbits are oriented with a horizontal major axis and a vertical minor axis; however, this is not always the case. Factors like bearing geometry and load orientation can determine the actual orientation of an orbit. Disagreement between the orbit orientation predicted by the model and the field measurement can indicate a problem.

- Stability plots: A plot that shows the effect of cross-couple stiffness on the log decrement. Stability plots are highly recommended when rotor speed or fluid conditions significantly impact the stiffness (direct and cross coupled) and damping values within the machine.

There are many different analyses that might go into a comprehensive rotor dynamic study. As an example, an axial compressor might have an analysis on the entire rotor-bearing-sealing-housing assembly and there might also be an analysis on the blades. The blade analysis might be looking at combination of fluid flow across the blade, heat transfer characteristics, and also a vibration response. An additional analysis might look at what happens if the blade were to be impacted by a solid or even a liquid slug. The corollary model from the rotordynamic stand point is to look at the response of the system due to a lost turbine blade or blades.

An outcome of the rotordynamic model is that it can allow a person to ask and address various "what if" scenarios. But not all rotor codes are created equal and not all codes are up to the task and are somewhat limited to the allowable input conditions. All is not lost though, as there are individuals and institutes (public and private) that are there to customize codes as needed or do research to investigate unusual rotordynamic behaviors.

16.3 Closing

Rotordynamics has been proven to be an indispensable tool for designing and troubleshooting industrial turbomachinery, such as pumps, compressors, gas and steam turbines, turbo generators, turbo expanders, turbochargers, etc. The study of rotordynamics of turbomachinery encompasses the structural analysis of rotors (shafts and disks) and the design of fluid film bearings and seals that determine the best dynamic performance given the required operating conditions.

This best machine dynamic performance is denoted by well-characterized natural frequencies (critical speeds) with amplitudes of synchronous dynamic response within required standards and demonstrated absence of sub-synchronous vibration instabilities. The underlying objective of modeling is to generate an analytical representation of any given machinery train that can be used to determine how it will respond under expected operating conditions.

Before the construction or installation of the machinery train, the rotordynamicist can assist the designers by predicting field performance and conducting "what if" analyses in order to optimize dynamic performance. The rotordynamic model can continue to be useful even after the machine is installed in the field. In the hands of an experienced machinery professional, rotordynamic knowledge gleaned from an analysis can assist in determining the most probable cause of a malady discovered in the field and help in determining the best path forward.

The rotordynamic model can even be given new life if there is interest in modifying the machine at some time in the future. For example, someone might ask what would happen if an impeller wheel was removed. The original analytical model could be modified to determine the effects on critical speeds if the modification was implemented.

The 5Qs to consider for Rotordynamic Issues

1. What is the problem? For a rotordynamic analysis to be required there has to be a rotor related vibration problem. Usually the problem is in the form of an unexpected critical speed or an unstable rotor.
2. Who should I talk to about the problem? The OEM who generated the original model or outside consultants that can create a new model that can reflect a new machine design. This is a very specialized modeling and requires proper understanding of machine elements and potential excitation forces.
3. When does the problem occur? High vibration issues can show

up at a specific rotational speed or when under a given a process load condition.

4. Where does the problem show up? "Where" can describe a particular bearing, orientation within a bearing, i.e. vertical, horizontal, or axial direction, or a particular machine within a train.
5. Why is the problem occurring? A rotordynamic model may be required to explain why high vibration is occurring. Typical explanations are a critical speed, imbalance, rotor instability, or bearing instability.

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17

Managing Critical Machinery Vibration Data

Beware of False Positives and False Negatives

Field vibration analysis errors can result in erroneous conclusions, which in turn can lead to unnecessary repairs or missed mechanical faults. Analysis accuracy is of paramount importance when monitoring a critical machine in order to control maintenance costs and reduce risks to acceptable levels.

Organization can reduce potential vibration analysis mistakes by adopting various data collection strategies aimed at improving the validity and reliability of the machinery vibration data. Before we discuss some recommended data collection strategies, let's explore the four possible outcomes from a machinery vibration analysis:

> True positive (TP)—This is the expected outcome from a vibration analysis when an actual machine malady is encountered. The analyst correctly detects a machine fault and correctly determines its cause. With the proper training and equipment, the analyst is expected to detect true machinery faults in their early stages in most cases.
>
> True negative (TN)—This is also an expected outcome from a vibration analysis. With the proper training and equipment, the analyst should be able to give a machine a "clean bill of health," when there are no internal mechanical faults.
>
> False positive (FP)—This outcome arises when the analyst discovers a fault or problem that does not really exist. The analysis error may be caused by inexperience or by using the wrong data collection methods. False positives lead to unneeded repairs and should therefore be avoided.
>
> False negative (FN)—This possibility is the most insidious of all those covered here. This outcome arises when the analyst or analysis equipment employed are incapable of finding a machine fault. In this case,

> the fault remains undetected and will continue to get worse until a secondary failure occurs. A false negative has the potential of putting your plant at risk by failing to detect a machine malady that could result in an undesirable resultant consequence, such as a product release, fire, etc.

The first decision a vibration program manager must make is determining the level of analysis required. There are three basic levels of vibration analysis:

> "First pass" vibration analysis (Level I)—An analysis, usually performed by a mechanic or operator, using a vibration data collector or vibration meter. This type of analysis uses a "pass or fail" approach to monitoring. Sites composed mostly of low consequence machines, such as small to medium horsepower process machines with low levels of secondary consequences if they fail unexpectedly, tend to employ this method.

> Basic vibration analysis (Level II)—An analysis, usually performed by a vibration technician, using a vibration data collector and analysis software. At this level the analysis, the technician investigates machines with vibration levels that are high or trending upward in order to pinpoint the cause and

severity of the problem. Sites with medium to high consequence machines tend to employ this second level of analysis. Medium to high consequence machines are medium to large horsepower process machines representing significant potential consequences if they fail unexpectedly.

Advanced vibration analysis (Level III)—An analysis, usually performed by a certified vibration analyst, using advanced vibration data collection tools and software. This level of analysis involves spectral analysis, phase comparisons, Bode plots, correlation analysis, etc. Sites with high consequence machines typically employ advanced vibration analysis methods. High consequence machines are process machines associated with high levels of secondary consequences. If these machines fail unexpectedly, bad things happen, i.e., fires, product releases, production outages, costly secondary mechanical damage, etc. This machine group normally represents less than 10% of the site's populations.

17.1 Vibration Analysis Strategies

The potential for false positives can be reduced by getting a second opinion from a qualified analyst. So, if machines that are costly to repair are initially monitored by the maintenance or operations group, they should be analyzed a second time by a trained vibration analyst whenever alert vibration levels are detected. This strategy will greatly reduce the likelihood of unneeded repairs due to a false positive.

The potential for false negatives can be reduced by using skilled machinery analysts who fully understand the machine characteristics and employ multiple technologies and methodologies. An example of multiple vibration technologies would be monitoring case velocity readings as well as proximity probe readings on a machine with fluid film bearings. This dual approach increases the chances of detecting a developing machine fault.

An excellent example of utilizing multiple technologies to ensure the detection of a potentially devastating failure are those often employed in API compressor with tilting pad thrust bearings. Because of the potentially costly consequences of an undetected compressor thrust bearing failure, additional instrumentation is recommended by the API standard. Thrust bearing monitoring systems will typically contain 1) dual axial proximity probes (see Figure 17.1), 2) proximity monitors with "OK" status indication, and 3) multiple embedded thermocouples on active

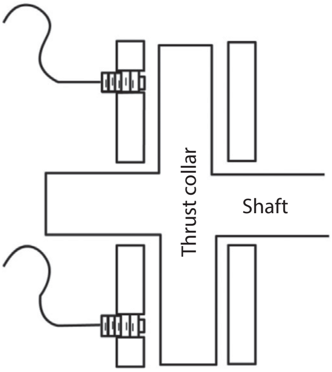

Figure 17.1 Thrust bearing position monitored by dual thrust probes.

Figure 17.2 Thrust bearing with multiple embedded thermocouples.

and inactive faces (see Figure 17.2). The hope is that if one monitoring sensor or system either fails or is ineffective, one of the other sensors systems will detect a fault and avert a disastrous failure.

The goal of a site's overarching vibration analysis strategy should be to avoid false positives on reparable machines and false negatives on

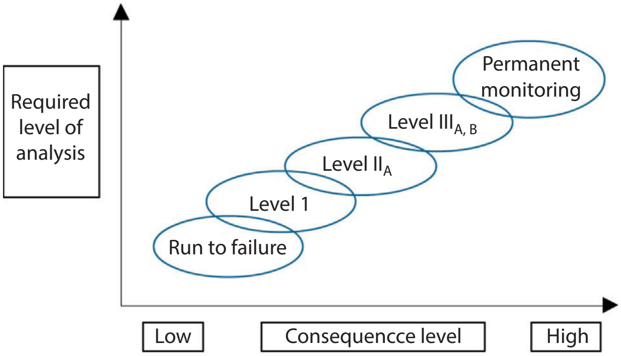

Figure 17.3 Vibration Analysis Hierarchy. Note A—If a potential failure is detected, take additional data or get a second opinion before making a decision to repair. Note B—Employ multiple condition monitoring technologies to improve the chances of detecting early failures, such as embedded thermocouples, temporary case mounted accelerometers, ultrasonic probes, etc.

high consequence machines. Site management will have to determine when repair costs and the potential for secondary consequences warrant higher machinery monitoring skill levels. Figure 17.3 provides a graphical view of a general vibration analysis strategy.

In closing, we will leave you with a few vibration analysis tips:

1. It is acceptable to use maintenance personnel or operators to monitor low and medium criticality machines for “first pass” assessments.

2. Only use highly certified vibration analysts for monitoring critical machines.
3. Consider multiple monitoring methods on critical machines with hard to detect internal defects.
4. Before recommending a repair, consider retaking data with another sensor.
5. Before recommending a repair, consider retaking data in another position to confirm the initial reading. (Note: Be more cautious when dealing with thrust position alarms. Every thrust alarm indication should be taken seriously and acted on quickly. Taking time to collect additional data may prove costly. Thrust bearing failures can occur rapidly and usually lead to costly repairs due to a loss of axial position of the rotor.)
6. When monitoring critical machines with accelerometers, check the effect of the sensor mounting method on your results.
7. When in doubt, get a second opinion.

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18

Closing Remarks

The authors would like to leave readers with some final advice:

18.1 Practice the Method

Whenever the opportunity presents itself, employ the troubleshooting methods in this guide to hone your machine analysis skills. Practice makes perfect. Eventually you and your organization will feel comfortable using these methods for all types of process machines.

18.2 Provide Training on Fault Trees and Cause Mapping

Cause mapping and fault trees are powerful tools in the troubleshooting process. To be proficient, users of cause maps and fault trees must obtain the proper training. At a minimum, mechanics, operators, engineers, and managers should be provided training on how to read and comprehend cause maps or fault trees. A combination of training and practice is required to attain a level of competence.

18.3 Employ Team Approach for Complex Problems

The authors have found that multidisciplinary analysis teams are invaluable for solving complex issues. A team composed of a 1) machinery professional who usually serves as the team leader, 2) process engineer, 3) mechanic, 4) operator, 5) control specialist, and 6) even an equipment manufacturer's representative, may be required to get to the bottom of things. The investigation leader must be able to keep the team focused and engaged at all times in order to arrive at meaningful conclusions. Each participant brings a unique point of view to the discussion, which can only improve the chances of success.

A team approach should include the following steps:

1. An initial meeting where the following is covered:
    a. Identification of the problem
    b. Clear assignment of duties, such as data collection and fact gathering
    c. Schedule of future follow-up meetings
2. Follow-up meetings with all the participants once all the data is collected
    a. Analysis of the collected information
    b. Cause mapping sessions
    c. Determination of most probable cause
3. Driving the entire team to a common set of conclusions and recommendations

18.4 Get Management's Support

For the troubleshooting methods to thrive at your site, it is vital to get management's support. Managers usually approve the time required for field troubleshooting and control training and equipment budgets. Inviting management to participate on a troubleshooting team and by publishing troubleshooting successes are two ways to show them what troubleshooting is all about. Without their support, the site's troubleshooting effort will never realize its full potential.

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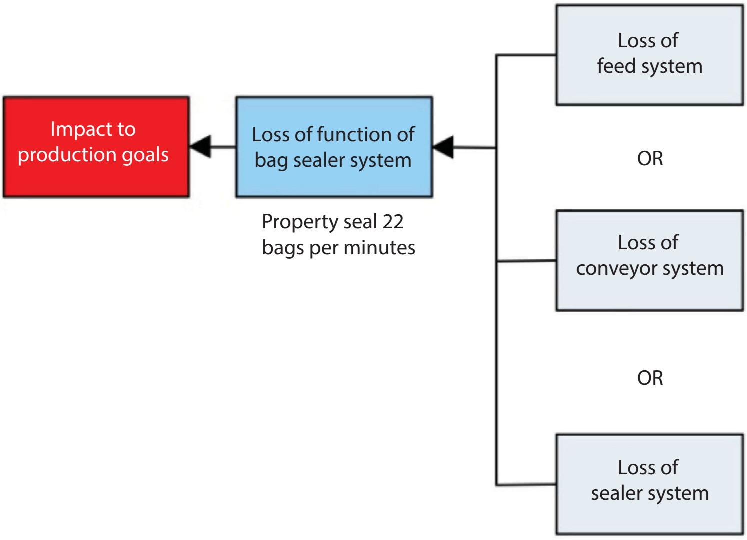
Appendix A

The Field Troubleshooting Process—Step by Step



The purpose of this section is to meld all the ideas presented in this guide together into a step-by-step procedure for quick reference. This handy summary can serve as a stand-alone document that can be taken into the field while engaged in the troubleshooting process. The basic troubleshooting steps that should be taken are: 1) Define the problem, 2) Collect data, 3) Analyze, and 4) Act and Confirm. Following this methodology, you can improve your chances of quickly finding the root of a machinery problem in order to implement the proper solution. The four troubleshooting steps are explained below.

Step 1: Define the problem

1. First you need to develop a preliminary problem definition. This step requires that you talk to the machine operator (or owner) about machinery issue at hand. Ask:
   a. What seems to be the problem?
   b. Where does the problem manifest itself?
   c. When was the problem first noticed?

   At this time, try to get a basic idea of the nature of the problem.

2. Next perform a field audit and take some preliminary data. (Chapter 6,

Is My Machine OK? describes how to conduct a field audit.) For complex machines consider inviting a mechanic or machinery professional to help with the audit. Two sets of eyes are always better than one.

3. After completing the audit and reviewing the field data, decide if the problem requires further action. This determination requires the following steps:
    a. Rate the machine's condition. Here are some common ways to rate a machine's condition:
        i. very unlikely to fail, likely to fail, very likely to fail
        ii. performance is affecting production significantly
        iii. internal wear may soon affect production rates
    b. Determine the machine's criticality, i.e., low, medium, or high
    c. A risk assessment can be performed once you know the machine's condition and criticality (What is the severity of the problem? See Chapter 7, *Is My Machine OK?* for more guidance). Rate the overall risk level as either low, medium, or high.

    d. You can now decide to either ignore the issue or proceed with analysis.
4. If you decide to proceed, write down a preliminary problem statement with as many details as possible. The problem statement should be in this form:

   The north hot oil bottoms pump is experiencing high vibration levels at the inboard bearing. The pump was last repaired last month.

Step 2: Collect all pertinent data

1. Now that you have decided to proceed with the analysis, you must first decide who knows the most about the problem. Some potential interviewees are:
    a. Process engineers
    b. OEM
    c. Control engineers
    d. Mechanics

   Compile a list of all the interviewees along with date and time you plan to perform the interviews. Make sure you take detailed notes during the interviews.

2. Based on the preliminary field audit, decide if additional data should be collected. For example, if vibration is the

predominant issue, you may need to perform a modal analysis or generate a Bode plot. Here are typical field data types that can be collected.

   a. Vibration: modal analysis, Bode plot, waterfall plot, etc.
   b. Temperatures: temperature survey, infrared photography, etc.
   c. Oil analysis: spectrographic analysis, water content test, etc.
   d. Process data: trend plots
   e. Performance testing

3. During the information collection process, frequently ask the following questions:
   a. What additional data do I need to collect?
   b. Who else should I talk to?
   c. Where does the problem show up?
   d. When was the problem first detected or noted?
   e. When was the last repair?
   f. When was the machine first installed?
   g. Is the machine at the beginning or end of a run?
   h. Does the problem only show up under certain process conditions,

i.e., low flow, high flow, light gas, dense gas, high driver loading, low driver loading, etc.

4. Now that you have reviewed the problem in some detail, determine if the preliminary problem statement is still accurate and decide if it needs to be revised. If your understanding of the problem has changed significantly, go back to Step 2 and continue the investigation.

Step 3: Analyze the body of data as a whole

1. Look through all the process data, vibration data, temperature data, performance data, etc. and look for changes, trends, and correlations that may provide clues to what is going on. (See Chapter 9 of this book and Chapter 5 of *Is My Machine OK?* for more insight into data analysis.) Carefully analyze the body of data as a whole.

2. If it is still not clear what the problem is, generate a list of plausible theories that can explain all the symptoms. (At this point, the more possible causes you can postulate the better your chances are of finding the root cause.)

   The following techniques can be helpful in paring down the possible causes to determine the most likely cause:

   a. Field testing or trials to support or refute some of the theories.
   b. Analytical modeling, such as rotordynamic or computational fluid dynamic modeling to validate certain theories.
   c. "Cause mapping" (see Chapter 11) to evaluate all potential causes
3. At this point, you must decide if there is enough information to make a definitive conclusion. If not, return to step 2 and continue with the analysis.

Step 4: Act and Confirm

1. Once you have decided to act, here are your choices:
   a. Make no immediate operating changes or maintenance adjustments but continue to monitor the machine's condition: Choose to either continue to monitor the machine based on the present inspection schedule, or increase monitoring intervals and/or points. Look for signs of deterioration and act accordingly.

b. Test and assess: 1) Vary operating condition speed, flow, pressures, suction level, etc. and observe how machine responds. 2) Check for off-design machine operation due to off-design process conditions, open bypasses, restrictions, control issues, etc. Correct any simple problems such as open bypass lines, low suction levels, and off-design conditions as you find them. If the problem can be resolved with simple field adjustments, then you are done.
c. If you determine that you are dealing with a system issue that cannot be corrected on-line, you will need to shut down. Here are few examples of issues that need to remedied off-line:
    i. Clearing line blockages
    ii. Repairing leaking valves
    iii. Replacing or adjusting troublesome control valves
    iv. Cleaning fouled coolers
d. If you determine that you are dealing with a machine issue, here are your options:
    i. Switch to spare, if available
    ii. Plan a shutdown for balancing, alignment, oil change out,

    piping modifications, regrouting, etc.
    iii. Plan a shutdown for repair (i.e., full machine overhaul if needed). Reduce stresses if possible while waiting for repair by reducing process induced loads
    iv. Shutdown immediately for balancing, alignment, oil change out, piping modifications, regrouting, etc.
    v. Shutdown immediately for repair

2. After the group's decisions have been made, a logical, safe, and efficient implementation plan should be put in place to address all the concerns from the investigation. Follow-up plans may be needed to address concerns that need to be taken care of at a future date.

3. You should always follow up with a field audit in order to confirm that the root cause of the problem has been addressed and that machine conditions are back to normal. If the problem has been solved, you are finished, if not, go back to Step 2 and continue the investigation.

4. If the problem is solved, take some time to document the final results. Place a copy of the final report in the equipment file and send copies to coworkers, team members, and management.

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Appendix B

Troubleshooting Matrices and Tables

This appendix includes troubleshooting matrices and tables designed to assist field troubleshooters in the identification and resolution of the following categories of process machinery problems:

1. Centrifugal pump problems
2. Centrifugal compressor problems
3. Reciprocating compressor problems
4. Reciprocating pump problems
5. Fans problems
6. Steam turbine problems
7. Electric motor problems
8. Hot bearing problems

Keep in mind that the following troubleshooting matrices and tables contain only the more common symptoms and causes found in the field. Theses matrices should be considered a starting point for your analysis. You may need contact the manufacture for assistance in solving rarely encountered or subtle problems.

Centrifugal Pump Troubleshooting Matrix

Here's an example illustrating how the centrifugal pump matrix can be used. Let's assume you are experiencing a high power load on an electric motor driver. You first select the column titled "Power too high" and then write down all the "Common Root Causes" for further review (see Table B.1). The matrix indicates that 1) an incorrect impeller diameter, 2) the incorrect impeller speed, 3) back pressure too low, 4) spillback or bypass valve is leaking or open, and 5) pump worn out are all potential causes. Next, you systematically pare down the list by determining which potential causes are unlikely based on the available information and data collected. This will leave you with the most likely cause, or root cause, of your problem.

Table B.1 How to use the centrifugal pump troubleshooting matrix.

	Common symptoms								
Instructions: First find the "Common Symptom" column that best describes your field condition and then follow the column down to find all the possible causes (denoted by the symbol "X"). The "Common Root Causes" identified with an "X" are all the possible causes that should be investigated to determine the actual root cause of the problem. Note: Refer to Chapter 8 in *Is My Machine OK?* for more information on centrifugal pump performance.	Flow too low	Flow too high	Unstable or erratic flow	Discharge pressure too high	Discharge pressure too low	High pressure pulsations	Power too high (2)	Power too low (2)	High vibrations or noisy (3)
a. Incorrect impeller diameter(s)	X	X	X	X	X	X	X	X	
b. Incorrect impeller speed	X	X	X	X	X	X	X	X	
c. Impeller installed backwards or rotor is turning backwards	X				X			X	
d. Back pressure too high (1)	X		X	X		X		X	X
e. Back pressure too low		X	X		X	X	X		X
f. Plugged suction strainer, valve, or piping	X		X	X	X	X		X	X
g. Suction level too low	X		X		X	X			X

Common root causes	h. Cavitation	X		X		X	X		X	X
	i. Air or vapor entrainment	X		X			X		X	X
	j. Flow much less than design (1)	▨		X	X		X		X	X
	k. Flow much higher than design		▨	X		X	X	X		X
	l. Spillback or bypass valve is leaking or open	X				X		X		
	m. Rotor imbalance									X
	n. Pump to driver misalignment									X
	o. Pump internal seals and/or bushing clearances worn excessively	X				X	X	X		X
	p. Driver issue or malfunction. Go to “Electric Motor” or “Steam Turbine” troubleshooting tables for more guidance	X	X	X	X	X		▨	▨	

(1) There is a potential for a no-flow condition If the pump has a check valve and the pump cannot generate sufficient pressure to open the check valve. Shut the pump down immediately if there appears to be no pump flow and thoroughly investigate the situation before attempting to restart.

(2) The potential root causes for these two columns only apply if horsepower increases with flow. These column headings must be reserved if horsepower decreases with flow. Refer to the “How Horsepower Varies with Flow” at the end of this section for more information on this topic.

(3) For more information on potential causes of vibration, refer to Chapters 14 and 15 in *Is My Machine OK?*

Table B.2a Centrifugal pump troubleshooting matrix.

	Common symptoms								
Instructions: First find the "Common Symptom" column that best describes your field condition and then follow the column down to find all the possible causes (denoted by the symbol "X"). The "Common Root Causes" identified with an "X" are all the possible causes that should be investigated to determine the actual root cause of the problem. Additional troubleshooting advice can be found in Table B.2b. Note: Refer to Chapter 8 in *Is My Machine OK?* for more information on centrifugal pump performance.	Flow too low	Flow too high	Unstable or erratic flow	Discharge pressure too high	Discharge pressure too low	High pressure pulsations	Power too high (2)	Power too low (2)	High vibrations or noisy (3)
a. Incorrect impeller diameter(s)	X	X	X	X	X	X	X	X	
b. Incorrect impeller speed	X	X	X	X	X	X	X	X	
c. Impeller installed backwards or rotor is turning backwards	X				X			X	
d. Back pressure too high (1)	X		X	X		X		X	X
e. Back pressure too low		X	X		X	X	X		X
f. Plugged suction strainer, valve, or piping	X		X	X	X	X		X	X

Common root causes	g. Suction level too low	X		X		X	X			X
	h. Cavitation	X		X		X	X		X	X
	i. Air or vapor entrainment	X		X			X		X	X
	j. Flow much less than design (1)	▨		X	X		X		X	X
	k. Flow much higher than design		▨	X		X	X	X		X
	l. Spillback or bypass valve is leaking or open	X				X		X		
	m. Rotor imbalance									X
	n. Pump to driver misalignment									X
	o. Pump internal seals and/or bushing clearances worn excessively	X				X	X	X		X
	p. Driver issue or malfunction. Go to "Electric Motor" or "Steam Turbine" troubleshooting tables for more guidance	X	X	X	X	X		▨	▨	

(1) There is a potential for a no-flow condition If the pump has a check valve and the pump cannot generate sufficient pressure to open the check valve. Shut the pump down immediately if there appears to be no pump flow and thoroughly investigate the situation before attempting to restart.

(2) The potential root causes for these two columns only apply if horsepower increases with flow. These column headings must be reserved if horsepower decreases with flow. Refer to the "How Horsepower Varies with Flow" at the end of this section for more information on this topic.

(3) For more information on potential causes of vibration, refer to Chapters 14 and 15 in *Is My Machine OK?*

Table B.2b Centrifugal pump troubleshooting tips

Instructions: This table is intended to complement Table B.2a by providing additional troubleshooting advice. Additional field inspections or tests may be required to identify the hidden cause of a given machinery problem. For example: If you suspect that "back pressure is too high" is a likely root cause, go to the "Field Troubleshooting Tips" column and read the advice provided. For this potential root cause, it is recommended that you check for a flow obstruction or a change in the downstream pressure.	Centrifugal Pump Field Troubleshooting Tips 

Common root causes	a. Incorrect impeller diameter(s)	1. Check repair records to see if there is any written record of the installed impeller diameter(s) and then compare it to the design diameter(s). 2. Check the speed to make sure you are at the rated speed before pulling the rotor to check impeller diameter(s).
	b. Incorrect impeller speed	Check the speed with tachometer and compare with design speed. A speed issue can be the result of an erroneous input speed signal to a VFD.
	c. Impeller installed backwards or rotor is turning backwards	1. First check that you have the correct driver rotation. 2. If the driver rotation is correct, the speed is correct, and the pump differential is only a fraction of the rated differential, then you should consider pulling the rotor to see if the impeller(s) are installed backwards.

(*Continued*)

Table B.2b Cont.

	d. Back pressure too high	1. Check for a flow obstruction, such as a partially closed valve or a plugged strainer, in the discharge line. If there is a strainer in the discharge line, pull the strainer to see if it's clean. Check with operator to see if there has been a history of line pluggage. 2. Check the downstream system pressure to see if it is higher than normal due to a change in the process or an upset condition.
	e. Back pressure too low	1. Check the downstream system pressure to see if it is lower than normal due to a change in the process or an upset condition. 2. Check for malfunctioning back-pressure control valve on the discharge of the pump.
	f. Plugged suction strainer, valve, or piping	1. Check for flow obstruction in the piping. 2. Check any strainers in the suction and discharge line to see if they are plugged. 3. Ask the operator if the pump piping has a history of pluggage.

	g. Suction level too low	Check to see if the product suction level is normal. If not, restore the level to normal and see if flow symptoms disappear.
	h. Cavitation	1. Check to see if the product suction level is normal. If not, restore the level to normal and see if cavitation symptoms disappear. 2. Check to see of the product temperature is normal. If not, attempt to restore back to normal and see if cavitation symptoms disappear. 3. Check for a flow obstruction such as a plugged strainer, in the suction line. Pull the strainer to see if it's clean. Check with operator to see if there has been a history of line pluggage. 4. Check to see if the pump flow is in a normal range, i.e. ± 20% of the best efficiency point. Low or high flow operation can result in cavitation-like symptoms. If possible, operate the pump at normal flows and see if cavitation-like symptoms disappear.

(*Continued*)

Table B.2b Cont.

	i. Air or vapor entrainment	1. Check to see if the product tank or sump suction level is normal. If not, restore the level to normal and see if flow symptoms disappear. 2. If this is a new installation, check to see if the suction entrance is at an adequate submergence depth.
	j. Flow much less than design	1. Check the flow and determine if you are significantly below (<50%) of the design flow. 2. Perform a test by temporarily increasing the flow through the pump. If symptoms disappear, you may need to resize the pump or install a minimum flow spill back line.
	k. Flow much higher than design	1. Check the flow and determine if you are significantly above (>120%) of the design flow. 2. Perform a test by temporarily decreasing the flow through the pump. If symptoms disappear, you may need to resize the pump to handle the higher flow.

	l. Spillback or bypass valve is leaking or open	1. Check all potential bypass valves to ensure they are closed or are not leaking. 2. Check relief valves with a ultrasonic gun for any indications of leakage.
	m. Rotor imbalance	1. The predominate vibrational component will be 1x running speed if imbalance is truly the problem. 2. The horizontal 1x component should be approximately equal to the vertical 1x component.
	n. Pump to driver misalignment	1. Usually this type of misalignment will show up as 1x or 2x vibrational components in the spectrum. High axial vibration is another indication of pump to driven misalignment. 2. Start by checking the driver to pump alignment if vibration analysis suggests misalignment is present. 3. Misalignment can be the result of piping strain. If driver to machine alignment looks okay, then check piping fit-up for possible pipe strain issues.

(*Continued*)

Table B.2b Cont.

	o. Pump internal seals and/or bushing clearances worn excessively	1. Begin by checking pump performance in the field to determine if degradation has occurred. Find out if the pump is on its performance curve. Refer to assessment methods described in Chapter 8 of *Is my Machine OK?* 2. Loss of seal and bushing clearances may lead to an increase in 1x amplitudes. 3. As clearances increase significantly, you may begin to see 1x, 2x, and 3x, and nx components in the vibration spectrums.
	p. Driver issue or malfunction. Go to "Electric Motor" or "Steam Turbine" troubleshooting tables for more guidance	1. Failing to reach rated speed is an indication of a driver issue. 2. Erratic speed is another indication of driver control issue. 3. It is a good idea to have the OEM on site whenever steam turbines or electric motors with VFDs are first commissioned.

Centrifugal Compressor Troubleshooting Matrix

The centrifugal compressor troubleshooting matrix below can be used to determine the most likely cause of a particular symptom. The troubleshooting procedure is similar to the centrifugal pump matrix example shown in Table B.3:

1. First, find the column with the symptom that best describes what is seen in the field.
2. Then, locate all the "Common Root Causes" with an "X" in the "Common Symptoms" column for further review.
3. Next, systematically pare down the list of potential root causes by eliminating those that are unlikely, based on the information and data collected.
4. The remaining potential cause of all the "Common Root Causes" represents the most likely cause, or root cause, of your problem.

Table B.3a Centrifugal compressor troubleshooting matrix.

	Common symptoms									
Instructions: First find the “Common Symptom” column that best describes your field condition and then follow the column down to find all the possible causes (denoted by the symbol “X”). The “Common Root Causes” identified with an “X” are all the possible causes that should be investigated to determine the actual root cause of the problem. Additional troubleshooting advice can be found in Table B.3b.	Flow too low	Flow too high	Unstable or erratic flow	High discharge temperature	Discharge pressure too high	Discharge pressure too low	High pressure pulsations	Power too high (1)	Power too low (1)	High vibrations or noisy (2)
a. Incorrect impeller diameter(s)	X	X		X	X	X	X	X	X	
b. Incorrect rotor speed	X	X		X	X	X	X	X	X	X
c. Impeller(s) installed backwards or rotor turning backwards	X					X			X	
d. Back pressure too high	X		X	X	X		X	X	X	X
e. Suction pressure too low	X			X		X		X	X	X
f. Plugged suction strainer or piping	X		X	X		X		X	X	

Common Root Causes	g. Gas density lighter than design	X					X	X		X	
	h. Gas density higher than design		X		X	X		X	X		
	i. Flow much less than design	▨		X	X	X		X	X	X	X
	j. Flow much higher than design		▨	X			X	X	X	X	X
	k. Open or leaking spillback valve	X					X		X	X	
	l. Rotor imbalance										X
	m. Compressor to driver misalignment										X
	n. Suction temperature higher than design	X			X		X			X	
	p. Excessive internal compressor wear	X			X		X		X	X	X
	q. Driver issue or malfunction. Go to "Electric Motor" or "Steam Turbine" troubleshooting tables for more guidance	X	X	X	X	X	X		▨	▨	
	r. Surge control system malfunction	X	X	X	X	X	X	X	X	X	X

(1) The potential root causes for these two columns only apply if horsepower increases with flow. These column headings must be reserved if horsepower decreases with flow. Refer to the "How Horsepower Varies with Flow" at the end of this section for more information on this topic.

(2) For more information on potential causes of vibration, refer to Chapters 14 and 15 in *Is My Machine OK?*

Table B.3b Centrifugal compressor troubleshooting tips.

Instructions: This table is intended to complement Table B.3a by providing additional troubleshooting advice. Additional field inspections or tests may be required to identify the hidden cause of a given machinery problem. For example: If you suspect that "back pressure is too high" is a likely root cause, go to the "Field Troubleshooting Tips" column and read the advice provided. For this potential root cause, it is recommended that you check for a flow obstruction or a change in the downstream pressure.	Centrifugal Compressor Field Troubleshooting Tips 

Common root causes	a. Incorrect impeller diameter(s)	1. Check repair records to see if there is any written record of the installed impeller diameter (s) and then compare it to the design diameter (s). 2. Check the speed to make sure you are at the rated speed before pulling the rotor to check impeller diameter (s).
	b. Incorrect rotor speed	Check the rotor speed indication if installed or by using a tachometer and compare with design speed. A speed issue can be the result of an erroneous input speed signal to a VFD.
	c. Impeller(s) installed backwards or rotor turning backwards	1. First check that you have the correct driver rotation. 2. If the driver rotation is correct, the speed is correct, and the pump differential is only a fraction of the rated differential, then you should consider pulling the rotor to see if the impeller(s) are installed backwards.

(*Continued*)

Table B.3b Cont.

	d. Back pressure too high	1. Check for a flow obstruction, such as a partially closed valve or a plugged strainer, in the discharge line. If there is a strainer in the discharge line, pull the strainer to see if it's clean. Check with operator to see if there has been a history of line pluggage. 2. Check the downstream system pressure to see if it is higher than normal due to a change in the process or an upset condition.
	e. Suction pressure too low	1. Check the upstream system pressure to see if it is lower than normal due to a change in the process or an upset condition. 2. Check for flow obstruction in suction piping.
	f. Plugged suction strainer or piping	1. Check for flow obstruction in the piping. 2. Check any strainers in the suction and discharge line to see if they are plugged. 3. Ask the operator if the compressor piping has a history of pluggage.

	g. Gas density lighter than design	Pull a representative process gas sample in order to determine its molecular weight. The compressor differential pressure and amp draw are directly proportional to the molecular weight of the gas. Watch out for significant deviations from the normal molecular weight of the gas during start-ups.
	h. Gas density higher than design	Pull a representative process gas sample in order to determine it's the molecular weight. The compressor differential pressure and amp draw are directly proportional to the molecular weight of the gas. Watch out for significant deviations from the normal molecular weight of the gas during start-ups.

(*Continued*)

Table B.3b Cont.

	i. Flow much less than design	1. Check the flow and determine if you are significantly below (<80%) of the design flow. 2. If the compressor has a surge control system, check to see it is functioning properly. 3. If the compressor doesn't have a surge control system, perform a test by temporarily increasing the flow through the compressor. If symptoms disappear, you may need to review the compressor sizing and piping system to understand the source of the problem.
	j. Flow much higher than design	1. Check the flow and determine if you are significantly above (>120%) of the design flow. 2. Perform a test by temporarily decreasing the flow through the compressor. If symptoms disappear, you may need to review the compressor sizing and piping system to understand the source of the problem.

	k. Open or leaking spillback valve	1. Check all potential bypass valves to ensure they are closed or are not leaking. 2. If the compressor has a surge control system, make sure it is working properly. 3. Check relief valves with a ultrasonic gun for any indications of leakage.
	l. Rotor imbalance	1. The predominate vibrational component will be 1x running speed if imbalance is truly the problem. 2. The horizontal 1x component should be approximately equal to the vertical 1x component.

(*Continued*)

Table B.3b Cont.

	m. Compressor to driver misalignment	1. Usually this type of misalignment will show up as 1x or 2x vibrational components in the spectrum. High axial vibration is another indication of compressor to driven misalignment. 2. Start by checking the driver to compressor alignment if vibration analysis suggests misalignment is present. 3. Misalignment can be the result of piping strain. If driver to machine alignment looks okay, then check piping fit-up for possible pipe strain issues.
	n. Suction temperature higher than design	Check to see of the compressor suction temperature is deviating from the design value by more than 5%. A deviation greater than 5% will affect horsepower and performance.

	p. Excessive internal compressor wear	1. Begin by checking compressor's performance in the field to determine if degradation has occurred. Plot a few performance points of the performance map to see if the compressor is on its curve. 2. Compare the actual discharge temperature to the design discharge temperature. The discharge temperature will begin to rise above the design discharge temperature as internal compressor wear occur.
	q. Driver issue or malfunction. Go to "Electric Motor" or "Steam Turbine" troubleshooting tables for more guidance	1. Failing to reach rated speed is an indication of a driver issue. 2. Erratic speed is another indication of driver control issue. 3. It is a good idea to have the OEM on site whenever steam turbines or electric motors with VFDs are first commissioned.

(*Continued*)

Table B.3b Cont.

	r. Surge control system malfunction	The combination of low flow, low pressure differential, and high horsepower indications usually point to an open spillback valve. If a surge control system is installed, it is possible that the surge valve is leaking or open. First check if the valve if open. If it is, determine if it's due to a malfunctioning surge control system or due malfunctioning valve. If in doubt, have the surge control system designer double check the surge algorithms to ensure they are correct.

How Horsepower Varies with Flow

Centrifugal Pumps

Common sense tells us that, for a given speed, the horsepower required by a centrifugal pump increase as flow increases—which is not always a correct statement. Let's review performance curves for three types of centrifugal pumps:

Figure A.1 shows that the head curve for a radial flow pump is relatively flat and that the head decreases gradually as the flow increases. You will also notice that the brake horsepower increases gradually over the flow range with the maximum normally at the point of maximum flow.

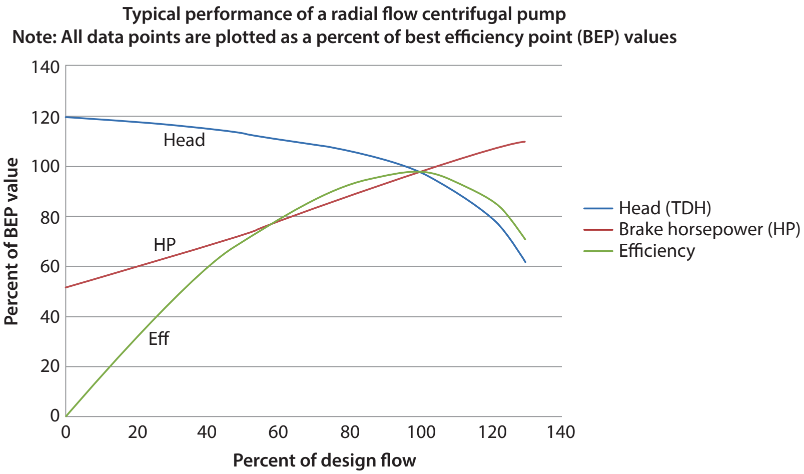


Figure A.1 Radial flow pump.

In contrast, mixed flow centrifugal pumps and axial flow or propeller pumps have considerably different characteristics as shown in Figures A.2 and A.3 below. The head curve for a mixed flow pump is steeper than for a radial flow pump. The shut-off head is usually 150% to 200% of the design head and the brake horsepower remains fairly constant over the flow range. For a typical axial flow centrifugal pumps, the head and brake horsepower both increase drastically near shutoff as shown in Figure A.3.

There are many pumps with characteristics falling somewhere between the three pump design examples shown here. These examples illustrate points on a continuum of pump performance designs. For instance, the Francis vane impeller would have a characteristic between the radial

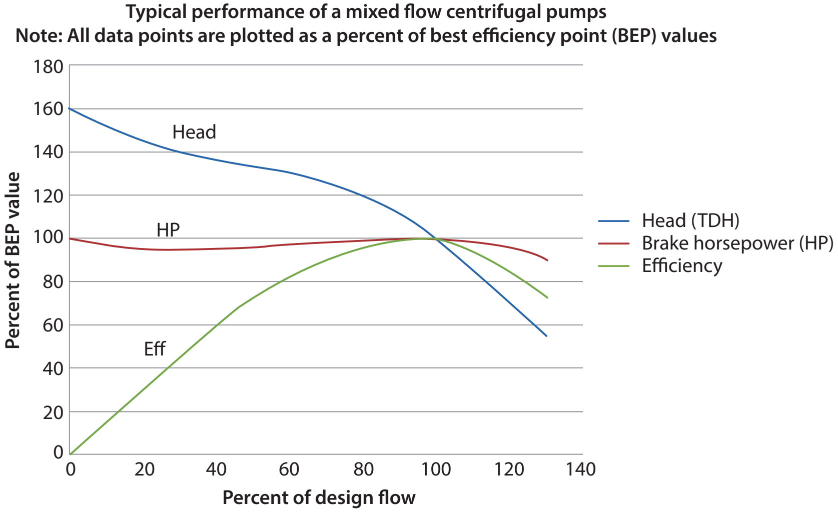


Figure A.2 Mixed flow pump.

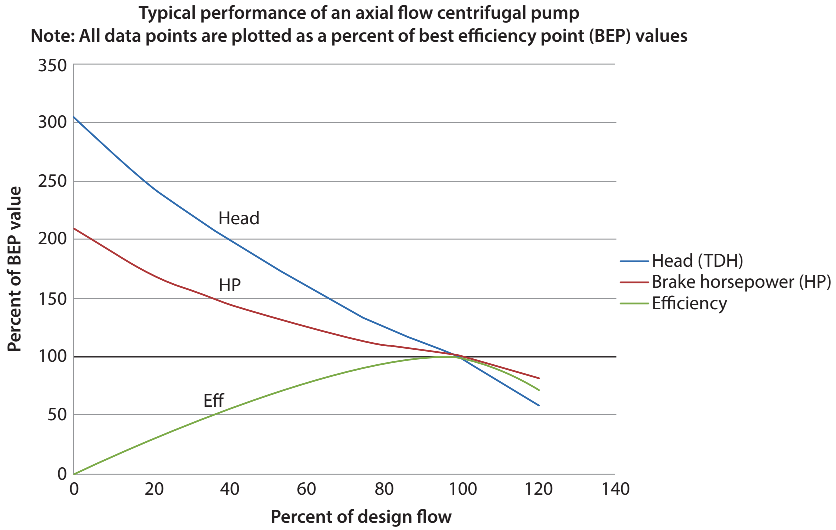


Figure A.3 Axial flow pump.

and mixed flow classes. The purpose of this discussion to illustrate how pump performance can vary based on their design.

Centrifugal Compressors

Just as the shape of a centrifugal pump head versus flow curve affects its horsepower versus flow curve, the shape of a centrifugal compressor head versus flow curve determines the shape of its horsepower versus flow curve. For a given gas density, speed, and inlet guide vane position (if applicable), we typically see:

1. Centrifugal compressors with relatively flat head versus flow curves, similar

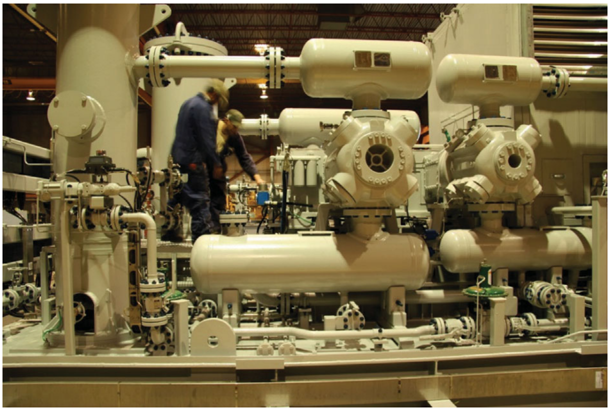
to Figure 1, tend to have horsepower curves that rise continuously as flow increases.

2. Centrifugal compressors with steep head versus flow curves, similar to Figure 3, tend to have horsepower versus flow curves that drop continuously as flow increases.

Conclusion

When dealing with centrifugal machinery, never assume that horsepower rises with flow. Always review the pump or compressor's performance curve for the specific machine you are dealing with to better understand the actual shape of the head versus flow curve and the horsepower versus flow curve.

Reciprocating Compressor Troubleshooting Matrix



The reciprocating compressor troubleshooting matrix below can be used to determine the most likely cause of a particular symptom. The troubleshooting procedure is similar to the centrifugal pump matrix example shown in Table B.4:

1. First, find the column with the symptom that best describes what is seen in the field.
2. Then, locate all the “Common Root Causes” with an “X” in the “Common Symptoms” column for further review.
3. Next, systematically pare down the list of potential root causes by eliminating those that are unlikely, based on the information and data collected
4. The remaining potential cause of all the “Common Root Causes” represents the most likely cause, or root cause, of your problem.

Table B.4a Reciprocating compressor troubleshooting matrix.

	Common symptoms								
Instructions: First find the "Common Symptom" column that best describes your field condition and then follow the column down to find all the possible causes (denoted by the symbol "X"). The "Common Root Causes" identified with an "X" are all the possible causes that should be investigated to determine the actual root cause of the problem. Additional troubleshooting advice can be found in Table B.4b.	Flow too low	Flow too high	High Discharge Temperature	Discharge pressure too high	Discharge pressure too low	High pressure pulsations	Power too high	Power too low	High vibrations or noisy
a. Incorrect cylinder clearance volume	X	X		X	X	X	X	X	
b. Wrong compressor speed	X	X		X	X	X	X	X	X
c. Intercooler ineffective (multistage units)	X		X					X	
d. Pulsation dampner damaged or plugged				X	X	X		X	X
e. Pulsation dampner ineffective						X			X

Common root causes	f. Suction pressure too low	X		X		X			X	
	g. Plugged suction strainer, valve, or piping restriction	X		X		X	X	X	X	
	h. Open or leaking spillback valve	X						X		
	i. Mechanical or acoustic resonance						X			X
	j. Inadequate compressor support									X
	k. Leaking cylinder valve	X		X		X			X	
	l. Unbalanced reciprocating weights									X
	m. Broken hold down bolt or support member									X
	n. Suction temperature higher than design	X		X				X		
	o. Gas is lighter than design	X				X	X		X	
	p. Gas is heavier than design		X	X	X		X	X		
	q. Leaking piston rings	X		X		X		X	X	
	r. Excessive cylinder valve losses			X		X		X		
	s. Driver issue or malfunction	X	X	X	X	X	X	▨	▨	

Table B.4b Reciprocating compressor troubleshooting tips.

Instructions: This table is intended to complement Table B.4a by providing additional troubleshooting advice. Additional field inspections or tests may be required to identify the hidden cause of a given machinery problem. For example: If you suspect that "wrong compressor speed" is a likely root cause, go to the "Field Troubleshooting Tips" column and read the advice provided. For this potential root cause, it is recommended that you check the compressor speed indication if installed or by using a tachometer and compare the indicated speed with the design speed.	Reciprocating Compressor Field Troubleshooting Tips 

Common root causes	a. Incorrect cylinder clearance volume	1. If volume unloaders are installed, first check to make sure they are all in the correct positions. Leaking volume unloaders can significantly affect compressor flow. 2. Check the repair records to determine if the clearance volumes were measured and recorded. 3. Conduct a compressor performance (PV) analysis and see if cylinder performance appears to be normal.
	b. Wrong compressor speed	Check the compressor speed indication if installed or by using a tachometer and compare with design speed.
	c. Intercooler ineffective (multi-stage units)	Check the inlet and outlet temperatures on your coolers and compare them to the design values. A high inlet temperature is an indication of a compressor issues. A normal inlet temperature with a high outlet temperature is an indication of a cooler issue.

(*Continued*)

Table B.4b Cont.

	d. Pulsation dampner damaged or plugged	If the problem has suddenly appeared, you may have a problem internal to the pulsation dampner. When possible, use a boroscope to inspect the pulsation dampner internals. Look for pluggage, or broken internal components.
	e. Pulsation dampner ineffective	If the problem is present immediately after commissioning, it may be a pulsation dampner design problem. Have someone verify the design.
	f. Suction pressure too low	1. Check the upstream system pressure to see if it is lower than normal due to a change in the process or an upset condition. 2. Check for flow obstruction in suction piping.
	g. Plugged suction strainer, valve, or piping restriction	1. Check for flow obstruction in the piping. 2. Check any strainers in the suction and discharge line to see if they are plugged. 3. Ask the operator if the compressor piping has a history of pluggage.

	h. Open or leaking spillback valve	1. Check all potential bypass valves to ensure they are closed or are not leaking. 2. Check relief valves for any indications of leakage.
	i. Mechanical or acoustic resonance	Check vibration and pulsations as a function of speed. Resonances will appear as defined spikes in the data. Refer to Chapter 18 in *Is My Machine OK?* for ways to identify resonances.
	j. Inadequate compressor support	Start you investigation by checking compressor vibration levels close to the skid or sub-base. If vibration levels are high near hold down bolts, then you skid or sub-base is not providing adequate support.
	k. Leaking cylinder valve	Use an infrared temperature gun or contact thermometer to check for hot valve caps. An isolated hot valve cap is an indication of a leaking cylinder valve. Then, replace all valves with hot valve caps and see if the symptoms disappear.

(*Continued*)

Table B.4b Cont.

	l. Unbalanced reciprocating weights	Imbalanced reciprocating weights should show up as high 1x vibrational components in the spectra.
	m. Broken hold down bolt or support member	If the vertical vibration levels are more than 2 times higher than the horizontal vibrating level, you should suspect that you have a broken or loose hold down bolt or support member.
	n. Suction temperature higher than design	Check to see of the compressor suction temperature is deviating from the design value by more than 5%. A deviation greater than 5% will affect horsepower and performance.
	o. Gas is lighter that design	Pull a representative process gas sample in order to determine its molecular weight. The compressor amp draw is directly proportional to the molecular weight of the gas. Watch out for significant deviations from the normal molecular weight of the gas during start-ups.

	p. Gas is heavier that design	Pull a representative process gas sample in order to determine its molecular weight. The compressor amp draw is directly proportional to the molecular weight of the gas. Watch out for significant deviations from the normal molecular weight of the gas during start-ups.
	q. Leaking piston rings	Conduct a compressor performance (PV) analysis to determine if excessive leakage is present.
	r. Excessive cylinder valve losses	Perform a compressor performance analysis (PV) to evaluate the magnitude of the cylinder valve losses. Compare the valve losses with the manufacturer's estimate.
	s. Driver issue or malfunction.	1. Failing to reach rated speed is an indication of a driver issue. 2. Erratic speed is another indication of driver control issue.

Reciprocating Pump Troubleshooting Table

The reciprocating pump troubleshooting table below can be used to determine the most likely cause of a particular symptom. The troubleshooting procedure is similar to the centrifugal pump matrix example shown in Table B.5:

1. First, select the symptom that best describes what is seen in the field.
2. Then, locate all the "Possible Causes" for further review.
3. Next, systematically pare down the list of possible causes by eliminating those that are unlikely, based on the information and data collected
4. The remaining possible cause represents the most likely cause, or root cause, of your problem.

Table B.5 Reciprocating pump troubleshooting table.

Symptom	**Possible cause**	**Field troubleshooting tips**
Low discharge pressure		
	1. Restriction in suction system	Check for potential flow obstruction in the piping.
	2. Leaking spillback valve or relief valve	1. Check all potential bypass valves to ensure they are closed or are not leaking. 2. Check relief valves with a ultrasonic gun for any indications of leakage.
	3. Pump not fully primed	Check to make sure the suction line is liquid full and vapor free. You may have to shut down the pump and vent the suction line to ensure it is liquid full. If you are unable to fill the suction line with liquid ensure there is an ample supply of liquid available to the pump.

(*Continued*)

Table B.5 Cont.

Symptom	Possible cause	Field troubleshooting tips
	4. Pump speed too low	Check the pump speed indication if installed or by using a tachometer and compare with design speed.
	5. Leaking pump valves	Pull valves and inspect for damage or installation issues.
	6. No back pressure on pump	Check to make sure the discharge pressure is normal.
	7. Gas entering fluid cylinder	1. Check to make sure the suction line is vapor free. You may have to shut down the pump and vent the suction line to ensure it is liquid full. 2. Check that you are not sucking in air or vapor in the suction tank due to vortexing.

	8. Low suction pressure causing cavitation due to inadequate NPSHa	1. First check to see if the suction pressure is normal. 2. Check for flow obstruction in the piping. 3. If possible, reduce the inlet fluid temperature. 4. Reduce suction lift or raise supply tank level.
	9. Excessive packing leakage	Visually inspect the packing boxes for external leakage. If leakage is excessive, have a qualified mechanical attempt to reduce leakage by adjusting packing glands.
	10. Driver issue or malfunction	1. Failing to reach rated speed is an indication of a driver issue. 2. Erratic speed is another indication of driver control issue.

(*Continued*)

Table B.5 Cont.

Symptom	**Possible cause**	**Field troubleshooting tips**
Low total flow into the process		
	1. Restriction in suction system	Check for flow obstruction in the piping.
	2. Leaking spillback valve or relief valve	1. Check all potential bypass valves to ensure they are closed or are not leaking. 2. Check relief valves with a ultrasonic gun for any indications of leakage.
	3. Pump speed too low	Check the pump speed indication if installed or by using a tachometer and compare with design speed.
	4. Leaking pump valves	Pull valves and inspect for damage or installation issues.
	5. Gas entering fluid cylinder	Check to make sure the suction line is vapor free. You may have to shut down the pump and vent the suction line to ensure it is liquid full.

	6. Insufficient suction pressure	1. Check the upstream system pressure to see if it is lower than normal due to a change in the process or an upset condition. 2. Check for flow obstruction in suction piping.
	7. Pump not fully primed	Check to make sure the suction line is liquid full and vapor free. You may have to shut down the pump and vent the suction line to ensure it is liquid full. If you are unable to fill the suction line with liquid ensure there is an ample supply of liquid available to the pump.
	8. Leaking packing	Visually inspect the packing boxes for external leakage. If leakage is excessive, have a qualified mechanical attempt to reduce leakage by adjusting packing glands.

(*Continued*)

Table B.5 Cont.

Symptom	Possible cause	Field troubleshooting tips
	9. Driver issue or malfunction	1. Failing to reach rated speed is an indication of a driver issue. 2. Erratic speed is another indication of driver control issue.
Excessive vibration		
	1. Insufficient NPSHA causing cavitation	1. Check the upstream system pressure to see if it is lower than normal due to a change in the process or an upset condition. 2. Check for flow obstruction in suction piping. 3. If possible, reduce inlet fluid temperature. 4. Reduce suction lift or raise supply tank level. 5. A malfunctioning or improperly sized pulsation dampner can result in cavitation due to excessive pressure swings in the suction line.

	2. Gas entering fluid cylinder	1. Check to make sure the suction line is vapor free. You may have to shut down the pump and vent the suction line to ensure it is liquid full. 2. Check that you are not sucking in air or vapor in the suction tank due to vortexing.
	3. Broken valve spring or foreign material under pump valve	Pull valves and inspect for pluggage, damage, or installation issues.
	4. Excessive valve lift	Have the pump OEM evaluate the valve lift for your application.
	5. Relief valve or other accessory causing noise	Check relief valve for internal issues using an ultrasonic gun.
	6. Pulsation dampners not properly primed	De-pressure pulsation dampner and ensure the bladder is properly charged.

(*Continued*)

Table B.5 Cont.

Symptom	Possible cause	Field troubleshooting tips
	7. Pulsation dampner bladder damaged or ineffective	De-pressure pulsation dampner and see if the bladder is holding the proper charge. If the bladder is holding the proper charge, the pulsation dampner may be undersized.
	8. Acoustic resonance in suction or discharge piping	Check pressure pulsations as a function of speed. Resonances will appear as defined spikes in the data. Refer to Chapter 18 in *Is My Machine OK?* for ways to identify resonances.
	9. Piping resonance	Check vibration as a function of speed. Resonances will appear as defined spikes in the data. Refer to Chapter 18 in *Is My Machine OK?* for ways to identify resonances.

	10. Broken hold down bolt or support member	If the vertical vibration levels are more than 2 times higher than the horizontal vibrating level, you should suspect that you have a broken or loose hold down bolt or support member.
	11. Inadequate baseplate stiffness	Start you investigation by checking pump vibration levels close to the skid or sub-base. If vibration levels are high near hold down bolts, then you skid or sub-base is not providing adequate stiffness.
	12. Inadequate mass of foundation	The mass of the foundation should be 5 to 10 times that of the pump.

(*Continued*)

Table B.5 Cont.

Symptom	Possible cause	Field troubleshooting tips
High temperature in the drive end		
	1. Pump overloaded due to an excessively high discharge pressure	1. Check for a flow obstruction, such as a partially closed valve or a plugged strainer, in the discharge line. If there is a strainer in the discharge line, pull the strainer to see if it's clean. Check with operator to see if there has been a history of line pluggage. 2. Check the downstream system pressure to see if it is higher than normal due to a change in the process or an upset condition.

	2. Discharge valve partially or completely closed	Check all discharge valves to ensure they are fully open.
	3. Internal pump valves have inadequate clearances	Pull and inspect the pump valves. Have a spare set of valves to compare them to. If this is a new installation, have the OEM check the valve design.
	4. Spillback control not operating correctly	If the pump has a spillback control, system, have the design and logic check out by an instrument engineer or technician. The control system must never force the pump to see a higher than normal discharge pressure.

Fan Troubleshooting Matrix

Instructions: First drop down to the "Symptoms" column and find all the combination of symptoms that best describe your field observations. The "Possible Causes" found in the far right column, corresponding to the identified symptoms, are all the possible causes that should be investigated to determine the actual root cause of the problem.

Table B.6 Fan troubleshooting.

Symptoms					Possible causes
Flow	**Pressure**	**Power**	**Vibration**	**Pulsations**	
Low	Low	Low			Speed lower than design
Low	Low	Low			V-belts slipping (If V-belts are slipping, tighten or replace.)
Low	Low	Low			Wrong drive sheaves (Make sure drive sheaves diameters are correct.)
Low	Low	Low			Suction pressure too low
Low	Low	Low			Air or gas density lower than design
Low	Low	Low			Excessive ducting losses (Compare fan inlet pressure to the upstream pressure to see if losses are excessive.)

(*Continued*)

Table B.6 Cont.

Symptoms					Possible causes
Flow	**Pressure**	**Power**	**Vibration**	**Pulsations**	
Low	Low	Low			Axial fan blade settings lower than design (Shut down the fan and check blade attack angles with protractor.)
Low	Low	Low			System losses higher than design (Compare fan exhaust pressure to the downstream pressure to see if losses are excessive.)
Low	Low				Driver issue or malfunction (Check driver or driver controls if speed is running well below rated speed.)

Low	High	Low			Blockage in system
Low	High	Low			Damper closed
Low	High	Low			Fan operating in stall below the peak pressure flow (Attempt to increase the flow and see of the symptoms disappear.)
High	Low	High			System pressure losses lower than design
High	Low	High			Missing system components
High	High	High			Speed is higher than design
High	High	High			Air or gas temperature lower than design
High	High	High			Air or gas density higher than design

(*Continued*)

Table B.6 Cont.

Symptoms					Possible causes
Flow	**Pressure**	**Power**	**Vibration**	**Pulsations**	
High	High	High			Wrong wheel rotation (Shut down; uncouple the fan from the driver in order to check the rotational direction of the driver.)
High	High	High			Fan running backwards (First check the driver rotation before considering inspecting or pulling the rotor.)
High	High	High			Axial fan blades set higher than design (Shut down the fan and check blade attack angles with protractor.)

High	High				Driver issue or malfunction (1. Failing to reach rated speed is an indication of a driver issue. 2. Erratic speed is another indication of driver control issue.)
Normal	Normal	High			Undersized motor or driver (Check with OEM on fan horsepower requirements.)
Normal	Normal	High			Excessive driveline losses (Wheel or seal rubbing, tight bearings, misaligned v-belts, etc.)
Normal	Normal	High			Motor has wrong voltage or is wired wrong (Recheck motor nameplate for proper wiring sequence.)

(*Continued*)

Table B.6 Cont.

Symptoms					**Possible causes**
Flow	**Pressure**	**Power**	**Vibration**	**Pulsations**	
Unsteady	Unsteady	Unsteady	High	High	Fan is blocked off (Check for blockages in the fan outlet ducting.)
Unsteady	Unsteady	Unsteady	High	High	Fan is operating in stall or on an unstable part of the curve (Consult the OEM concerning this potential issue.)
Unsteady	Unsteady	Unsteady	High	High	Fan operating in parallel and not properly rated (Shut one of the fans down and see of the symptoms disappear.)
			High	High	Blade-pass frequency due to tight wheel clearance (Consult the OEM concerning this potential issue.)

▨	▨	▨	High	High	Rotating stall due to low flow or wrong fan selection (Consult the OEM concerning this potential issue.)
▨	▨	▨	High	High	Surging due to low flow (Check to see if you are well below rated flow. IF you are, raise flow to see if symptoms disappear.)
▨	▨	▨	High	High	Vortex shedding (Consult the OEM concerning this potential issue.)
▨	▨	▨	High	High	Flow turbulence due to poor installation or obstruction (Look for flow turbulence vibrational components in the vibration spectra.)

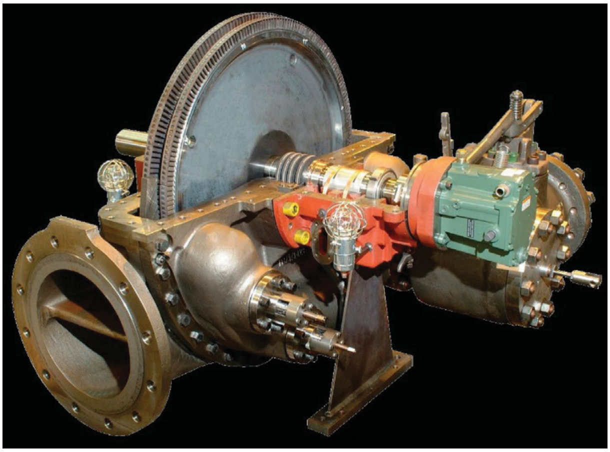
(*Continued*)

Table B.6 Cont.

Symptoms					Possible causes
Flow	**Pressure**	**Power**	**Vibration**	**Pulsations**	
			High		Imbalance (1. The predominate vibrational component will be 1x running speed if imbalance is truly the problem. 2. The horizontal 1x component should be approximately equal to the vertical 1x component.)
			High		Resonance (Check vibration as a function of speed. Resonances will appear as defined spikes in the data. Refer to Chapter 18 in *Is My Machine OK?* for ways to identify resonances.)

			High		Looseness (In the vibration spectra, indications of looseness usually appear as a predominant 1x vibrational component with higher order multiples, i.e. 1x, 2x, 3x, 4x, etc.)
			High		Internal rubbing (1. More likely on a new installation or after a rebuild. 2. Check for duct to fan fit-up issues.)

Steam Turbine Troubleshooting Table



Note: This troubleshooting table only applies to general purpose steam turbines rated at 1000 horsepower or less. It should not be applied to condensing turbine installations.

Instructions: Find the symptom that best describes your observation. Next record all the possible causes listed in the "Possible Cause" column. These are all the possible causes that should be investigated to determine the root cause of the problem.

Table B.7 Steam turbine troubleshooting.

Symptom	**Possible cause (Advice)**
Steam turbine does not achieve rated power.	
	1. Too many hand valves closed
	2. Speed governor set too low
	3. Inlet steam pressure too low
	4. Exhaust pressure too high
	5. Malfunctioning governor
	6. Horsepower required by driven machine too high
	7. Throttle valve not opening completely
	8. Nozzles plugged
	9. Inlet steam strainer plugged
	10. Turbine steam pathway fouled due to poor steam quality

(*Continued*)

Table B.7 Cont.

Symptom	**Possible cause (Advice)**
Speed increases excessively when load is decreased	
	1. Throttle valve not closing completely
	2. Throttle valve and valve seats cut or worn
	3. Malfunctioning governor
	4. Salt build-up on trip and throttle valve stem
Excessive speed variation	
	1. Governor droop adjustment required
	2. Malfunctioning governor controls
	3. Throttle assembly friction (Replace components that are sticking or binding)
	4. Throttle valve looseness
	5. Horsepower load too light with full inlet pressure

Table B.7 Cont.

Symptom	Possible cause (Advice)
	6. Rapidly changing load from the driven machine due to process conditions
	7. Backpressure too low
Slow turbine speed acceleration	
	1. See all possible causes for "Insufficient power" above
	2. High starting torque of driven machine
	3. High rotational inertia of entire machine train
Governor not operating properly	
	1. Restricted throttle valve travel
	2. Governor not installed properly
	3. Verify governor is designed for the proposed speed range
	4. Trip and throttle valve sticking due to salt build-up on stem

(*Continued*)

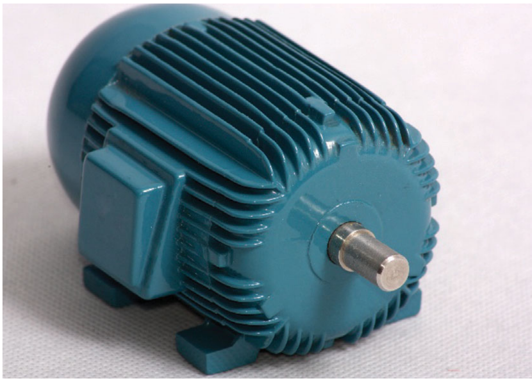
Table B.7 Cont.

Symptom	Possible cause (Advice)
Overspeed trip activates at normal operating speed	
	1. Excessive vibration
	2. Trip speed setting too low
	3. Malfunctioning governor
	4. Incorrect tachometer signal
Overspeed does not trip at set speed	
	1. Trip speed setting set too high
	2. Bolt trip mechanism problem (Examine trip mechanism)
	3. Over speed trip valve unable to close (Inspect trip valve)
	4. Sticking trip and throttle valve due to salt build-up
Excessive vibration or noise	
	1. Misalignment
	2. Worn bearing

Table B.7 Cont.

Symptom	**Possible cause (Advice)**
	3. Worn coupling (Likely with gear type couplings)
	4. Unbalanced coupling
	5. Unbalanced rotor
	6. Piping strain (Check cold piping fit up and ensure allowances have been made for thermal expansion)
	7. Excessive end play
	8. Bent shaft
	9. Excessive rubbing at shaft seal
	10. Worn steam seals. Look for a) water in the oil and/or b) a temperature increase on bearing housing.

Electric Motor Troubleshooting Table



Note: This troubleshooting table is not intended to cover variable frequency drive and motor systems.

Instructions: Find the symptom that best describes your observation. Next record all the possible causes listed in the "Possible Cause" column. These are all the possible causes that should be investigated to determine the root cause of the problem.

Table B.8 Electric motor troubleshooting table.

Symptom	**Possible cause (Advice)**
Motor starts up and runs but then trips off line	
	1. Voltage drop
	2. Load increases beyond rated horsepower
	3. Incorrect wiring (Recheck motor nameplate for proper wiring sequence)
Motor takes too long to accelerate	
	1. Voltage too low
	2. Rotational inertia of entire train too high
	3. Bad bearings
	4. Internal rub
	5. Load of driven machine too high
Motor frequently trips	
	1. Load of driven machine too high
	2. Ambient temperature too high

(*Continued*)

Table B.8 Cont.

Symptom	Possible cause (Advice)
	3. Fuse(s) or circuit breaker(s) may be incorrectly sized or is defective (Check and replace if required)
	4. Winding shorted or grounded
	5. High winding temperature
Motor vibrates	
	1. Motor misaligned to driven machine
	2. Bad bearings
	3. Rotor out of balance
	4. Rotor short or cracked rotor bars
	5. Loose stator
	6. Soft foot (Check for soft foot issues)
	7. Weak baseplate or foundation
	8. Broken grout
	9. Rubbing or imbalance due to excessive bearing grease getting into the motor windings

Hot Bearing Problems

High radial or thrust bearing temperatures are commonly encountered machinery field problems that have the potential of leading to catastrophic bearing failures and costly repairs. High bearing temperatures are either determined by embedded thermocouples or measured manually with temperature measuring devices, such as infrared or contact thermometers or infrared thermography camera. The first question to ask is: Is the bearing failing or is the high temperature caused by a support system issue or a design or lubrication problem? Before drawing any conclusions, it is important to conduct a field survey yourself using an infrared temperature gun, contact thermometer or infrared thermography camera. Between an infrared temperature gun and a contact thermometer, the contact thermometer is preferred due to its accuracy. You can use the IR thermometers for quick field surveys to pinpoint problem areas and then use the contact thermometers for accurate surface temperature values.

Should I use an infrared gun or contact thermometer?

If a quantitative temperature analysis is required, a contact thermometer should be considered over an infrared thermometer. Contact thermometers are inexpensive and accurate temperature measuring devices that deliver repeatable results, regardless of the color or finish of the surface being analyzed. In contrast, infrared thermometers are more accurate when used on flat, dark-colored surfaces and tend to yield low readings on shiny surfaces.

Here are locations where temperatures should be taken:

Closed looped oil circulation systems

1. Bearing cap or bearing housing temperatures
2. Inlet and outlet oil cooler temperatures — A small differential on the cooler means the cooler is not removing heat from the return oil.

3. Bearing supply oil and drain oil temperatures
    a. A high inlet temperature indicates an oil cooling issue
    b. A normal inlet temperature and high drain temperature indicated a problem at the bearing or with the lubricant properties.

Sump lubrication systems

1. Bearing cap temperature
2. Oil sump temperature
3. Cooling water supply and outlet temperatures (if cooling coils are used)

Greased bearing

1. Bearing cap temperature

How Serious Is the Problem?

Two factors determine the extent of the problem. The first is the actual bearing temperatures. Chapter 19 in *Is My Machine OK?* contains bearing temperature guidelines for the various bearing types. The second factor is how temperatures are trending with respect to historical temperature data. If the temperature is in the alarm range and climbing rapidly, it is time to shut down; however if the bearing is in the alarm range or close to it but stable, then there is time to investigate the problem further.

The bearing temperature troubleshooting table below can be used to hone in on potential causes of the high temperature issue. Use this information along with the 5Qs method to decide how to proceed. Keep in mind that once the bearing temperature reaches the danger range, it is time to shut down before secondary damage occurs.

Table B.9 Troubleshooting tips for hot bearings.

Lubrication method	**Problem category**	**Potential Issue**	**Comment(s)**
C,S,G	Design	Bearing design errors	Have manufacturer or OEM review design.
C,S,G	Design	Bearing undersized (load miscalculated)	Have manufacturer or OEM review design.
C,S	Installation	Wrong bearing clearance	Check clearance.
C,S	Installation	Wrong bearing crush	Check crush.
C,S,G	Installation	Wrong bearing	Check bearing part number.
C,S,G	Installation	Wrong installation procedure	Confirm the proper installation procedure was used.
C,S,G	Installation	Bearing damage during installation	Confirm that the proper installation procedure was used.
C	Cooling	Oil cooler bypassed (pressurized lube systems)	Check operation of thermostatic bypass valve. Use temperature gun to check operation of bypass valve.

(*Continued*)

Table B.9 Cont.

Lubrication method	Problem category	Potential issue	Comment(s)
C	Cooling	Oil cooler undersized (pressurized lube systems)	Check inlet and outlet oil temperatures on cooler. Low delta T indicates the cooler is ineffective. Possible design issue.
C	Cooling	Oil cooler plugged (pressurized lube systems)	Check inlet and outlet oil temperatures on cooler. Low delta T indicates the cooler is ineffective. Maintenance issue.
C,S	Cooling	Oil cooler fins plugged or damaged	Check inlet and outlet oil temperatures on cooler. Low delta T indicates the cooler is ineffective. Maintenance issue.
C	Cooling	Oil cooler louvers closed (pressurized lube systems)	Check inlet and outlet oil temperatures on cooler. Low delta T indicates the cooler is ineffective.
S	Cooling	Cooling coils fouled or plugged (small oil sumps)	Check inlet and outlet cooling water temperatures. Low delta T indicates the cooling coil is ineffective. Maintenance issue.

C	Flow	Wrong oil flow orifice (pressurized lube systems)	A single hot bearing might indicate that a wrong orifice was supplied. Installation or assembly issue.
C	Flow	Flow orifice plugged (pressurized lube systems)	A sudden increase in temperature of single bearing might indicate that an oil flow orifice is plugged. Maintenance issue.
S	Flow	Oil ring, slinger or flinger ineffective.	Open bearing housing view port and inspect operation of oil ring, flinger or slinger. This could be a design or maintenance issue.
C	Flow	Oil supply pressure too low (pressurized lube systems)	Look for 1) leaking spill back valve or 2) relief valve or worn pump(s).
S	Flow	Oil level too low (small oil sumps)	Check sump level. 1) A clogged oil level gauge line can give a false reading of lubrication level. 2) For closed systems use an expansion chamber or a balance line to prevent pressure buildup in bearing housing. 3) For open systems watch for clogged vent.

(*Continued*)

Table B.9 Cont.

Lubrication method	**Problem category**	**Potential issue**	**Comment(s)**
C,S,G	Operational Issue	Speed too high	Check machine speed and compare with design speed.
C,S,G	Operational Issue	Excessive load	Check to see if operating conditions are normal (pressures, flows, density, etc.).
C,S,G	Lubrication	Wrong lubricant	Review lubricant data or test lubricant properties.
C,S	Lubrication	Oil sump contamination (pressurized oil systems and oil sumps)	Analyze lube oil.

G	Lubrication	Lack of grease or old grease (greased bearings)	Remove grease drain plug. If nothing comes out of drain, add fresh grease and recheck bearing temperature.
G	Lubrication	Too much grease (greased bearings)	Remove grease drain plug. If grease or oil comes out, wait until bearing reaches operating temperature. Then replace drain plug and recheck bearing temperature.

Lubrication Methods: C-closed loop oil circulation system, S-sump oil system, G-grease lubrication

Review Questions & Exercises

1. Select the best statement that completes the definition of **Failure analysis**:

Failure analysis is the process of ____________

   a. Determining why a machine is not performing as expected
   b. Collecting and analyzing data to determine the cause of a machine failure
   c. Collecting and analyzing data to better understand a machine's environment

2. Complete the definition for Field troubleshooting

Field troubleshooting is a process of determining the cause of an apparent machine problem ________________.

   a. After it has failed and has been dissembled in a repair shop

   b. After its installation, but before it's started up
   c. While it is still operating under process conditions and before it has failed.

3. There are two types of machine loads:

   a. Static and modal loads
   b. Modal and pressure loads
   c. Static and dynamic loads

4. The Pareto Principle, also known as the 80–20 rule, states that, for many events, roughly __________ of the observed effects come from ___________of the causes.

5. One of the most challenging aspects of machinery professional or operator's job is deciding whether an operating machine should be __________ due to a perceived problem or be allowed to _________.

6. Machines are mechanical systems composed of internal elements that basically fall under various categories of functions.

   a. Give three examples of internal elements that make up a centrifugal pump.
   b. Give two examples of internal elements that make up centrifugal compressors.

7. How a machine component responds to a load depends on:

   a. The component's geometry and material properties
   b. The component's length and finish
   c. The type of coating applied to the component

8. Give an example of how a process system problem can affect pump performance.
9. Give an example of how a process system problem can affect compressor performance.
10. List some potential risks associated with a catastrophic centrifugal compressor failure.
11. List some potential risks associated with a catastrophic pump failure.
12. List some potential risks associated with an electric motor.
13. Rank the following list of risks in order of highest to lowest:

    a. Likely possibility of $500,000 in production losses
    b. Likely possibility of an injury
    c. Very likely possibility of $10,000 repair costs
    d. Very likely possibility of a major environmental release of a regulated liquid

14. Who would you talk to if you needed to get information on each of the following situations?
    a. Details about a new compressor installation
    b. Details on a pump bad actor
15. If a vibration problem is detected immediately following a centrifugal compressor repair, what possible causes could be postulated?
16. If pump performance has dropped off after seven years of operations, what possible causes could be postulated?
17. If centrifugal compressor vibration levels are extremely speed sensitive, what possible causes could be postulated?
18. What data plot could you generate to prove that a high discharge temperature on a compressor coincides with a changing high discharge pressure?
19. Let's assume you measure high vibrations in the vertical direction of a motor foot. If you find that the baseplate is not vibrating but the foot is, what can you conclude?

20. What can you infer if one radial bearing of a compressor train with a force feed lubrication is running hot and the other bearings are operating at normal temperatures?
21. Describe a possible test to determine if a pump bearing housing resonance is aggravating a vibration problem.
22. Describe a possible test to prove low pump flow is causing high pump vibration.
23. Describe a possible test to prove that low reciprocating compressor flow is caused by a leaking spillback valve.
24. Name the 5Qs that apply to news reporting and troubleshooting.
25. Draw a cause map that can explain the reasons a light bulb in your house won't turn on.
26. Pump troubleshooting exercise:

Using the troubleshooting matrix below, draw a cause map with all the possible causes that can cause a high pump pressure.

Centrifugal Pump Troubleshooting Matrix

		Common symptoms								
Instructions: Find the "Common Symptom" that best describes your field condition and then go down and find all the possible "Common Root Causes," which are denoted by the symbol "X." These are all the possible causes that should be investigated to determine the actual root cause.		Flow too low	Flow too high	Unstable flow	Pressure too high	Pressure too low	High pressure pulsations	Power too high (1)	Power too low (1)	High vibrations or noisy (2)
	a. Wrong impeller diameter(s)	X	X	X	X	X	X	X	X	
	b. Wrong impeller speed	X	X	X	X	X	X	X	X	
	c. Impeller installed backwards	X				X			X	
	d. Pump turning backwards	X				X			X	

(*Continued*)

		Common symptoms								
Common root causes	e. Back pressure too high	X		X	X		X		X	
	f. Back pressure too low		X	X		X	X	X		
	g. Plugged suction strainer or piping	X		X		X	X		X	X
	h. Suction level too low	X		X		X	X			X
	i. Cavitation	X		X		X	X		X	X
	j. Air or vapor entrainment	X		X			X		X	X
	k. Too far away from BEP, i.e., flow too high or too low relative to design			X	X		X			X
	l. Rotor imbalance									X
	m. Pump to driver misalignment									X
	n. Pump worn out	X				X		X		X

(1) The potential root causes for these two columns only apply if horsepower increases with flow. These column headings must be reserved if horsepower decreases with flow. Refer to the "How Horsepower Varies with Flow" at the end of this section for more information on this topic.

(2) For more information on potential causes of vibration, refer to Chapters 14 and 15 in *Is My Machine OK?*

27. Using the centrifugal pump troubleshooting matrix list all the "Common Root Causes" of high flow.

28. Using the reciprocating troubleshooting matrix in the back of the book list all the "Common Root Causes" of high horsepower load.

29. List the team members you would select for a complex problem involving steam turbine driving a centrifugal pump. The steam turbine can't reach rated speed during start-ups.

30. Assume you have concluded that a centrifugal compressor is failing and needs to be shut down for repair. Who would you invite to a meeting to finalize your plan of action?

31. Assume you have concluded that a fully spared reciprocating compressor has some failing cylinder valves. What are your options going forward?

32. _______________ is the methodology that uses information gathered with internally or internally mounted motion sensors to assess a machine's mechanical condition.

33. The methodology in question 32 can be used to:

    a. Determine when a catastrophic failure is going to occur

b. Determine the general nature of the machine defect by identifying the magnitude of the dynamic motion
c. Determine the general nature of the machine defect by identifying the predominate frequency of the dynamic motion

34. A rotordynamics analysis uses rotor geometry and bearing support information to determine:

a. Critical speeds
b. How the rotor will respond to imbalance
c. How rotor or bearing design changes will effect vibration
d. All of the above

35. A ________________________ (choose from the options below) should be performed before any major modifications to the rotor or bearings:

a. Rotordynamic analysis
b. Oil Analysis
c. Hazard analysis

36. List a few ways you can improve troubleshooting capabilities at your site.

Answers to the Review Questions & Exercises

1. Select the best statement that completes the definition of **Failure analysis**:

Failure analysis is the process of collecting and analyzing data to determine the cause of a machine failure.

2. Complete the definition for Field troubleshooting

Field troubleshooting is a process of determining the cause of an apparent machine problem while it is still operating under process conditions and before it has failed.

3. There are two types of machine loads:

   a. Static and dynamic loads

4. The Pareto Principle, also known as the 80–20 rule, states that, for many events, roughly **80%** of the observed effects come from **20%** of the causes.

5. One of the most challenging aspects of a machinery professional or operator's job is deciding whether an operating machine should be shut down due to a perceived problem or be allowed to keep operating.

6. Machines are mechanical systems composed of internal elements that basically fall under various categories of functions.
   a. Give three examples of internal elements that make up a centrifugal pump.
      i. Shaft, seal, bearing, impeller, coupling hub, pump casing, etc.
   b. Give two examples of internal elements that make up centrifugal compressors
      i. Shaft, seal, bearing, impeller, coupling hub, compressor casing, diaphragms, etc.

7. How a machine component responds to a load depends on: c. The component's geometry and material properties.

8. Give an example of how a process system problem can affect pump performance.

   a. A blockage in the discharge of a pump can lead to low pump flow.
   b. Entrained vapors in the suction of a pump can lead to a low pump discharge pressure.

9. Give an example of how a process system problem can affect compressor performance

   a. Light gas will reduce the head capability of the compressor
   b. Light gas could cause a compressor to surge
   c. Heavy gas can lead to high horsepower requirements

10. List some potential risks associated with catastrophic centrifugal compressor failure

    a. Loss of containment
    b. Major equipment damage
    c. Potential fire if gas is flammable
    d. Loss of production

11. List some potential risks associated with catastrophic pump failure

    a. Loss of containment
    b. Major equipment damage

c. Potential fire if pumped liquid is flammable
d. Loss of production if pump is not spared

12. List some potential risks associated with an electric motor

a. Major equipment damage
b. Loss of production if unspared

13. Rank the following list of risks in order of highest to lowest:
Here is how the authors rank these risks:

a. Likely possibility of an injury
b. Very likely possibility of a major environmental release of a regulated liquid
c. Likely possibility of $500,000 in production losses
d. Very likely possibility of $10,000 repair costs

Answer: The actual ranking depends on your personal risk profile. Here is one risk ranking that seems reasonable: b, d, a, c.

14. Who would you talk to if you needed to get information on each of the following situations?

a. Details about a new compressor installation: 1) The project manager for the design details, 2) the construction foremen for insight into the compressor's installation, and 3) the mechanics for insight into compressors start-up issues.

b. Details on a pump bad actor: The operators of the pumps and the mechanics that work on them.

15. If a vibration problem is detected immediately following a centrifugal compressor repair, what possible causes could be postulated? 1. A bad repair, 2. Poor alignment, 3. Poor rotor balance.

16. If pump performance has dropped off after seven years of operations, what possible causes could be postulated? 1. Pump wear clearances have opened up. 2. Impeller has experienced severe erosion.

17. If centrifugal compressor vibration levels are extremely speed sensitive, what possible causes could be postulated? Speed sensitivity either means a critical speed is present or there is a rotor instability present.

18. What data plot could you generate to prove that a high discharge temperature on a compressor coincides with a changing high

discharge pressure? A correlation plot of the compressor's discharge temperature versus the compressor discharge pressure should reveal is there is a strong correlation between these two variables.

19. Let's assume you measure high vibrations in the vertical direction of a motor foot. If you find that the baseplate is not vibrating but the foot is, what can you conclude? The hold down bolt is probably loose or broken.

20. What can you infer if one radial bearing of a compressor train with a force feed lubrication is running hot and the other bearings are operating at normal temperatures? Either the oil feed to the hot bearing is plugged or the hot bearing is failing.

21. Describe a possible test to determine if a pump bearing housing resonance is aggravating a vibration problem. An impact test, also known as a bump test, can be used to determine if there is a bearing housing resonance present. The bearing housing will "ring down" when impacted sharply. The frequency of the ringing is the bearing housing resonance frequency.

22. Describe a possible test to prove low pump flow is causing high pump vibration. Increase

the pump flow by opening a bypass line and see if vibration levels change.

23. Describe a possible test to prove that low reciprocating compressor flow is caused by a leaking spillback valve. Perform a field audit and ensure all potential spillback lines are closed. Also, check for possible leaking valves.
24. Name the 5Qs that apply to news reporting and troubleshooting. What, Who, When, Where, and Why.
25. Draw a cause map that can explain the reasons a light bulb in your house won't turn on.

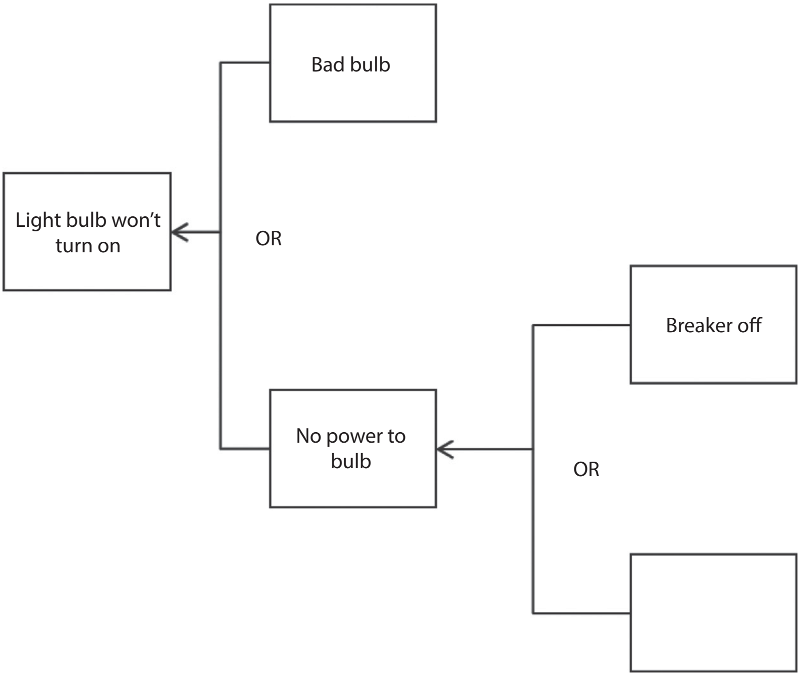


Figure A Light bulb cause map.

26. Pump troubleshooting exercise:

Using the troubleshooting matrix below, draw a cause map with all the possible causes that can cause a high pump pressure.

Centrifugal Pump Troubleshooting Matrix

By inspection, we see that there are four possible causes of a high pump pressure:

1) Wrong diameter impeller, 2) wrong impeller speed, 3) back pressure too high, and 4) too far away from BEP

	Common symptoms								
Instructions: Find the "Common Symptom" that best describes your field condition and then go down and find all the possible "Common Root Causes," which are denoted by the symbol "X." These are all the possible causes that should be investigated to determine the actual root cause.	Flow too low	Flow too high	Unstable flow	Pressure too high	Pressure too low	High pressure pulsations	Power too high (1)	Power too low (1)	High vibrations or noisy (2)
a. Wrong impeller diameter(s)	X	X	X	X	X	X	X	X	
b. Wrong impeller speed	X	X	X	X	X	X	X	X	
c. Impeller installed backwards	X				X			X	
d. Pump turning backwards	X				X			X	
e. Back pressure too high	X		X	X		X		X	

		Common symptoms								
Common root causes	f. Back pressure too low		X	X		X	X	X		
	g. Plugged suction strainer or piping	X		X		X	X		X	X
	h. Suction level too low	X		X		X	X			X
	i. Cavitation	X		X		X	X		X	X
	j. Air or vapor entrainment	X		X			X		X	X
	k. Too far away from BEP, i.e. flow too high or too low relative to design			X	X		X			X
	l. Rotor imbalance									X
	m. Pump to driver misalignment									X
	n. Pump worn out	X				X		X		X

(1) The potential root causes for these two columns only apply if horsepower increases with flow. These column headings must be reserved if horsepower decreases with flow. Refer to the "How Horsepower Varies with Flow" at the end of this section for more information on this topic.

(2) For more information on potential causes of vibration, refer to Chapters 14 and 15 in *Is My Machine OK?*

Using the four possible causes found in the troubleshooting table we can draw the following cause map:

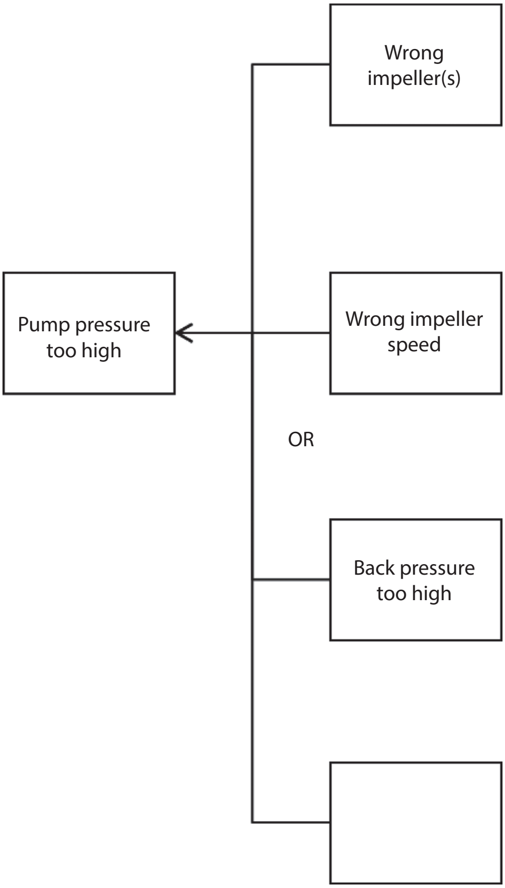


Figure B Centrifugal pump cause map

27. Using the centrifugal pump troubleshooting matrix list all the "Common Root Causes" of high flow.

    a. Wrong impeller diameter
    b. Wrong impeller speed
    c. Back pressure too high

28. Using the reciprocating troubleshooting matrix in the back of the book list all the "Common Root Causes" of high horsepower load.

    a. Wrong clearance volume
    b. Wrong compressor speed
    c. Discharge pressure too high
    d. Plugged strainer or piping restriction
    e. Gas denser than design
    f. Leaking piston ring
    g. High valve losses

29. List the team members you would select for a complex problem involving steam turbine driving a centrifugal pump. The steam turbine can't reach rated speed during start-ups. Answer: Operations, maintenance mechanics, instrument specialist, and a machinery specialist. The steam turbine and centrifugal pump manufacturers may also need to be included in the team if the initial team can't determine the cause of the problem.

30. Assume you have concluded that a centrifugal compressor is failing and needs to be shut down for repair. Who would you invite to a meeting to finalize your plan of action? Answer: Operations, maintenance planning, compressor specialist, and the contractor performing the compressor repair.

31. Assume you have concluded that a fully spared reciprocating compressor has some failing cylinder valves. What are you options going forward?

    a. Run to failure
    b. Monitor compressor performance and hope to get a few more weeks of life out of the valves.
    c. Preemptively replace valves.

32. ________________ is the methodology that uses information gathered with internal or internal mounted motion sensors to assess a machine's mechanical condition? Answer: Vibration Analysis.

33. The methodology in question 32 can be used to: Answer: c. Determine the general nature of the machine defect by identifying the predominant frequency of the dynamic motion.

34. A rotordynamics analysis uses rotor geometry and bearing support information to determine: Answer: d. all the above

35. A rotordynamic analysis should be performed before any major modifications to the rotor or bearings:

36. List a few ways you can improve troubleshooting capabilities at your site.

    a. Practice the 5Qs method whenever possible
    b. Provide training on fault trees and cause mapping to all those in a position to use these methods
    c. Employ team approach for complex problems
    d. Get management's support

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