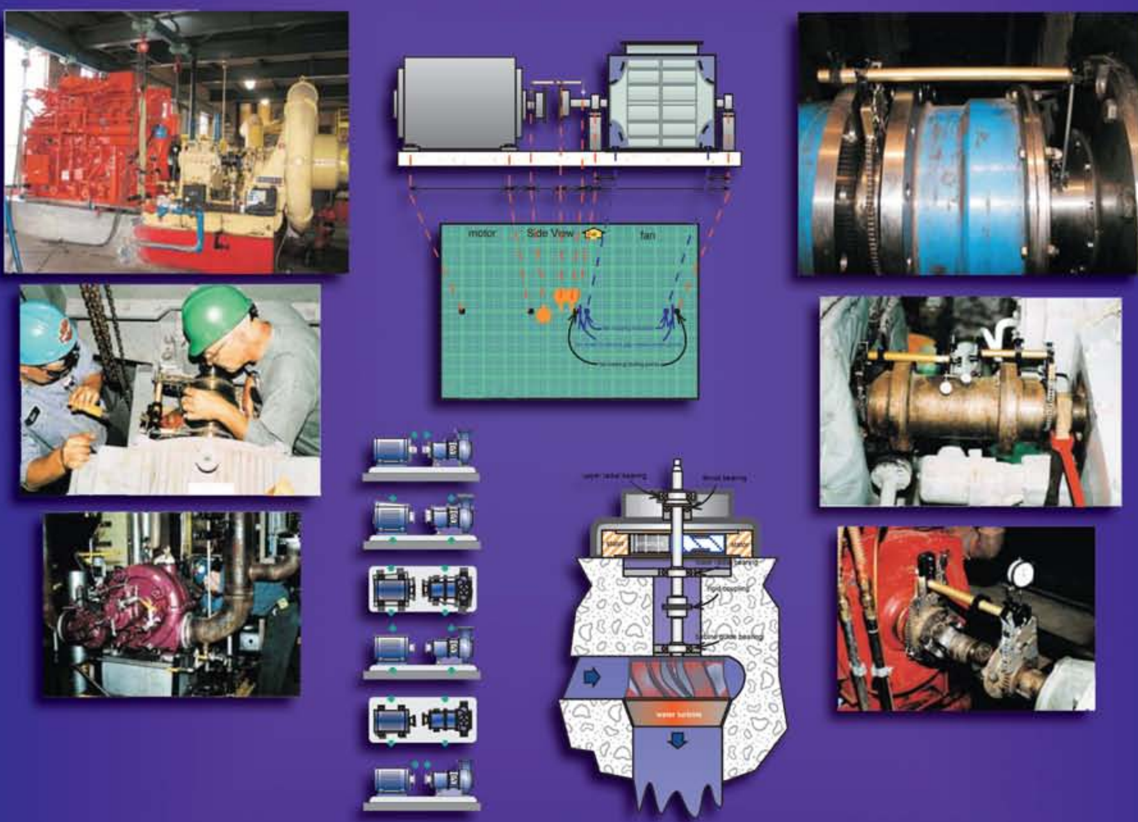
Shaft Alignment Handbook

Third Edition



John Piotrowski

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Shaft Alignment Handbook

Third Edition

MECHANICAL ENGINEERING
A Series of Textbooks and Reference Books

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Third Edition

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Dedication

To my wife, Bobbie Jo, who has provided the inspiration and motivation for me to write this book and who has sacrificed thousands of hours of her time to allow me the chance to learn and record this information

To my children, Tracy, Paula, and Peter who have proofread much of this information and provide me with an outsiders view of this material and

To my parents, Joseph and Magdalena, who have taught me that any honorable path will be difficult, but with hard work, discipline, and inspiration . . . anything is possible.

Preface

Many of the material conveniences taken for granted in today's society have been made possible by the numerous rotating machinery systems located in every part of the world. Virtually everything we use or consume has somehow been produced or touched in some way by rotating equipment. The multitude of industrial facilities that generate our electricity, extract and deliver our fossil fuels, manufacture our chemicals, produce the food we eat, provide our transportation, furnish the clothing we wear, mine and refine metals, manufacture the paper and printing products used for books, require millions of pieces of rotating machinery to create all the products we use.

It makes good sense to keep the motors, pumps, gears, turbines, fans, diesels, and compressors running for long periods of time to prevent financial losses due to decreased production and overhaul costs. Repair or replacement of this equipment is expensive and the loss of revenue when this machinery is is not in operation can spell the difference between continued prosperity or financial disaster for any company. Keeping these machines running requires a thorough understanding their design and operating envelope, careful attention during their installation and overhauls, the faculty to prevent or predict imminent failures, and the expertise to modify and enhance existing hardware to extend its operating lifespan.

In the past 30 years, easily half of the rotating equipment problems I have experienced had something to do with misaligned shafts. Additionally, operating rotating equipment under misalignment conditions can be dangerous. I have seen a coupling burst apart on a 500 hp, 3600 rpm process pump that literally sheared a 10 in. pipe in half and coupling pieces landed 400 yards away from its point of origin. Keep in mind that rotor speeds above 100,000 rpm and drivers pushing 60,000+ hp are now commonplace.

With all of the rotating machinery in existence, you would think that shaft misalignment is well understood and that everyone who is involved with installing, maintaining, and operating this equipment is well versed in preventing this. When in fact, just the opposite is true. The information contained in this book is not taught in any high schools or junior colleges, is not a required course for mechanical engineers, is not discussed in business schools, and is typically not taught in trade schools for mechanics, millwrights, pipe fitters, or electricians.

Over the past 100 years, hundreds of technical books and articles have been published on rotor balancing, flexible coupling design, vibration analysis, structural dynamics, and industrial productivity. The first technical article on shaft alignment, on the other hand, was not published until after World War II and not until the late 1960s did anyone begin paying attention to this.

I feel very fortunate to have been granted the opportunity to work in a wide array of different industries and the hundreds of different plant sites after studies at the University of Pittsburgh in 1974 as a bright eyed, eager, fledgling mechanical engineer. Back then, I had no idea how many talented, patient people I would have the pleasure working with over the next 32 years. It wasn't clear, at least for the first few years working in industry, what exactly it was that I was destined to do or where I could make a contribution.

My first experience with rotating machinery came working at a automotive tire plant. The tires were cured using hot water circulated through a closed loop piping system. The water was heated to 400°F and the pumps delivered it to the supply headers at 400 psi. Once you got the system up, everything seemed to work fine (generally). The problems usually appeared when the plant was shut down every Friday night at midnight and then started back up

Sunday night at midnight. As the circulating water was heating up, the tremendous change in temperature from ambient to 400°F wrecked havoc on the piping and the pumps, causing many seal and bearing failures on both the pumps and the motors driving them. It was not uncommon to overhaul at least one of the pump drive systems every month.

On one particular occasion, after rebuilding one of the pumps, I was working in the pump room on a control valve and a mechanic was working on finishing up the installation of the rebuilt pump. I noticed that he had a magnetic base attached to the motor shaft and a dial indicator touching the pump shaft. He would rotate the motor shaft so it would sweep around the perimeter of the pump shaft looking at what happened to the indicator as he rotated. I had never seen anyone do that before. I went over to ask if I could watch what he was doing. He glanced up and stared at me for about 30 seconds not saying a word. OK, I got the picture. I left him alone and went back to work setting up the control valve.

I was there for about three hours and every so often, would glance over to see what he was doing. He would sweep the indicator around the pump shaft, stop, loosen the motor bolts, add some shim stock, tighten the bolts, and sweep the indicator around the pump shaft again. He would then loosen the motor bolts, push the motor sideways, tighten the bolts, and sweep the indicator around the pump shaft again. He would then loosen the motor bolts, remove some shim stock, tighten the bolts, and sweep the indicator around the pump shaft again. Then he would then loosen the motor bolts, push the motor sideways in the opposite direction from the last sideways move, tighten the bolts, and sweep the indicator around the pump shaft again. After I saw this back and forth up and down iteration four times, it dawned on me that he was guessing. This went on for three hours and the level of his frustration began to show. I left for a few minutes and when I came back, he was gone, with the coupling guard in place. I have no idea if the alignment was correct. I thought to myself "Thank goodness I'll never have to do that." Six weeks later the bearings in the pump and motor failed. No one bothered to figure out what happened or why the bearings failed. It happened so often and for so long that the consensus was "that's the nature of these beasts."

In 1977, I was interviewed for a job at an ammonia plant in Ohio. They were looking for a rotating equipment engineer. I had become somewhat proficient at instrumentation and attempted to convince them that's why they needed to hire me. The engineer interviewing me indicated that they already had an instrumentation engineer and he was doing a fine job, what they really needed was a rotating equipment engineer. He asked "Do you have any experience with rotating machinery?" "I did order parts and oversee the rebuilding of some hot water circulating pumps at the plant I am currently employed at," I explained. "Well then, we would like to offer you a job," he said. "You are the eighth engineer we've interviewed and you are the first one who has some experience with rotating machinery."

I took the job, expecting to convince them that I was their new instrumentation engineer but they had other plans. I still remember my first day. My supervisor gave me a plant tour. The ammonia plant had four major compressor trains and the acrylonytrile plant had three. "There are over 1500 pieces of rotating machinery in the plant ranging from 2 to 32,000 hp and speeds ranging from 150 to 126,000 rpm and they are now your responsibility," he said to me. I got a lump in my throat and wondered what I had gotten myself into. To say the least, I was overwhelmed. Within the first three months the entire plant was shutdown twice due to rotating equipment failures one involving a 32,000 hp, 11,000 rpm steam turbine driving three barrel compressors that tripped off line due to high vibration. All of the major compressor trains had permanently installed proximity probe vibration sensors that were fed to the control room, which displayed the overall vibration levels and thrust positions. For those of you old enough to remember, vibration spectrum analyzers and laser alignment systems did not exist in 1977. We did eventually purchase a swept frequency analyzer and an oscilloscope. The alignment tooling consisted of custom Xmas tree brackets we made and some hand built alignment brackets for the machinery under 1000 hp. We also had an optical tilting level and a hp jig transit that no one knew how to use.

I was also tasked with the job of maintenance training. I was asked to train the maintenance personnel in rotating machinery basics, pump overhaul, mechanical seals, basic vibration, and shaft alignment. Reference material and books on these subjects were few or nonexistent. I had never taught anyone anything before in a formal classroom setting and I had no visual aids or training equipment besides an overhead projector, a screen, a flip chart, and a training room. So I began preparing overhead slides with hand drawn sketches in pen and ink. For those of you old enough to remember, personal computers and software did not exist then so you either printed words by hand or if you wanted to be fancy, you could use a typewriter. That was the beginning of the contents of this book. As a farewell gift, my coworkers gave me a 35 mm camera, which was used to take most of the photographs in this book.

I left for another position in 1979 for a job at an aircraft engine plant where I managed a high-pressure high flow air compressor facility. I became involved with the Vibration Institute and we formed a local chapter in the Cincinnati, Ohio area. We had meetings every month where a guest speaker was invited to give presentations on vibration and other topics. We would solicit the attendees for future topics and one of the requests was for someone to do a presentation on shaft alignment. The other board members suggested that I do a presentation on alignment since they knew I had some material from the maintenance training I had done at the chemical plant. After I gave the presentation, which went much longer than the one hour allotted for the discussion due to questions from the audience, several people came up to me suggesting that I write a book on shaft alignment. I laughed. You must be kidding! Me? Write a book? I shrugged it off as a nice compliment and didn't think anything about it until another presentation I gave a few months later when I was asked again. So, around 1981, I started writing trying to expand on the material I already had and writing down the things I was still learning. Three years passed and bit by bit I generated six chapters, working on the draft copy at night and for a little bit early in the morning before I went to work. I bought a typewriter transferring my hand written text and gluing my pen and ink drawing to the pages. I made five photocopies and sent them out to five publishers. I got five rejection letters. The letters were cordial and short. The general consensus in the letters was "We don't think this material would be of any help or interest to anyone." I put the manuscript into the closet and forgot about it. What a waste of time I thought. About a year later I gave another presentation at the annual meeting of the Vibration Institute and the director of the institute came up after the presentation and suggested that I write a book on alignment. I mentioned that I had and that it was rejected. He suggested that I contact a publisher called Marcel Dekker, Inc. who had approached him for anyone he might know who would be interested in writing engineering books. I resurrected the manuscript from the closet and submitted it one more time.

The first edition of the *Shaft Alignment Handbook* was published in 1986 and had 278 pages. The second edition was published in 1996 and had 14 chapters and 579 pages. The contents of this edition have been rearranged based on feedback from thousands of people who read the first two editions. Additional information has been included in Chapter 2 on detecting misalignment on operating rotating machinery. Chapter 3 on foundations, baseplates, and piping strain has been expanded considerably and addresses just about every type of interface between the rotating machines and how they are attached to building, structures, or Earth. Chapter 6 through Chapter 16 reflect suggestions and improvements from readers of the previous two editions. Rather than have one huge chapter that not only discusses the myriad of both mechanical and electronic alignment measurement tools, but also covers how to perform the five basic alignment measurement methods, the five basic alignment measurement methods are now covered in separate chapters (Chapter 10 through Chapter 14) as well as a chapter solely dedicated to electro-optical tools (Chapter 15). For those who have mastered alignment graphing and modeling, it becomes apparent that there are many similarities between the different modeling methods for each of the alignment techniques described in Chapter 10 through Chapter 14. It was suggested that a chapter be added that covers the basic concepts of alignment graphing and modeling prior to covering the specific modeling procedure for each of the five alignment methods, which is the intent of Chapter 8. Chapter 16, which discusses movement of rotating machinery from off-line to running conditions, has been expanded considerably and includes some very interesting information from equipment that has been studied in the field since the publication of the second edition. The chapter on aligning multiple element drive trains has also been expanded to include new information learned about these complex drive systems. Chapter 18 on alignment of belt/sheave driven machinery now includes information on the tooling and techniques developed since the second edition. Chapter 19 and Chapter 20 on bore and parallel alignment are brand new to this edition. Information on specific types of rotating machinery covered in Chapter 21 has had a significant amount of new and expanded information, including hydroelectric generators and alignment of rudders on ships.

There are several people who have made valuable contributions to this book as indicated by the multitude of references at the end of each chapter. None of these people had to do any research in this area nor did they have to write down what they learned for the benefit of everyone else who works in this area . . . but they did and I, for one, am thankful for that. It is very unsettling to be responsible for machinery that is typically the heart and soul of your operation and realize that you don't know enough about this equipment to keep it running satisfactorily. I have made many mistakes over the years trying to learn about rotating machinery and I wouldn't want you to go through what I had to, so this book is an opportunity to share with you what I have learned.

I have had the opportunity to work with many people in industry over the years and can't remember anyone not wanting to know how to align machinery properly or anyone who purposely wanted to damage machinery because it was operating in a misaligned condition. There are several people who have expended a tremendous effort to get their equipment alignment correct and very few of the people they work with have a clue what they had to go through to accomplish that goal. They often do it with no acknowledgment when it's done right and no increase in pay. In my humble opinion, there is no better feeling than walking by a piece of machinery that you aligned 10 years ago and know that equipment is still running great. These people do it right because it makes them proud of the quality of workmanship they perform and although they might not be able to take that to the bank, they can certainly take that to their grave when they reflect back on their accomplishments.

The primary reasons why machinery is misaligned is lack of proper training, improper tools to do the job, and that people are not given enough time to do it right. This book will help with the training and the tools; the rest is entirely up to you.

Acknowledgment

To all of my teachers through grade school, high school, and college who made math and science interesting enough for me to pursue a career in these subjects. To my supervisors: Neal Corbett (tire plant), Jim McBeth (chemical plant), Ted Martin and Joe Uhler (aircraft engine plant); Ted Snider (maintenance forman at the chemical plant); and the plethora of skilled trades personnel who guided, trained, and inspired me. To Dr. Ron Eshleman of the Vibration Institute who suggested that I submit the manuscript one more time. To the proofreaders of all three editions of this book, particularly Malcolm Murray, who, in my opinion, is not only the best technical editor I have ever met but also an outstanding engineer.

The Author

John Piotrowski is the president and founder of Turvac Inc., which provides engineering field services, industrial training, and products in shaft alignment, vibration analysis, balancing, and performance analysis. He has written numerous technical articles for several engineering and maintenance publications. Piotrowski frequently a guest lecturer for several engineering organizations has been active in the Vibration Institute for 25 years. He received a B.S. degree (1974) in mechanical engineering from the University of Pittsburgh.

Table of Contents

1 Introduction to Shaft Alignment

1.1 BENEFITS OF GOOD MACHINERY ALIGNMENT

Industry worldwide is losing billions of dollars a year due to misalignment of machinery. The heart and soul of virtually every industrial operation pivots on keeping rotating machinery in good working order. Countless processes are dependent on the successful operation of rotating machines that produce electric power, fuels, paper, steel, glass, pharmaceuticals, the food we eat, the clothes we wear, the buildings we live and work in, and the vehicles that transport us across the surface of the Earth. Just about everything you see around has somehow been influenced by rotating machinery of some kind.

The primary objective of accurate alignment is to increase the operating life span of rotating machinery. To achieve this goal, machinery components that are most likely to fail must operate well within their design limits. As the parts that are most likely to fail are the bearings, seals, coupling, and shafts, the accurately aligned machinery will reduce excessive axial and radial forces on the bearings to insure longer bearing life and rotor stability under dynamic operating conditions. Precise alignment will reduce the possibility of shaft failure from cyclic fatigue; it will minimize the amount of wear in the coupling components, alleviate the amount of shaft bending from the point of power transmission in the coupling to the coupling end bearing, and it will maintain proper internal rotor clearances.

In a nutshell, accurate alignment will do nothing, but the good things and the key part of making this happen centers on the people who are responsible for installing, troubleshooting, maintaining, and operating this machinery.

1.2 CONSEQUENCES OF DEFECTIVE ALIGNMENT

Despite popular belief, misalignment can disguise itself very well on industrial rotating machinery. What we witness are the secondary effects of misalignment as it slowly damages the machinery over long periods of time. Some of the common symptoms of misalignment are as follows:

1. Premature bearing, seal, shaft, or coupling failures.
2. Elevated temperatures at or near the bearings or high discharge oil temperatures.
3. Excessive amount of lubricant leakage at the bearing seals.
4. Certain types of flexible couplings will exhibit higher than normal temperatures when running or will be hot immediately after the unit is shut down. If the coupling is an elastomeric type, look for rubber powder inside the coupling shroud.
5. Similar pieces of equipment seem to have a longer operating life.
6. Unusually high number of coupling failures or they wear quickly.
7. The shafts are breaking (or cracking) at or close to the inboard bearings or coupling hubs.

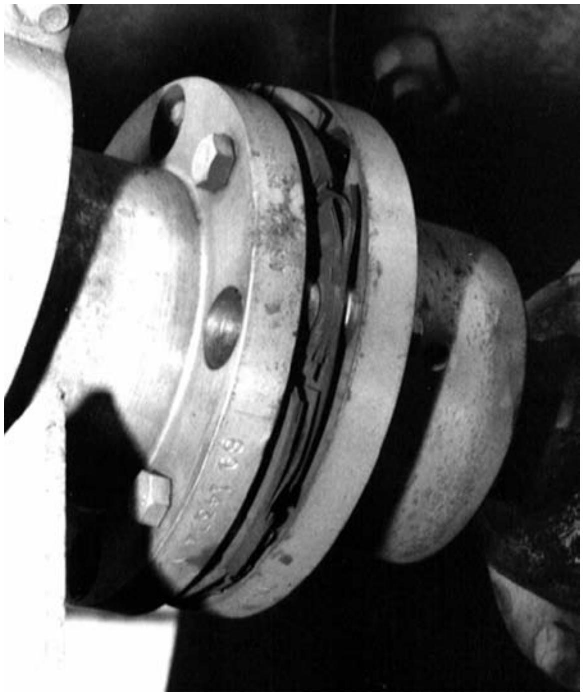


FIGURE 1.1 Disk coupling failure due to shaft misalignment.

8. Excessive amounts of grease (or oil) on the inside of the coupling guard.
9. Loose foundation bolts, typically caused by a "soft foot" condition, are exacerbated by misalignment.
10. Loose or broken coupling bolts. This is frequently due to improperly torquing the coupling bolts and aggravated by a misalignment condition.

If you are expecting to see a statement on how misalignment increases the vibration levels in machinery, it is recommended that you thoroughly review the information in Chapter 2.

Without a doubt, the greatest loss of revenue attributable to misalignment is due to loss of production. If a piece of machinery fails, then whatever it was producing stops and so does the revenue it was making, which then leads to the second largest amount of financial loss. Now that the machine broke, new parts have to be purchased and someone has to be paid to repair or completely replace the defective components or the entire unit. As production is lost, there is a tendency to rush the installation process, frequently sacrificing the time needed to perform an accurate alignment of the machinery. And the degradation process starts anew.

A large percentage of industrial plants do not understand how bad their misalignment problems are. Conservatively more than half of all the equipment operating today exceeds 4 mils/in. of misalignment when it is running. Figure 1.2 shows data from an alignment survey taken during a 1 week period of time. Bear in mind that acceptable misalignment deviation for rotating machinery is 1 mils/in. (that is the first tick mark on the y-axis).

Disappointingly the vast majority of plant sites cannot produce the alignment records for every piece of rotating machinery they operate. Even in facilities where a good preventive and predictive or condition-based maintenance (CBM) program exists, typically there are 100 times more data collected on vibration, temperature, oil analysis, and motor current than on machinery alignment. The vast majority of people who measure vibration

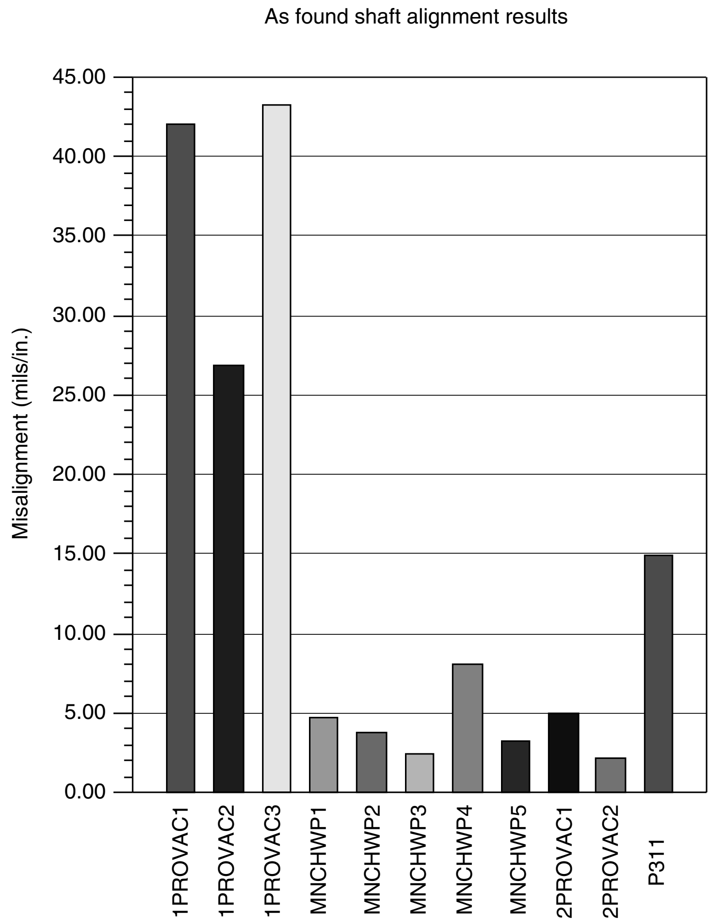


FIGURE 1.2 Alignment survey taken on 11 drive systems during a 1 week period of time showing the as-found alignment condition.

and other data have received incorrect technical information about what symptoms occur on misaligned machinery, frequently resulting in an incorrect analysis of the problem (refer to Chapter 2 for more info). Additionally, the same people are usually not the ones doing the alignment work, so communication gets scrambled between the people identifying the problem, the people assigning the work, and the people actually doing the work. Countless times I have been told by a mechanic that they were reprimanded for sloppy workmanship because vibration levels on a machine stayed the same or increased after they completed realignment. Surprisingly to many, this is quite normal. For a detailed explanation for why this occurs, see Chapter 2.

1.2.1 What Happens to Rotating Machinery When It Is Misaligned a Little Bit, or Moderately, or Even Severely?

Figure 1.3 illustrates what will happen to rotating machinery when it is subjected to moderate to severe misalignment conditions. When two shafts are subjected to a slight misalignment condition (2–5 mils/in.), the coupling connecting these two shafts together flexes internally to accept the misalignment condition. Keep in mind that as the shafts rotate the internal parts of the coupling are continually having to move around, or bend in one direction then the other,

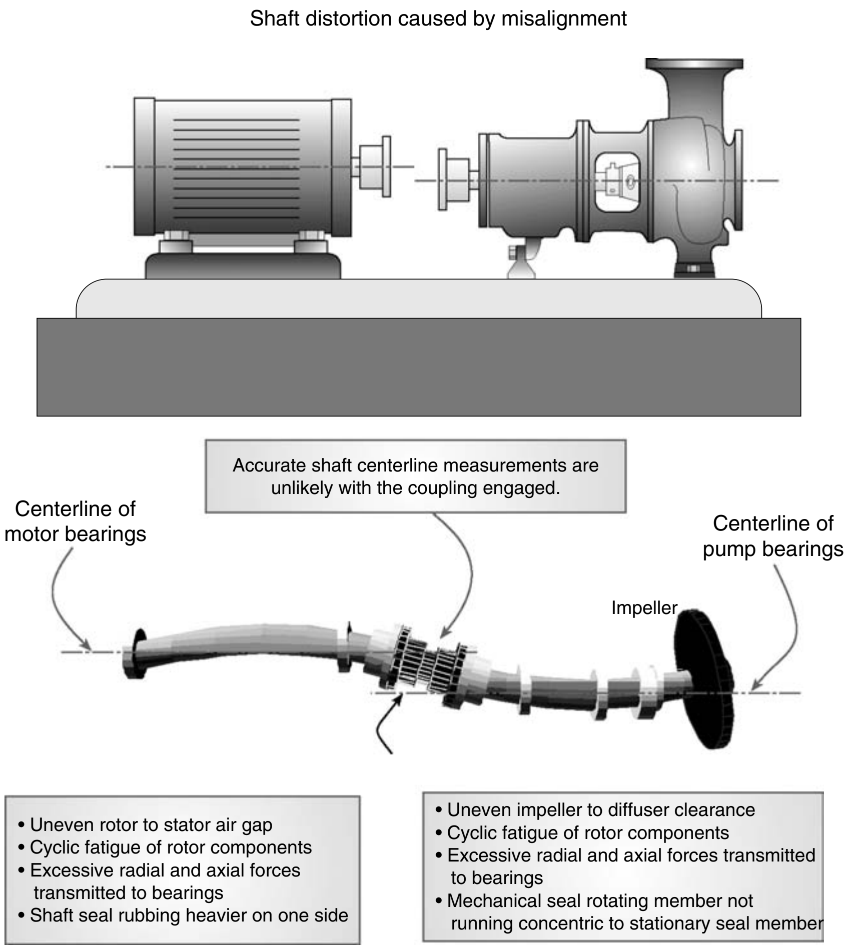


FIGURE 1.3 Problems caused by shaft misalignment.

or stretch then compress. If the cyclic movement, bending, or distortion is not severe, the coupling may survive for some time.

Most people forget that the majority of the industrial machinery runs 24 h a day, 7 d a week for months or years without stopping. If your automobile engine were operated at 3600 rpm (about 80 mph for most vehicles) without stopping, in 1 year your vehicle would have traveled 700,800 mi. That is over 28 times around the circumference of the Earth. I wonder what the tires would look like if the front end of the vehicle were out of alignment?

As the misalignment becomes greater (5–10 mils/in.), and the coupling approaches its maximum allowable misalignment condition, the movement of the internal parts begins to interfere with other parts that do not want to move, the bending gets worse, and the distortion starts to tear things apart on a microscopic level. Heat begins to build up and the shafts and bearings of the machinery begin to realize that something is beginning to tug on them and that something is seriously wrong.

When the misalignment gets into the severe range (above 10 mils/in.), the coupling has exhausted its maximum possible operating capacity and now the shafts start bending elastically in an attempt to accommodate the misalignment imparting high radial loads on the bearings. We are in big trouble now since the lubricating film in the bearings is getting squeezed thinner, running the risk of metal-to-metal contact. High stress concentration areas on the shafts near the inboard bearings and coupling hubs begin to experience cyclic fatigue. The oil seal clearances begin to open up, allowing the lubricant to leak out of the bearing chamber. Lubricant in the coupling starts to get squirted out. Tremendous amounts of heat are generated in certain types of flexible couplings. The bearings are getting hotter from the excessive forces. Somebody better get ready to call the ambulance because this is not going to last much longer under these circumstances! Boom! There it went! Oh my! Even though it is two o'clock in the morning, we need to call someone in here to get this back up and running. Should not take more than 30 min to get this fixed, right?

Albeit, the last misalignment condition shown here is exaggerated but this is exactly what happens. The rotating machinery shafts will undergo elastic bending when vertical or lateral loads are transferred from shaft to shaft.

It is fully understood that flexible couplings do just what they are designed to do; they flex to accommodate slight misalignment. But the shafts are flexible also, and as the misalignment becomes more severe, the more the shafts begin to flex. Keep in mind that the shafts are not permanently bent, they are just elastically bending as they undergo rotation.

Notice also that the pump shaft in this example is exerting a downward force on the inboard motor bearing as it tries to bring the motor shaft in line with its centerline of rotation. Conversely, the motor shaft is exerting an upward force on the inboard pump bearing as it tries to bring the pump shaft in line with its centerline of rotation. If the forces from shaft to shaft are great enough, the force vector on the outboard bearing of the motor may be in the upward direction and downward on the outboard bearing on the pump. This explains why misaligned machinery may not vibrate excessively due to the fact that these forces are acting in one direction at each bearing. Forces from imbalanced rotors, for instance, will change their direction as the "heavy spot" is continually moving around as the shaft rotates, thus causing vibration (i.e., motion) to occur. Shaft misalignment forces do not move around; they act in one direction only.

The chart in Figure 1.4 illustrates the estimated time to failure of a typical piece of rotating equipment based on varying alignment conditions. The term "failure" here implies a degradation of any critical component of the machine such as the seals, bearings, coupling, or rotors. The data in this graph were compiled from a large number of case histories where misalignment was found to be the root cause of the machinery failure.

1.3 FOUR BASIC INGREDIENTS NECESSARY TO INSURE ALIGNMENT SUCCESS

If machinery alignment is so important and we are wasting billions of dollars due to the fact that it is not done correctly, why has not this problem been eradicated? Perhaps the best way to illustrate the root cause of the problem is to relay what I hear from the people in industry and show you what they have to say about this. Every so often I receive correspondence that goes something like this:

John:

How long does it take to convince seemingly intelligent trades people of the importance of proper alignment and what steps can be taken to help lead them to this belief? We are using an S&M system (i.e., laser alignment) to perform our alignment jobs. Our intent when purchasing this system was to educate the trades people on the use of it, then give them part ownership, in hopes of encouraging more usage. Their acceptance was, and is good to the concept of proper alignment, as long as we (predictive maintenance) will come out and do the work for them. When left on their own, the way it came off is the way it will go on. Any suggestions?

Sincerely

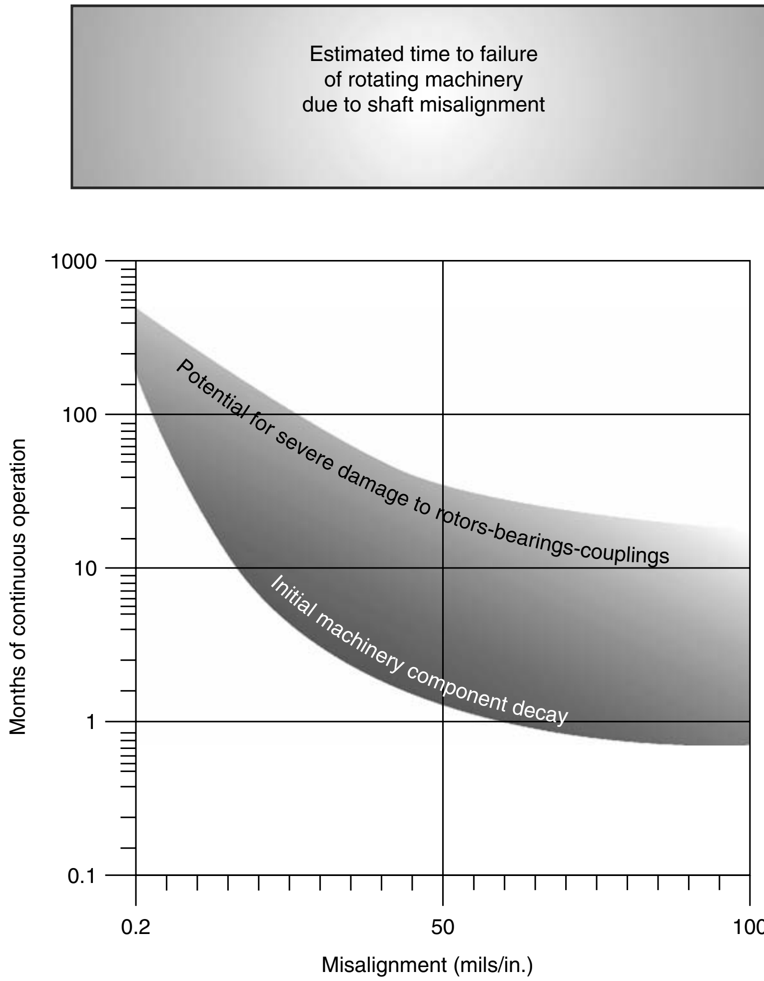


FIGURE 1.4 Statistical information on survivability of rotating machinery subjected to various misalignment conditions.

Name withheld by request

My reply to the above letter:

Your question concerning the length of time it takes to convince trades people about the importance of shaft alignment is most difficult to answer. Perhaps the best way to respond would be to relate observations I have made over the years and also to tell you what I hear from the trades people themselves. Their concerns are most valid and in many cases cut to the root of the problem.

The philosophical foundation of machinery alignment (and perhaps a wide variety of other assignments) are successfully implemented only if the following four ingredients are employed. I refer to it as the "T-T-T-I solution" (Training, Tools, Time, and Inspiration).

1. *Training*

I firmly believe that many chores that need to get completed don't simply because people do not realize the significance of the assignment and its long-term implications. It is indeed possible to perform a difficult task with no formal training but there is a greater chance of success if a knowledgeable individual instructs someone why and how the job should be done. For most people it is best to cover the "why" aspect before the "how" process. An explanation of "why" will invariably provide the trainee the incentive to reduce the pain that could ensue if the task is not undertaken in an orderly fashion.

Concerning instructing personnel in machinery alignment, here are key issues that need to be discussed in any training situation:

- Who is responsible for machinery alignment?
- What consequences will occur if the alignment is not acceptable?
- What rewards will I garner if the alignment is done successfully?
- What is involved in the overall requirements of this job and what role do I play in the larger scheme of things?
- For the tasks that I am not responsible for, how do I interface with others who are participating in the overall job to inform them that I have completed my duties or that I am having some problems?

Shaft alignment should be a major concern to every conscientious manager, engineer, foreman, and trades person. All of these job descriptions in a typical industrial organization have a role to play.

The tasks of the trades personnel (mechanics, electricians, pipe fitters) are to perform the preliminary alignment steps, measure the position of the shafts, determine and perform the proper moves on the machinery to achieve acceptable alignment tolerances, and communicate the as-found and final alignment results or problems encountered during the alignment job to their supervisor.

The foreman or unit manager's task is to assign the right people to do the alignment job, insure the necessary and appropriate tools are available and in working order, provide adequate time to complete the job, answer any questions the trades personnel may have, provide guidance for potential problems that might occur during the alignment job, coordinate and communicate these problems to engineers and managers for resolution, and keep records of what was done.

The job of vibration technicians and vibration engineers is to identify problems with the machinery, one of which is shaft misalignment. Are you 100% sure you know what this really looks like? If you're only looking for 1 or 2 times running speed vibration components in the spectrum with higher axial vibration levels than radial vibration levels and a 180 degree phase shift across the coupling.... you are in for a big surprise, because misalignment doesn't always show up that way. Do you know that vibration can actually decrease if you misalign equipment? If you don't understand why this can happen, you need some good training, not just what you've heard others say.

Some of the roles of a maintenance or plant engineer may be to purchase rotating machinery, design foundations, specify installation procedures, buy couplings, design and oversee piping installation, and insure the equipment is aligned properly when it's installed or rebuilt. Engineers frequently are responsible for specifying and procuring the types of measuring tools used to determine the positions of the machinery shafts, provide the technical expertise and tooling to measure off-line to running (OL2R) machinery movement, design piping/duct support mechanisms to minimize induced stress in machine casings or coordinate piping/ducting rework, review new methods and techniques that could be used on the rotating machinery in their plant, analyze failures of rotating machinery to determine if the root cause can be traced to misalignment, listen and respond to any and all problems that were reported to them by the trades personnel and the foremen, provide training to the trades personnel, foremen, and managers, and work side-by-side with the trades personnel if necessary to fully understand what actually occurs in an alignment job to determine if more efficient means can be found to improve the alignment process or accuracy.

The responsibility of plant and/or engineering managers is to provide the funds necessary to procure the tools needed to accomplish the job, to insure that the personnel have been given proper training to understand how to do alignment, and to provide due credit to the individuals who have done the alignment job properly.

Proper training must also provide information on runout detection and correction, soft foot correction, measurement instrument basics, rotating machinery design basics, foundation and baseplate repair techniques, bearing information, coupling information, machinery movement tools, alternative machinery movement solutions, OL2R machinery movement measurement (and recognition of when it is and is not needed), finding and relieving piping stresses, and record keeping. We also cannot expect training to just be given to trades people only. Rarely will I see management personnel or engineers or foremen attend a hands-on alignment training class. The ones who do attend get an opportunity to see first hand what's involved in the process and they finally get a full understanding of why alignment jobs can't be done properly in 45 minutes. Also some of the alignment tasks should probably be done by technicians and engineers. I don't feel that it is the responsibility of trades people to specify a new coupling design, or to use a proximity probe alignment bar system to measure OL2R machinery movement, or to maintain maintenance record files, or to procure the right kind of tools to do the job right. Management and engineering must get involved to assist in the successful completion of an alignment task. How can they direct what is to be done if they don't understand what's involved in the overall process?

2. *Tools*

The people performing the alignment job have to be given the proper tools to do the job correctly. Purchasing an alignment measurement system is a good start but that is not the only tool one needs to perform the job. An alignment measurement system does one task . . . measures the amount of misalignment that exists. The alignment measurement system does not correct the problem. There are a myriad of other related issues that need to be addressed before the actual alignment corrections begin. What tools have been procured to verify that people aren't aligning bent shafts or improperly bored coupling hubs? What tools are available to control the position of the machines when correcting the misalignment? What tools do the people have to insure they are aligning reliable pieces of rotating machinery? Also, if the alignment measurement system contains a software program that suggests how to correct the misalignment, it must inform the operator to make an intelligent move and offer that person other options if a suggested corrective action does not make sense. For example, the software program may tell the operator to move a machine 120 mils sideways to correct a lateral misalignment condition. However if the unit becomes "bolt bound" before the move is accomplished, and the alignment measuring system does not have an alternative suggestion to get that person out of the jam it proposed, the software program is flawed and may significantly increase the amount of time needed to achieve satisfactory alignment.

3. *Time*

Undoubtedly the number one complaint I hear from people in industry is that they are not given enough time to perform all the necessary tasks required for successful alignment. The reason for this is due to a lack of understanding on the part of operations, production, and management personnel who have not received training on alignment. If many foremen or supervisors have no idea of how to do an alignment job, how can they tell a trades person that it should only take 45 minutes to do it right? What authority should an operations manager have to tell the maintenance department that a machine should be put back on line even if it means that its not installed properly? That operations manager isn't going to be down there fixing the machine again in two months some early Sunday morning.

4. *Inspiration*

This is perhaps the most important ingredient and the one that seems to be lacking in many industrial sites. The answer to this is as complex as the human personality itself. I guess to begin, I'll ask these questions. What incentives does the trades person have to do the job right? Do they feel that they have some ownership for the equipment they work on? Are they constantly instructed on how to fix a problem and how much time they should take to fix it? Have they ever been told that there is not enough time to do it right, that operations needs the equipment right now and that compromises will have to be made? Have they been denied all of the tools to do a job properly? Are they really doing shaft alignment properly and the machinery is being shoved back out of alignment after a brief period of time due to excessive piping strain or unstable foundations? Do the trades people have a clear understanding about how accurate the alignment has to be? Has anyone asked them if they like the alignment measurement system that they were given without choice? Have they ever been congratulated for doing a job correctly? Do they get to make decisions on how to do a job, when to do it, and how long it should take? If someone prefers to do alignment with dial indicators, are they given that option and then given training on how to use other types of measurement tools? Can they go back into the maintenance records on every piece of machinery in their plant and find information on . . . how accurate the alignment was done the last time, when it was done the last time, who did the alignment last time, how many shims and what thickness of what material are under all of the machinery feet, what soft foot corrections were made, was there any piping strain present, if any of the bolts were undercut, how long the machinery has been there, were any special tools needed to do the alignment, was there any runout on the shafts or the coupling hubs, how much "free-play" existed in the bearings, what is the shaft to shaft distance supposed to be, what type of coupling could be substituted if the one that's there gets damaged and there are no replacements in stores, what type of lubricant should be used in the coupling and how much should be added, etc.? I could go on about this for quite some time and I've only mentioned a few items that seem to go overlooked in many organizations. Indeed, some of the blame for lackluster maintenance correction methods falls on the shoulders of the trades people, but definitely not all of it.

Sincerely . . . yours truly

Not even one of my shorter letters is by any stretch of the imagination. Here is another typical one:

John:

I work for XYZ Chemical (name changed by request) in a Midwestern state in the U.S.; I'm the engineering superintendent. In addition to my site engineering responsibilities, I also have responsibility for the maintenance department.

Our plant is a union facility. We have approximately 30 folks in maintenance, of which 15 of them work on pumps, seals, etc. People come into the maintenance department based on their seniority. Their maintenance training is gained by working with other maintenance personnel, learning from onsite vendor seminars, and from their maintenance supervisor.

I have been here at this facility for 4 years now. During the past 4 years, I have seen a lot of turnover in the maintenance department, due to retirements, etc. As you can see, I do not have an easy job keeping people in their positions and also providing them with the necessary training. It seems to me that any training we do here goes in one ear and out the other.

I have conducted training with my maintenance personnel in seal repair, pump repair, laser alignment, etc. but we don't seem to get any better at it. As you say in your article, we operate in the "Breakdown or Run-to-Failure Maintenance Mode."

I would like to solicit your opinion on what steps I can take to get our maintenance department out of this mode and move into the "Preventive or Time Based Maintenance Mode." I know this takes desire and a want to attitude, I have it, but they don't. Do you have any recommendations that I can use to make this shift? Would appreciate your ideas/comments.

Regards,

Name withheld by request

My reply to the above letter:

Due to the opportunities I've had in being able to visit and work at a wide variety of plant sites in virtually every industry, I'd like to reassure you that the problems you are facing in trying to get the maintenance personnel to get out of the breakdown/run to failure mode and into something that is more effective is virtually a universal problem. Not that this is any consolation to you, however. My recommendation is to move toward a Pro-Active/Prevention Maintenance approach rather than a Preventive or Time Based approach. I know that might be quite a leap but the benefits would be justified.

I'm not quite sure where to start. I remember an Engineering Manager at a plant I worked at once telling me, "We need to hire psychologists and sociologists and stop hiring engineers." As an engineer myself, I was crestfallen to hear him say this but there is some substance to his remark.

Over the past 26 years in industry, I have seen many changes occur yet many things have stayed the same and in some cases, gotten worse. Here are some observations, comments, and ideas that hopefully may address your concerns and desires.

1. *There must be at least one person in any organization who is willing to spearhead the movement to elevate the quality of maintenance work being done*

The buzzwords (Reliability Engineering, Pro-Active, Prevention, Predictive, Maintenance etc.) used to describe this effort are irrelevant. What is important is to have a leader who has devised a clear plan on what needs to be done and mechanisms to ensure that they will be carried out. At a minimum, this person needs to coordinate, and in many cases perform, the following efforts:

- Assume that there could be a problem with every piece of equipment in the facility and devise a process to find every detrimental condition.
- Identifying existing problems with the equipment and determining the severity of the problem.
- Illustrate evidence to support the validity of the problem.
- Recommend a course of action to correct the problem.
- Investigate the cause of the problem or unexpected failure by performing root cause failure analysis.
- Suggest and incorporate changes to insure the problem does not occur again or at least not as often.
- Communicate all of the above to the production and maintenance personnel involved and have a way for others to communicate what they discovered during the repair/improvement process.
- Set standards for the quality of workmanship to be performed during the repair process.
- Financially justify the work that was performed.
- Become an evangelist who supports the reasons for the program.

Every company that is serious about minimizing failures and increasing productivity must be able to say that this person or that person is doing each of the things listed above. Who is doing all of this in your company? Where is it being done? What is missing? Why should we do it in the first place?

2. *When a piece of equipment needs repair, the maintenance department should be in control, not the production department*

Everyone knows that disruption of service or production is uncomfortable and there is a strong pus to "Get this up and running as quickly as possible." Production's job is to get a quality product out the back door as efficiently as possible and they are generally very good at that. In many cases the operations personnel do not know the intricacies of the machine or process that makes the product and are therefore not qualified to decide what needs to be done or how quickly it should happen. It is important for them to understand that it is not immediately evident what transpired to cause the failure and troubleshooting can take more time than the correction phase of a repair. They also need to know that if the cause of the failure is not determined, there is a good possibility that it will occur again and again. During the time the repairs are being made, frequently twiddling their thumbs, rather than continually asking "Uh, when do you think you'll be done?" they should be working on reviewing what transpired prior to the failure to determine if the mishap was process related and communicate their findings to the maintenance or engineering department for review. Sometimes we get very lucky and things happen quickly. More often we have to remove several thorn bushes before we can actually find the path. The maintenance people I work with are very talented but don't ask us to perform miracles.

3. *We have a great education system in this country but it does not prepare our work force for the specific tasks required by industry*

After four years in engineering school it took only a month working in industry for me to realize that I did not know what I was doing. I was taught how to go about solving a problem, not how to solve very specific problems. I probably studied harder for the next 16 years in industry than I did the previous 16 years when I was in a formal education setting. The one thing that I realized is that pretending that I knew everything alienated me from those who did know something. Working closely with the maintenance and production personnel on a daily basis, watching what they were doing, asking them questions, being a technical resource for them, having the courage to try something new, and learning from each failure was a key part of my continuing education. Thank goodness every company I worked for provided some way for me to expand my knowledge base. As far as I'm concerned, I'm still in school and so is everyone else.

I think that there should be a list of skills generated for every job in the industry. Each list should have minimum requirements to perform the job and additional skills that should or could be acquired over time. I believe that those who acquire the additional skills should be paid more for these additional abilities. I also think that there should be some way to reward those who utilize these abilities to their fullest extent. In my opinion, the last year of a maintenance persons time in a facility should be spent teaching others what they have learned prior to retirement. I also think that any retiree should be granted the opportunity to come back as a consultant/trainer on a part time basis and be paid well for such efforts.

4. *There should be a mechanism to reward people for what they have done correctly and a process for inferior work to be done over by the people who did the slipshod work initially*

This is somewhat related to what was mentioned above concerning those who utilize these abilities to their fullest extent. I have noticed that some people do higher quality work than others. What is disappointing is that they don't seem to be rewarded for their efforts. Nor do I see those who do poor quality work held responsible for their shortcomings. In my humble opinion, if a piece of machinery fails within three months after someone worked on it and the failure was due to shoddy workmanship, that person should be required to work on the same machine again and continue working on it until it is done correctly. If that person is doing poor quality work because they don't know how to do the task, they should admit this and be given proper training on how to do it correctly.

5. *It is important for people to feel that their contribution is valuable to their company*

One minute for what someone did right, one minute for what they did wrong, and one minute for what they are supposed to be doing. What I call the "Well Done!. . . . Not that, please!. . . . Which way do we go?" approach.

We need to abrogate the industrial caste system. Everyone's job is important.

In maintenance, the personnel need to be shown the results of higher quality workmanship and what benefits it reaps them and their company. There are two prime motivational tools: fear and inspiration. Both work but inspiration works better. If fear is the motivator, when the tyrant leaves, the subjects will become idle or vengeful. If someone is told they are doing well, they have a tendency to continue when no one is looking.

6. *Industry is not preparing itself for the long haul*

It's what I call "the under 40 void." What percentage of your maintenance department is between the ages of 20 and 40? What percentage of the population is between the ages of 20 and 40? Get the drift?

Can we expect qualified maintenance people to appear from thin air when people retire? If we don't groom the individuals ourselves, who will? For those who decide that the work force needs to be culled, their names should be at the top of the list for allowing the flock to get out of control.

7. *Installation of new equipment is frequently not being done correctly*

Just as you noticed that a maintenance organization can get into the breakdown or run to failure mode there is an equally disturbing and similar practice with construction work. A large percentage of machinery is being installed wrong or shoddily. The reason that this has gone unnoticed is because poorly installed equipment can actually run, it just doesn't run for long periods of time before failures begin to occur. Too often the quality of workmanship in construction projects is ignored by the end user. Usually the end user does not know enough about good installation practices to insure the equipment is installed correctly and no checks are made during the construction process to verify the quality of workmanship.

8. *Any training should be quickly reinforced with jobs that reflect the material covered in the training session*

Several years ago, after conducting a two day basic shaft alignment training course at a food plant, the company requested that I stay for another day for on the job training with the students who attended the course. I arrived there early the next morning and all of us met back in the training room to discuss what we were going to be working on that day. We split the group up into two person teams and the maintenance supervisor handed me a list of machinery that was available for us to work on and we began deciding which team was going to work on which piece of machinery. After each team selected the machine they wanted to work on, I asked if anyone had any questions before we went out and began work on the equipment. One of the more outspoken students from the class raised his hand as asked, "Hey Teach, the information you went through over the past few days in the shaft alignment course was very interesting but now that we have to work on real pieces of machinery, what are we really going to be doing?" I was puzzled at his question but after a brief pause I looked at him and said, "The work that you were doing on the demonstrators in the training course is exactly what I would like you do to do with 'real' machines in your plant." For a moment it appeared that he got the Uh-oh, I-should-have-listened-better-look on his face but he said nothing and just stared in what appeared to me to be disbelief.

As we left, the group of us went to each machine we decided to work on, discussed what needed to be done to get started, then that team stayed there and began work while the rest of us moved on to the next machine until the entire group was dispersed and working on their respective equipment. While this was happening, I noticed that many of the students, some of whom had several years of experience in industry, when arriving at their machine would ask, "Do you want us to do the same process on our machine?" "Yes, please," I would answer.

After an hour or so, each team was at their machine and I began to loop back to the first group that we dropped off to see how they were doing. As I approached I noticed that they were busily working on the machine and as I walked up one of the mechanics noticed I arrived and with a big smile on his face said, "Hey Teach, look at what we found here!" showing me some problem that had not been observed before. "I bet this is what has been causing some of the problems with this thing," he said. "Now that we found this, do you think we need to do all of the other things you talked about too?". "Great job, and yes, please do all of the other things we discussed. You never know what other problems you're going to find until all of this is checked and corrected," I exclaimed. Throughout the day, I would go back to each team one by one to see how they were doing and answer any questions they had. There was a recurring theme all day long with every team. Things that had never been checked before on the machinery were disclosing why certain machines were performing a certain way or why failures were occurring more frequently than expected. Some of the problems that were discovered were corrected on the spot, others required new parts to be purchased, and other issues that were revealed needed some major work or design changes.

At the end of the day, all of us reconvened back at the training room to discuss what went on that day. It was bedlam. You couldn't hear yourself think! Everyone was telling each other what they discovered, what problems they corrected, and what else needed to be done. There seemed to be a contest going on to determine who found the worst problem, each team trying to convince the others that they did the best work or found the biggest problem. The maintenance supervisor looked at me and said, "I've never witnessed anything like this before with these guys."

After things quieted down, the same outspoken student who asked "What are we really going to do?" before work got started, raised his hand again. "Hey Teach," he said, "I learned more today that in the entire 14 years I've been working here. This stuff is really great. I would have never believed what you told us would work, it just sounded too good to be true!"

9. *Be explicit about what needs to be done and nurture the desire to exceed the basic requirements*

"It broke and you need to fix it" is not a satisfactory maintenance work request. Despite my best attempts to perform consistently high quality workmanship, I have the tendency to skip or forget items that should be done. I don't like having an itemized list of things to do on a job, but it sure beats the sinking feeling I get after assembling a piece of machinery only to find three parts lying on the work bench that were supposed to be installed inside the machine I just "finished."

At an electric generating plant where I worked recently, every maintenance job had a written "work packet" describing the tasks to be done. At the beginning of every shift all of the participants got together for 15 to 30 minutes and the step by step instructions were discussed by the front line supervisor and the maintenance personnel. After the meeting was done and everyone understood what needed to be done, we left and went out to the job site and started working. As each step was completed, it was checked off the list. When problems were encountered, the front line supervisor, an engineer, a manufacturer's representative, or outside consultant(s) were contacted to assist in rectifying the concern. Near the end of the shift, the completed items were discussed with the next crew who had a 30 minute overlap time with the personnel on that shift to discuss what was done and what yet needed to be done. When the job was finished, a complete review of the work was conducted by the front line supervisor(s) with the maintenance personnel, engineers, and the individual who wrote the work packet. If things were missing or wrong with the work packet, it was changed. If things went badly, suggestions were made to improve the process. Often the mishaps were due to a lack of knowledge, experience, or skill and the people realized that training was needed and then the appropriate training was immediately scheduled. If things went well, accolades were distributed to the appropriate personnel which boosted morale. For me, it was a very enjoyable process and the time flew by. If it feels like you've worked for eight hours instead of eight minutes every work day, something needs to change.

One final note. This work was initiated not because there was a failure on this pump but because there was higher than desired axial vibration at the outboard bearing of the pump and the rotating machinery engineers wanted to determine the cause of the excessive vibration. This pump was a safety backup pump for two other pumps and had logged six hours of operation in the last twelve months. In fact, the six hours were test runs that were conducted to insure proper operation of the unit. The level of vibration prior to the work was not threatening, but it was near a predetermined alarm limit they set and it bothered the people enough to investigate the cause. In the first of the two different visits I made to the plant site to investigate the source of the vibration, we decided to include some additional checks not mentioned in the work packet. When we suggested that the additional work be done, there was some resistance from the mechanics who did not want to deviate from the scripted plan but we explained our concerns to them and made it understood that we might not find anything and we were willing to "take the blame" for slowing the work down. I remember three of them staring at me when I said that and the group leader exclaimed "No, we will do what you ask and still try to get all the work done. You're here with us and we will accept any blame together." These additional checks led to the discovery of a locked up gear coupling. The shaft alignment was checked with their laser alignment system and it was slightly out of their specifications but well within traditional alignment tolerances. The gear coupling was replaced in a few weeks and another test run confirmed that there was no change in the vibration.

They could have quit right then, and explained the vibration as the "nature of the beast," but they didn't. Another work packet was generated for further investigation. On the next visit the thrust of the work was to improve the alignment to near perfect conditions to see if that would reduce the vibration. One of the first tasks was to use the laser alignment system to check for a soft foot condition. The check was made and the laser indicated that a soft foot condition was not present. As they began to move onto the next step, I asked them if we could again deviate from the work plan and conduct another soft foot check by loosening all of the motor foot bolts and attempt to slide a feeler gauge between each of the motor feet and the frame contact points. Again, they resisted and again they agreed after hearing my plan despite the fact that ‘‘We never had to do anything like this before’’ exclaimed one of the mechanics. When one of the mechanics slid a 30 mil feeler gauge under the inside edge at one of the inboard feet everyone stopped what they were doing as he said, ‘‘Uh, you better take a look at this because something is not right here.’’ That was the understatement of the day. As it turned out there was a soft foot condition at all four feet of the motor which took the remainder of the shift to correct. Not a single person flipped out because we didn't get through the eight steps scheduled for our shift. No one from production asked why the machine wasn't ready for the scheduled post realignment test run. Instead the conversation was centered around the fact that the laser alignment system was unreliable in determining a soft foot condition and that some major changes were needed in the alignment procedures and that everyone needed additional training in alignment. The final test run showed that the axial vibration of the pump had decreased substantially. Without the resolve of all of the people at all levels from the Plant Manager to the apprentice mechanic in this particular facility, this work would have never been done. That is the kind of commitment that is needed to elevate an organization to superior maintenance excellence. It takes just one or two key personnel to choke this process.

Sincerely . . . yours truly

Sorry, I can get carried away responding to these types of letters. I suppose I could show you dozens of other letters like this but I am sure you get the idea. It seems somewhat disheartening to read about the plight of these individuals and situations they convey. I get the sense that these problems are quite commonplace and I applaud the honesty of these people to be forthright in describing their situation.

1.4 EIGHT BASIC STEPS TO ALIGN MACHINERY

Below are the eight basic steps involved in aligning rotating machinery. The ‘‘Tasks’’ section summarizes the items that should be done in each step and the ‘‘Time requirements’’ section attempts to give you an idea how much time each step will take to perform. If you do each step in the process, your chance of aligning successfully is pretty good. Decide to skip a few steps here and there and you are apt to run into some trouble. It is your choice.

Step 1

Tasks: Get the tools you need and train the personnel who will be performing the alignment

Purchase or fabricate the necessary tools and measuring devices. Insure that the people involved in the alignment process have been adequately trained on various alignment procedures and techniques, how to care for delicate measuring instruments and how to use them, what tools should be used to reposition the machinery, whether a machine is really ready to be aligned and operated or whether it should be removed and rebuilt, when a baseplate or foundation has deteriorated to the point where repairs are needed or corrections should be made, correcting problems that exist between the underside of the machine case and the points of contact on the baseplate, how to check for static and dynamic piping stress, what the desired off-line machinery positions should be, how to measure OL2R machinery movement, what the alignment tolerance is for the machine they are working on, and how to keep records on what was done during the alignment job for future reference.

Time requirements: The information contained in this book is not taught in any K-12 educational system, so it is unrealistic to expect a high school or college graduate, lacking such training, to know how to perform an alignment job. The burden of training personnel to understand and apply this body of knowledge falls on the employer and the companies who own and operate their machinery or on dependable outside personnel if such maintenance is contracted rather than done by in-house forces. For someone who has no experience in machinery alignment, it is recommended that somewhere between 24 and 40 h of classroom training is needed to educate the person on this information and give the person opportunity to practice alignment on simulation training devices rather than production machinery. After the classroom training has been completed, it is suggested that the individual who attended the course performs an alignment job on a process drive system within a short period of time. Someone who is experienced in aligning machinery should oversee the trainee and enforce the material taught in the course with on the job training. Since there are a wide variety of different alignment techniques taught in this book, one field alignment job is not going to be sufficient to learn every method. The progress of each individual should be tracked as they become more knowledgeable in this field of endeavor. On the average, it usually takes 2–5 y for someone to become proficient at machinery alignment assuming they encounter alignment tasks about once a month.

Step 2

Tasks: Obtain relevant information on the equipment being aligned

Are there any special tools needed to measure the alignment or reposition the machines? Do the machines move from off-line to running conditions? If so, how much and do you have to purposely misalign them so they move into alignment when they are running? Procure any historical information on the drive system to prevent yourself from having to discover problems that have already been detected and corrected.

Time requirements: Gathering information about each drive system in your plant can take a considerable amount of time and effort. Also getting the machinery nameplate data, coupling information, bearing information, shaft diameter information, ideal shaft-to-shaft distances, OL2R machinery movement data, recommended and alternative alignment measurement methods, historical records on the drive system, runout data, current soft foot shims, current final shim packs, shim sizes and material, final alignment measurements (e.g., the last alignment readings obtained and maybe a complete history of "as-found" and "final" readings), bolt torques, wrench sizes for foot and coupling bolts, piping stress tests, current and historical vibration data, normal bearing and coupling temperatures, number of operating hours since the last work was performed, type of lubrication for the bearings and coupling, how much lubrication should be installed, how often the lubricant should be refreshed, correct direction of rotation, safety tag lockout procedures, and an alignment task checklist.

Where would you find this information on all the rotating machinery in your plant? Is it readily available for everyone to use and can you get to it quickly? Who is responsible for entering and updating the information? Should it be kept in a printed book and kept in a library or should it be put on a computer database program and available over a network, or both? To be honest, I do not know of many facilities that have anything close to having this information in printed book form or on a computer network. Most often, the people who go out to align a piece of machinery approach the job as if they are doing it for the first time even though the drive system may have been in operation for decades. No records, no information, no help, no clue. Why do we have to start from square one every time we do this?

Step 3

Tasks: Work safe

Before you begin working on any machinery remember safety first. Properly tag and lock out the equipment and inform the proper people that you are working on the machine. Obtain any required work permits and perform flammable gas tests in the work area.

Time requirements: I cannot emphasize the need for safety enough here. There are times when I have been negligent about properly safety tagging the equipment before I start working on it. Rotating machinery can hurt or even kill you or your coworkers. Please be extra careful when handling this machinery.

Probably the best credo is LO TO TO (Lock Out, Tag Out, Try Out). Insure that you have identified the right equipment that you will be working on by talking to the operations personnel. It may be a good idea to walk out to the equipment with someone from operations and point at the machine so there is no mistake which one you are talking about. Has the person indicated to you where the disconnection hardware is and the correct procedure for locking it out? Is the machine running now? If it is and you shut it down, what effect will that have on the process? Ask if the equipment can be started remotely by a computerized control system that may bypass local switches near the drive system. If it can, how do you prevent that from happening while you are working on it?

If you are working on an electric motor, where is the local disconnect switch? Is it labeled correctly? Once you disarm (Lock Out) the disconnect, and hang your safety tag on it (Tag Out), then try to start it (Try Out). Won't start? Good, you did it right.

If you are working on a centrifugal pump, is there a possibility of the pump rotating backward if the suction and discharge valves are open? If you are working on a fan, is there a possibility of the fan rotating if the dampers won't close all the way? In other words, think about all the possible things that could go wrong and stop them from happening.

Depending on the complexity of the drive system and its controls, Lock Out, Tag Out procedures will take anywhere from 30 min to several hours to complete. It may end up being the best time you ever spend, unless of course you prefer to spend your time in a hospital or eternity someplace else.

Step 4

Tasks: Conduct any preliminary checks before starting the alignment

Perform bearing clearance or looseness checks, measure shaft and coupling hub runout, inspect the coupling for any damage or worn components, find and correct any problems with the foundation or baseplate, find and correct any soft foot conditions, and find and eliminate any excessive piping, conduit, or ductwork stresses on the machines.

Time requirements: This is perhaps the most overlooked step in the alignment process and possibly the most important. The vast majority of people who align rotating machinery skip this step. Then they start having problems later on in the ensuing steps only to discover there is one or more than one thing in here that was causing them their grief. There is an entire chapter devoted to the items listed above so I will not dwell on this here. It is not unusual to spend anywhere from 2 h to 2 weeks finding and correcting these problems depending on what you find and how committed you are to fixing them.

Step 5

Tasks: Measure the amount of misalignment

First, rough align the machinery and check that all of the foot bolts are tight. Then measure the shaft positions using accurate measurement sensors (± 0.001 in. or better) such as dial indicators, laser detectors, proximity probes, optical encoders, charge couple devices, or some other types of precise sensors. From these data, determine if the machinery is within acceptable alignment tolerances.

Time requirements: Regardless of the type of measuring instrument and associated tooling you use, it is going to take somewhere between 15 min and 1 h to mount the fixtures on the shafts, set up the instruments, rotate the shafts to capture a set of measurements, determine your misalignment conditions, and calculate your alignment deviation. This typically is not where the majority of time is spent in the alignment job so do not be in a rush. Make sure you get accurate measurements since how you plan on correcting the misalignment problem depends on how accurate your measurements are in this step.

Step 6

Tasks: Correct the misalignment condition

If the machinery is not within adequate alignment tolerances, first, determine the current positions of the centerlines of rotation of all the machinery; then, observe any movement restrictions imposed on the machines or control points; next, decide which way and how much the machinery needs to be moved; and finally, go ahead and physically reposition the machines in the vertical, lateral, and axial directions. After you have made a move, be sure to check the alignment as described in Step 5 to determine if the machines really moved the way you hoped they did. When the final desired alignment tolerance has been satisfied, record the final alignment position for future reference, the orientation of the soft foot shim corrections, and the final shim packs used to adjust the height of the machinery. If lateral and axial jackscrews exist, touch each jackscrew against the side of the machine case, then draw them out so there is a 10–20 mils gap between the machine case and the tip of the jackscrew, lock the jackscrew in that position, and make sure the foot bolts are secured.

Time requirements: The amount of time spent to correct the misalignment is often directly related to the size of the machinery that you are working on. For a 100 hp or smaller drive system, it may take you anywhere from 1 to 3 h to correct the misalignment. If you are attempting to align a 50 t steam turbine and a 75 t generator, it may take you 12 h or more to install just one set of shims and move the equipment sideways to correct the problem. That is not to say that 100 hp or smaller equipment is going to be a cakewalk. If you change the position of a machine, you need to go back to Step 5 and measure the shaft-to-shaft alignment again to insure the move was successful. Besides Step 4 (the preliminary steps), here is typically where the majority of time is spent on an alignment job.

Step 7

Tasks: Get ready to operate the machinery

Make sure the drive system is ready to run before you remove the safety tags. Make sure the correct type and amount of lubricant is in the bearings of all the machinery in the drive system. Insure all the foot bolts are tight. If you replaced an electric motor, you may want to temporarily remove the disconnect Lock Out tag and insure the motor is rotating in the correct direction. If you were working on a steam or gas turbine, you may want to check overspeed trip settings. With the driver disconnected from the driven unit, now might be a good time to measure vibration levels on the bearings (as well as any other performance parameters). After the driver "solo" test runs are complete, install the Lock Out tag again. Make sure the shaft end to shaft end distance is correct for the coupling. Assuming the coupling was inspected for damaged components during the alignment job, replace any defective parts, reassemble the coupling, and check for rotational freedom of the entire drive train if possible. Make sure any connections (piping, wiring or conduit, ductwork, etc.) to the machinery is secure. Install the coupling guard and make any final checks on the drive train prior to removing the safety tags.

Time requirements: Depending on what items you are going to do, this step will usually take anywhere from 30 min to 3 h to perform assuming weather is not a factor.

Step 8

Tasks: Start the drive system and insure it is operating satisfactorily

Operate the unit at normal conditions checking and recording vibration levels, bearing and coupling temperatures, bearing loads, flow rates, suction and discharge pressures, current drawn, and other pertinent operating parameters.

Time requirements: Assuming you have healthy machinery, the balance characteristics of the rotors are good, the lubrication is the right kind and it is getting where it needs to be, and the operational parameters are normal, now is a great time to capture ''baseline data'' on the equipment for future comparison. Baseline data describe the point where the mechanical and operational performance is at the best it can be. The type of information that may be collected might include vibration, temperature, pressure, flow, and power consumption, to name a few. Over time, as the components begin to wear, these parameters may change. To extract the greatest amount of performance from the drive system, it is important to know what a healthy machine looks like and at what point should the equipment be shut down for corrective actions to prevent a catastrophic failure from occurring. Depending on what data you want to collect, this step may take anywhere from 30 min to 2 h to perform.

1.5 HOW QUALIFIED ARE YOU TO DETECT AND CORRECT MACHINERY MISALIGNMENT?

Purchasing an alignment measurement system does not necessarily qualify you as an alignment expert. What is the best method to measure misalignment under different circumstances? What effect do excessive soft foot, runout, and piping stress have on rotating machinery? What are the different levels of testing that can be performed at your plant to determine the skill level of the people responsible for alignment? What sort of training is required to become proficient in this area? The effectiveness of written or oral exams, simulated misalignment test, and actual on the job skills testing on process machinery will henceforth be discussed.

1.6 WHY SHOULD PEOPLE BE TESTED ON THEIR ALIGNMENT SKILLS?

Perhaps several true life examples will illustrate the need for certification and qualification testing in machinery alignment.

- A maintenance technician at a chemical plant was asked to align a motor and a pump with a newly purchased laser shaft alignment system. Shaft position measurements were captured with the instrument and the alignment corrections required to align the motor (assigned as the movable machine) to the pump indicated that the outboard end of the motor had to be lowered 85 mil and the inboard end of the motor had to be lowered 37 mil and there was no shim stock under any of the motor feet. After completely removing the motor, the technician began grinding the baseplate away. The motor was placed back on the base and shaft position measurements were captured again. The technician then added shims under the motor since too much metal had been ground away and several side-to-side moves were made to bring the equipment into alignment.
- A company was in the process of installing several large air compressors to expand the capacity of the compressed air system. Requests for bids were sent out to several general contractors to install the 11,000 hp motors, gearboxes, and compressors. Very detailed specifications were sent to each of the general contractors including very specific instructions on installation of the foundations, sole plates, correcting soft foot conditions, rough

alignment procedures, final cold alignment procedures, and hot alignment procedures. The general contractor was told to subcontract the alignment work to companies who specialize in machinery alignment. When the alignment specifications were sent to the alignment subcontractors, several of the contractors did not understand many of the detailed specifications for the required work but submitted bids anyway believing that no one would check their work. The contract awards were dispensed and toward the completion of the project the company discovered that the alignment work was not performed to the written specifications and withheld payment to the contractors who performed the work (or lack thereof).

- A company, which was in the process of becoming ISO compliant, requested information on who administers certification testing for their maintenance personnel for shaft alignment. Several of their people had been certified in vibration analysis and thermography and they wanted to show documentation that their personnel were adept at not only finding problems but also adept at fixing them.
- A petroleum company decided to sell one of their facilities and several of the prospective buyers were interested in retaining as many employees as possible. However they only wanted to hire the people who were adequately trained and were certified to do certain tasks. When asked to provide information on task certification of their employees, the petroleum company was unable to provide the information.
- A steel company was having some problems with a fairly complex, multiple element drive train where misalignment was found to be the root cause of the failures. No one in the plant knew how to align the drive system. An alignment service company was contacted and the technician said that they could align the drive system in less than 4 h. When the work was actually done, the job took several days to complete.
- An electric utility company had experienced several failures on a critical pump. The in-house maintenance personnel had been using a laser shaft alignment system to measure the positions of the shafts. The pump was driven by a variable speed hydraulic clutch and the manufacturer of the clutch stated in the instruction manual that the clutch would rise upward 15 mils once it attained normal operating conditions. The maintenance personnel henceforth set the clutch 15 mils lower than the pump shaft assuming that the pump would not move from off-line to running conditions. A survey was conducted that showed that the pump shaft rose upward far more than the clutch did forcing the unit to run under severe misalignment conditions.

Most of us are keenly aware that purchasing this equipment does not mean that we know how to use it. Buying a vibration analyzer does not make one a vibration analyst, nor does purchasing an infrared imaging camera qualify someone as knowledgeable in thermography, or a scalpel magically transform someone into a surgeon. The learning curve for this equipment and the knowledge to use it properly is long and steep. Determining what buttons to push, how to operate the software program that came with the instrument as well as learn how to use a computer can consume several months of time. Once you have figured out how to operate the equipment and begin to collect data, the next task is to ascertain what the data is telling you, so some sort of judgment on the condition of your machinery can be made. This part can take years to become proficient at as the equipment being monitored at your plant does not necessarily follow generic equipment deterioration patterns, and proper condition assessment can only be realized with experimentation and experience. During its infancy, many CBM programs have disappointed people because one or two bad calls were made, assessing incorrectly the condition of the machinery. People can get upset after disassembling a machine to find that nothing or very little was wrong, when it was made to sound like the machine was about to catastrophically fail.

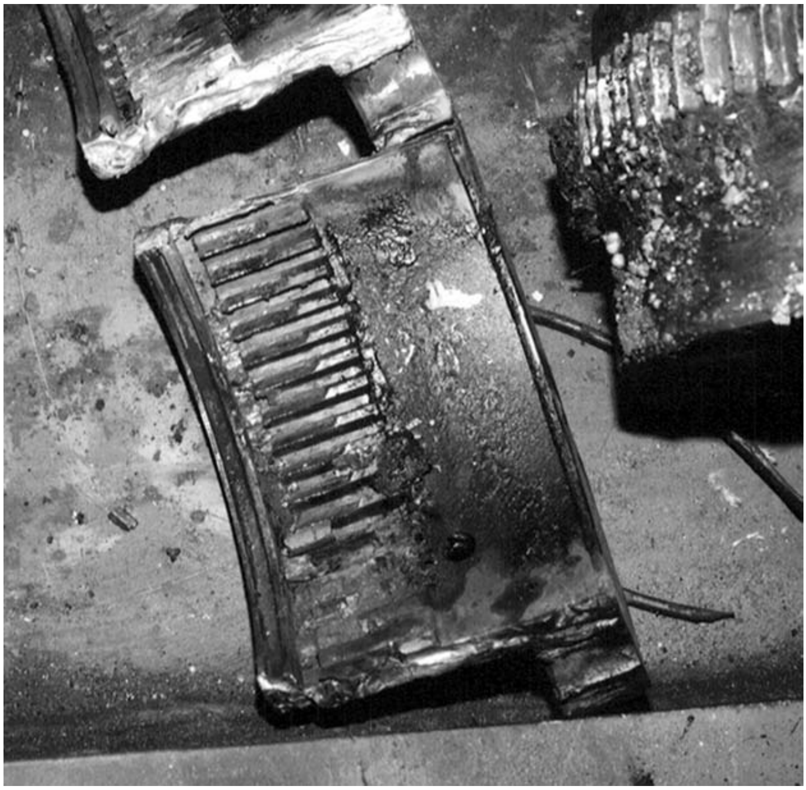


FIGURE 1.5 Excessively worn gear coupling due to operation under moderate misalignment conditions.

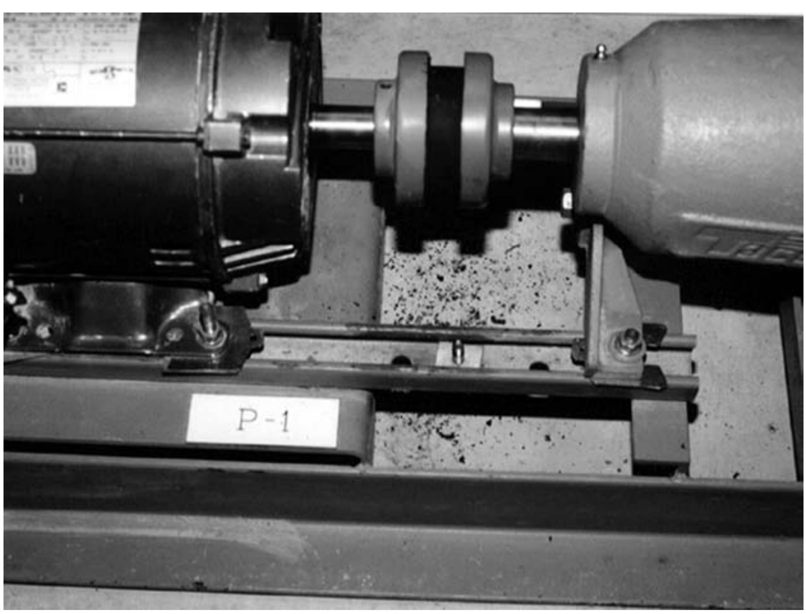


FIGURE 1.6 Rubber dust under coupling on a misaligned motor and pump after running intermittently for 2 months.

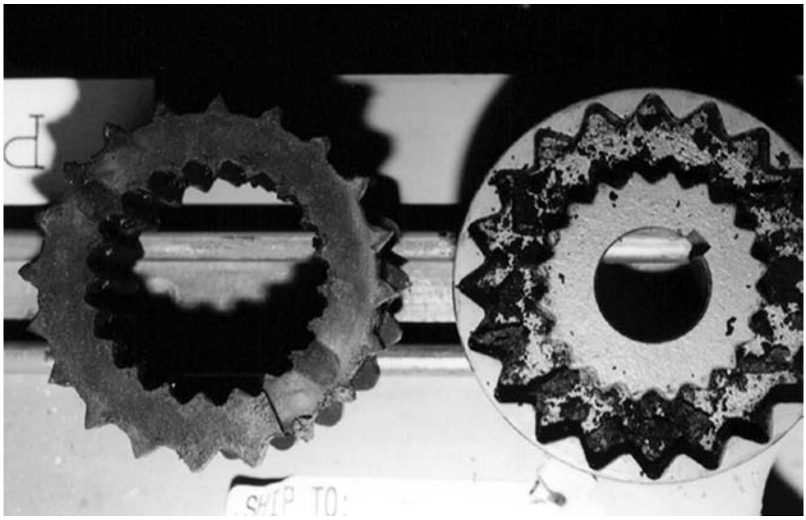


FIGURE 1.7 Coupling hub and rubber insert from drive system shown in Figure 1.6.

FIGURE 1.8 Worn gear coupling hub.

So it became apparent that these condition-based and predictive maintenance programs only worked effectively after the people attended some training courses. Some people learned a lot, some learned a little, and some had their minds occupied elsewhere during the training courses. Those who worked hard and learned a lot started wondering how they could prove that they knew more than those who did not. Certification testing appeared to provide the best proof of a person's skills in vibration analysis and infrared thermography. Some people may disagree with the need for testing, but it has become a way of life and many companies are requiring their employees to become certified in these nondestructive testing methods. In fact, this made people begin thinking about certification for several other kinds of tasks performed in the industrial work place. If certification is desirable for methods to detect problems with rotating machinery, then certification should also be desirable for correcting problems with rotating machinery such as balancing, shaft alignment, and tribology, for example. How qualified are people in finding and correcting misalignment conditions on rotating machinery? As more companies are turning to task-based training and task-based testing, what is the best way to determine if employees and contractors are suitably qualified to do machinery alignment?

1.7 EXPERIENCE EVALUATION FOR MACHINERY ALIGNMENT

Before qualification testing begins, you should have a fairly good idea of how knowledgeable you, your coworkers, or the contractors you hire are in the field of machinery alignment already, so unnecessary training is not done. Assessing what you and your coworkers know about shaft alignment can be done by soliciting the employees through an experience evaluation form that queries their knowledge and experience on specific types of machinery and specific types of tasks performed on this machinery. The next step is to test each individual on the tasks that they said they were adept at to determine if they are truly capable of performing that task and if not, what supplementary training would be required to elevate their level of proficiency. In summary, what do they think they know, what do they actually know, and what do they need training in?

1.8 WHO NEEDS TO BE TRAINED AND QUALIFIED IN SHAFT ALIGNMENT?

Many organizations feel that the full responsibility for machinery alignment rests solely in the hands of the trades people (e.g., mechanics, millwrights, pipe fitters, electricians). But should it be the responsibility of a trades personnel to:

1. Pick training courses they feel they need and send themselves to the courses?
2. Research all of the available types of shaft alignment measurement systems and purchase a system that best fits the needs of their organization?
3. Tell a contractor that they are not installing new rotating machinery correctly?
4. Hire some new people or a contractor to help with the work overload?
5. Rebuild a piece of rotating machinery due to excessive runout conditions?
6. Determine that a rotating machinery foundation or baseplate has to be removed and reinstalled if it has deteriorated excessively or been installed improperly?
7. Redesign and rework improperly installed piping that is putting an excessive strain on the rotating machinery it is attached to?
8. Purchase and install piping supports or design a custom piping anchor on a computer-aided design system, purchase the materials, and install the anchor?
9. Select a new flexible coupling design to replace one that does not work well or fails often?

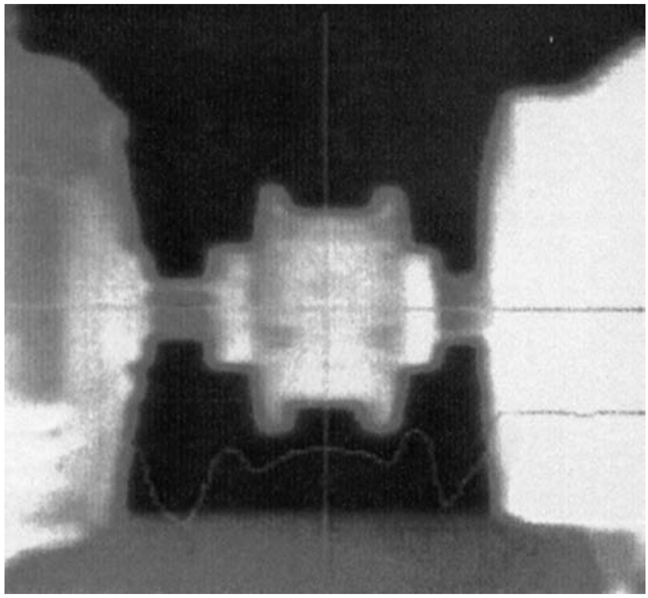


FIGURE 1.9 Infrared thermal image of misaligned metal ribbon coupling operating under a misalignment condition. (Courtesy of Infraspection Institute, Shelburne, VT.)

10. Pick a pump to be the "movable" machine and leave the motor as the "stationary" machine?
11. Issue work orders to check the alignment of all the rotating machinery every year?
12. Shut a machine down based on vibration and temperature data that indicates a misalignment or a soft foot condition?
13. Determine which machinery might need to have the hot alignment checked, select an OL2R machinery movement measurement technique, install the equipment on the machinery, measure and analyze the data, and alter the cold alignment position based on the data collected?
14. Maintain records of the alignment work that was performed and save it in the equipment files or computer database?
15. Install X–Y proximity probes on a machine supported in sliding-type bearings to analyze the Lissajous orbit for signs of running misalignment?

I would not be surprised if a lot of managers, engineers, front line supervisors, vibration technicians, and trades people felt that some, if not several, of the above items are not their responsibility (let alone what some of them mean). If the trades people are not responsible for many of the above items, then who should be?

Machinery alignment training should be for managers (who cannot understand why alignment takes longer than 45 min), engineers (who were never taught this in school and are rarely allowed to do hands-on work), technicians (who are asked to identify it through CBM programs but do not know how to correct it), front line supervisors (who need to help the trades people if they get stuck or need a special tool for the work), and trades people (who are the ones ultimately responsible for the final outcome) to give them the minimum working knowledge to achieve accurate alignment and to let them know what is involved in the overall alignment process. As it is apparent that trades personnel should not be accountable for every facet of shaft alignment, several people need to be trained and qualified in whatever tasks they are responsible for. Engineering and maintenance managers, rotating equipment and maintenance engineers, maintenance technicians, vibration specialists, foremen and front line supervisors, as well as the trades personnel all should be trained and qualified to do their respective tasks.

1.9 ASSESSING A PERSON'S KNOWLEDGE AND EXPERIENCE LEVEL IN SHAFT ALIGNMENT

Field experience evaluation forms similar to those shown in Figure 1.10 through Figure 1.14 could be used for your in-house personnel or for contractors working at your plant site.

Rotating machinery and shaft alignment field experience evaluation

Part 1. Background information.

Name: ____
Company: ____
Address: ____
City: _________________ ST: _____ Zip: ________________
Phone: ___________________ FAX: _________________
E-Mail: __________________________

Current job title or responsibility

Number of years — Job description

______ Plant manager
______ Engineering manager
______ Maintenance manager
______ Engineer
______ Front line supervisor/foreman/planner
______ Technician
______ Mechanic
______ Millwright
______ Pipefitter
______ Electrician
______ Electronic repair/instrumentation
______ Other (please list) ______________________________________

Past job titles or responsibilities

Number of years — Job description

______ Plant manager
______ Engineering manager
______ Maintenance manager
______ Engineer
______ Front line supervisor/foreman/planner
______ Technician
______ Mechanic
______ Millwright
______ Pipefitter
______ Electrician
______ Electronic repair/instrumentation
______ Other (please list) ______________________________________

FIGURE 1.10 Shaft alignment experience evaluation form—Part 1.

Rotating machinery and shaft alignment field experience evaluation

Part 2. Rotating machinery experience.

You have been working on the following types of industrial rotating machinery for __X__ number of years.

Number of years	Machinery type
_____	Synchronous motors
_____	Induction motors
_____	Steam turbines
_____	Gas turbines
_____	Water turbines
_____	Internal combustion engines
_____	Up to 50 hp
_____	50 to 200 hp
_____	200 to 1000 hp
_____	1000 to 5000 hp
_____	5000+ hp
_____	Single stage centrifugal pumps
_____	Multiple stage centrifugal pumps
_____	Centrifugal air compressors
_____	Reciprocating air compressors
_____	Screw or sliding vane air compressors
_____	Gearboxes
_____	Fans
_____	Blowers
_____	AC generators
_____	DC generators
_____	Cooling tower fan drives
_____	Multiple element drive trains
_____	Other machinery (please list)

____
____
____

FIGURE 1.11 Shaft alignment experience evaluation form—Part 2.

Figure 1.10 (Part 1) identifies the person and what his or her job titles are (or have been). Figure 1.11 (Part 2) gives an indication of what type of rotating machinery a person has worked on in the past. Figure 1.12 (Part 3) gives some idea of the training a person has received in different alignment measurement tools and techniques. Figure 1.13 (Part 4 and Part 5) lists the amount of actual field experience a person has in measuring shaft alignment when the equipment is off-line and the amount of actual field experience a person has in measuring off-line to running machinery movement.

1.10 ALIGNMENT QUALIFICATION OR CERTIFICATION TESTING

The experience evaluation forms can be used to determine what training is required for personnel installing, maintaining, or aligning rotating machinery. However anyone could fill out the form and say they were proficient and experienced working with every type of rotating machine and alignment method listed but how can they verify what they say they know? Written or oral examinations are one mechanism to verify a person's knowledge level for each item in the experience evaluation forms. There could be one comprehensive test

Rotating machinery and shaft alignment field experience evaluation

Part 3. Shaft alignment training.

I have received training in the following shaft alignment methods, procedures, or tasks. Formal training means you attended a training course, on the job training (OTJT) means you where shown this information by a coworker or you were self taught.

Formal OTJT Shaft alignment method(s), procedures, tasks
_____ _____ Foundation and baseplate/soleplate installation and repair
_____ _____ Soft foot detection and correction
_____ _____ Excessive runout detection and correction
_____ _____ Excessive piping strain detection and correction
_____ _____ Straightedge, eyeball, feeler gauge
_____ _____ Face–rim indicator
_____ _____ Reverse indicator
_____ _____ Shaft to coupling spool
_____ _____ Double radial
_____ _____ Face–face
_____ _____ Laser/detector system(s)—model(s)_______________
_____ _____ Calculating growth using the thermal strain equation
_____ _____ Inside micrometer/tooling ball/angle measurement devices
_____ _____ Proximity probes with water cooled stands
_____ _____ Optical alignment tooling
_____ _____ Alignment bars and proximity probes (aka Dodd/Dynalign bars)
_____ _____ Laser/detector system(s)—model(s)___________________
_____ _____ Ball-rod-tubing connector system
_____ _____ Vernier–Strobe method
_____ _____ Instrumented coupling system
_____ _____ Shaft alignment software programs
_____ _____ Other (please list)
____
____

FIGURE 1.12 Shaft alignment experience evaluation form—Part 3.

administered that encompasses every facet of machinery alignment or there could be a series of tests given for discrete blocks of information. By breaking down the overall body of information into separate blocks, the people with little or no experience could be tested incrementally as their level of knowledge grew.

A Basic or Level 1 examination would test the individual's knowledge on the following blocks of information:

1. The detrimental consequences of poor alignment on rotating machinery
2. Detecting misalignment on running rotating machinery (i.e., vibration, infrared methods)
3. Use and care of measuring tools and instruments (feeler gauges, dial indicators, optical encoders, laser-detector system, proximity probes, etc.)
4. Finding and correcting excessive runout conditions
5. Finding and correcting soft foot problems
6. Finding and correcting excessive piping strain
7. Foundation and baseplate design, installation, and care
8. Concrete and grouting installation
9. Alignment tolerances

Rotating machinery and shaft alignment field experience evaluation

Part 4. Shaft alignment field experience.

I have performed the following off-line shaft alignment methods for __X__ number of years.

Number of years Shaft alignment methods you have used

_____ None
_____ Eyeball
_____ Straightedge, eyeball, feeler gauge
_____ Face–rim indicator
_____ Reverse indicator
_____ Shaft to coupling spool
_____ Double radial
_____ Face–face
_____ Optical alignment tooling
_____ Laser/detector system(s)—model(s) ________________________
_____ Other (please list)
____
____

Part 5. Off-line to running (OL2R) machinery movement measurement and alignment compensation methods hot and cold alignment) field experience.

I have performed the following OL2R methods for __X__ number of years.

Number of years OL2R machinery movement measurement methods you have used

_____ Calculating machine case thermal expansion (thermal strain equation)
_____ Inside micrometer/tooling ball/angle measurement devices
_____ Proximity probes with water cooled stands
_____ Optical alignment tooling
_____ Alignment bars & proximity probes (aka Dodd bars/Dynalign system)
_____ Laser/detector system(s)—model(s) ________________________
_____ Ball-rod-tubing connector system
_____ Vernier–Strobe method
_____ Instrumented coupling system
_____ Other (please list)
____
____

FIGURE 1.13 Shaft alignment experience evaluation form—Part 4 and Part 5.

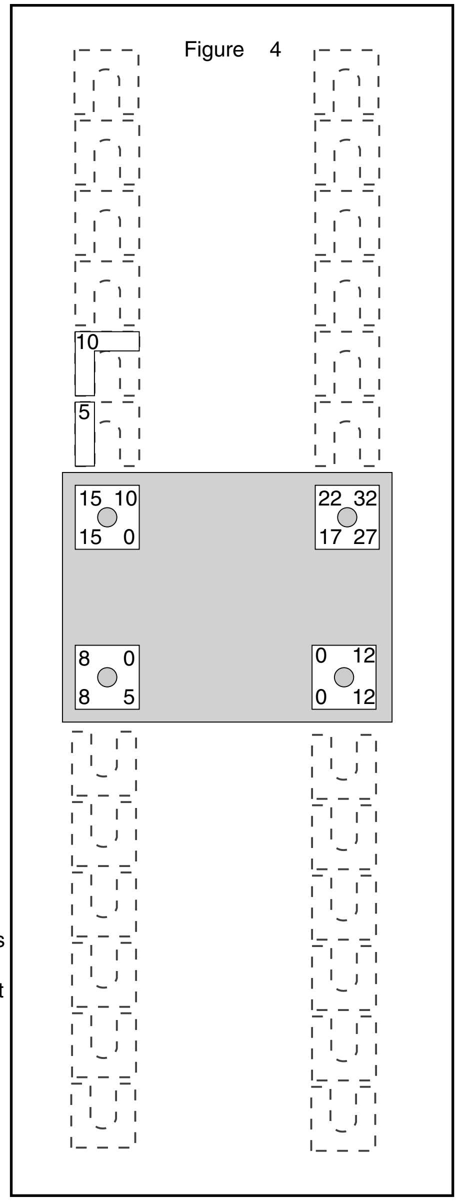
10. Rigid and flexible coupling design, installation, and care
11. How to perform the reverse indicator method
12. Basic mathematical- or graphical-modeling principles for realignment
13. How to determine effective alignment corrections using the reverse indicator technique
14. Keeping records of alignment work

An Intermediate or Level 2 examination would test the individual's knowledge on the following blocks of information:

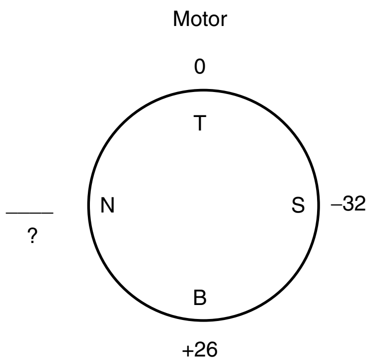
1. How to perform and determine effective alignment corrections using the face and rim technique.
2. How to perform and determine effective alignment corrections using the shaft to coupling spool technique.

Basci / Level 1 Certification Test

15. Show how you would correct the soft foot conditions found on an electric motor as shown in Figure 4. Draw in the shape of the shim(s) and the shim thickness to correct the soft foot conditions at the other three feet. Standard shim thicknesses are 1, 2, 3,4, 5, 10, 15, 20, 25, 50, 100, 125 mils. (6 pts)



16. Fill in the missing dial indicator reading. (2 pts)



17. A motor and pump running at 3600 rpm has a maximum misalignment deviation of 1.9 mils per inch. Is that an acceptable amount of misalignment? (2 pts)

a. yes
b. no

FIGURE 1.14 Sample question from a Level 1 shaft alignment certification exam.

3. How to perform and determine effective alignment corrections using the double radial technique.
4. How to perform and determine effective alignment corrections using the face–face technique.
5. How to generate mathematical- or graphical-modeling principles for all of the above methods.

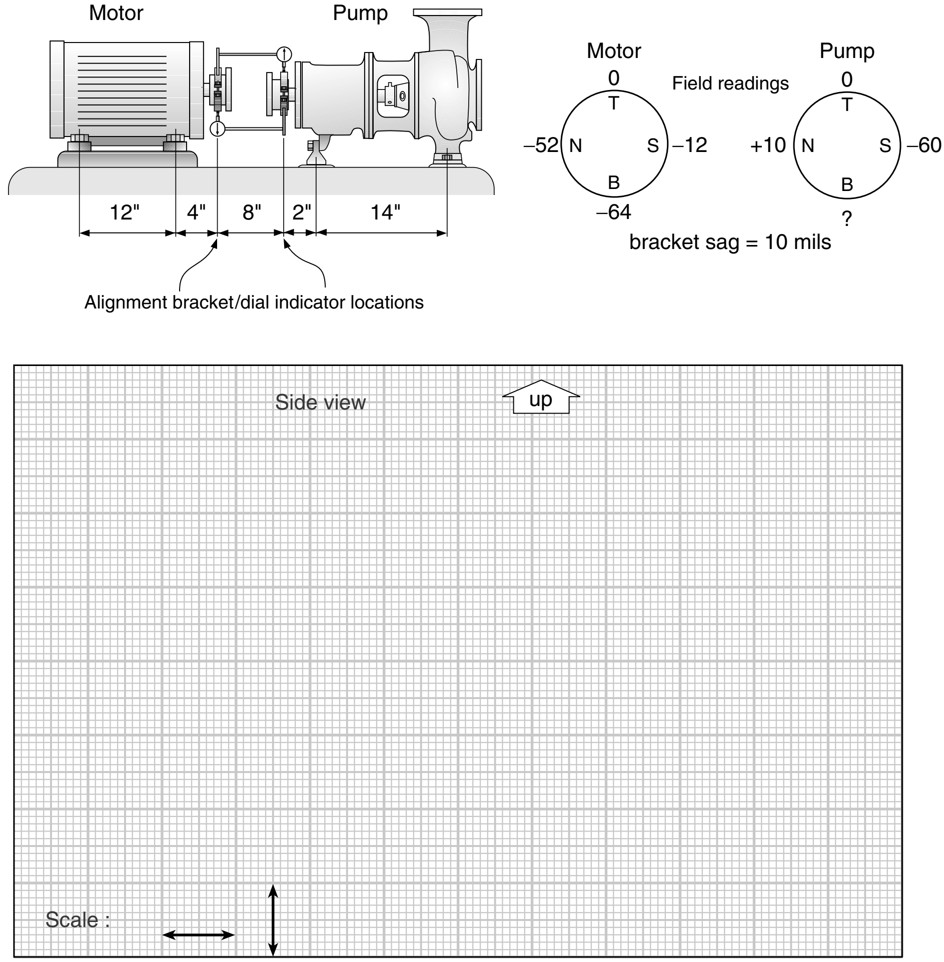
An advanced or Level 3 examination would test the individual's knowledge on the following blocks of information:

1. How to align multiple element drive trains.
2. How to align right angle drives.
3. The four general categories for measuring OL2R machinery movement (hot and cold alignment)
4. Calculating machine case thermal expansion
5. Inside micrometer-tooling ball–angle measurement methods
6. Proximity probes with water cooled stands technique
7. Using optical alignment tooling for OL2R machinery movement
8. Alignment bars with proximity probes OL2R method
9. Using laser-detector systems to measure OL2R machinery movement
10. Using the ball-rod-tubing connector system to measure OL2R machinery movement
11. Using the Vernier–Strobe system to measure OL2R machinery movement.
12. Mathematical- or graphical-modeling principles for all of the above methods
13. How to compensate for OL2R machinery movement when aligning rotating machinery

Figure 1.14 and Figure 1.15 show sample problems that might appear on a Level 1 exam. Written or oral exams can test a person's knowledge on a subject but is somewhat inadequate in determining a persons skill level in performing specific tasks. Machinery alignment is a hands-on task. Someone can understand how the reverse indicator alignment method works but not be able to perform the method correctly. Perhaps the most effective means of verifying a person's knowledge and skill level is to have the person perform the task on a simulation machine or directly on an operating rotating equipment drive system at the plant site. However using process machinery as a test platform may not be possible. What if the equipment cannot be shut down for a scheduled test time, or what if the person being tested misaligns the machine by mistake and no one checks to see that it is correct? By having simulation equipment available, testing can occur at virtually any time without impacting production or maintenance schedules. For accurate skills assessment, it is important to insure that the test equipment simulate real life conditions.

In today's society, specialized jobs in many different areas require some sort of certification to verify that an individual is proficient in that task. In the health, education, and finance industries, for example, doctors, nurses, teachers, and accountants must show that they are certified in those areas before they are even considered for employment. In industry, welders must be certified before they can work on pressure vessels and heating, ventilation, and air conditioning (HVAC) technicians must be certified to work with Freon refrigerants. You cannot even drive a car or fly a plane without a license. The need for qualification or certification testing in specialized tasks such as vibration analysis, thermography, and shaft alignment is justifiable. Establishing the requirements for qualification or certification can be accomplished by appraising the experience level of personnel through an evaluation form that addresses all of the aspects of the task. Skill requirements for each individual can then be assessed and appropriate training can be administered. Written or oral exams and task simulation tests can then be conducted to determine the true proficiency of the individual. Although most of us do not like to be tested on what we know (or think we know), appraising our skill level is beneficial to the companies or customers we all work for. Certification, qualification, and licensing examinations can be used as an effective tool in verifying an individual's level of proficiency in any specific task and a viable mechanism to let someone know where he or she needs additional training.

20. Plot the position of the motor and pump shafts in the side view (up/down) direction from the following reverse indicator readings. (10 pts)



21. How would you correct the misalignment condition in the example shown above assuming there are no shims under any of the motor or pump feet?. (10 pts)

FIGURE 1.15 Sample question from a Level 1 shaft alignment certification exam.

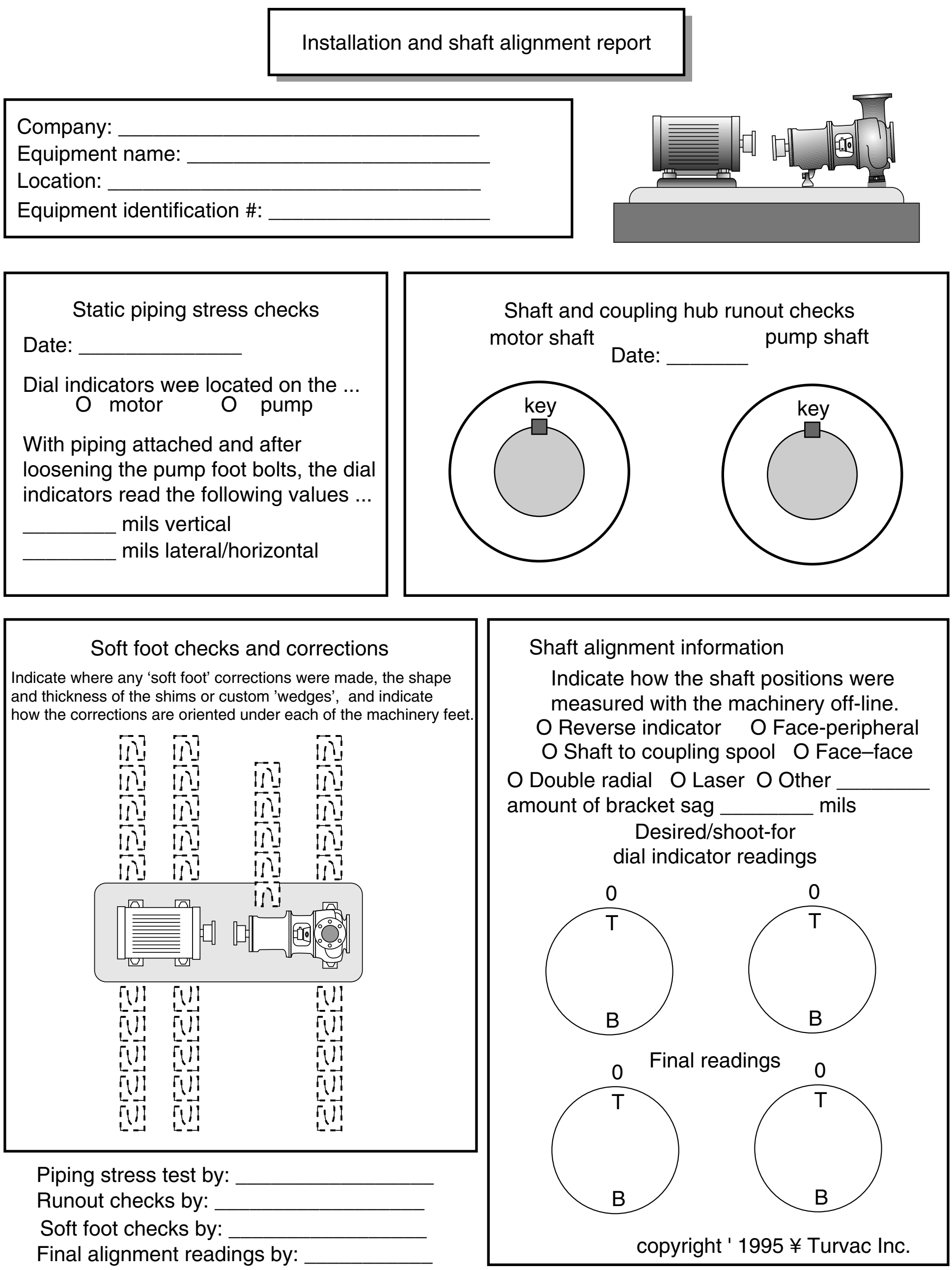
1.11 PERIODIC ALIGNMENT CHECKS

Typically, it is assumed that once a piece of machinery has been aligned, it stays that way forever. What a surprise it is for many to learn that is not always true. Just as you should check the alignment on your personal vehicle periodically (typically recommended around 25,000 miles), the alignment of rotating machinery should also be checked periodically.

Here are some recommended guidelines. For newly installed machinery, the alignment should be checked between 500 and 2000 h of intermittent operation or 1–3 months of continuous operation. If there was no apparent shift in the alignment position then the next check should be made between 4500 and 9000 h of intermittent operation or 6 months to

1 year of continuous operation. If no apparent shift occurred during that period of time then checks should be made every 2–3 years.

If a moderate shift in alignment occurred at any time, then the equipment should be aligned within acceptable tolerances. If a radical shift occurred, then additional investigation should be conducted to determine what is causing the shift to occur. The most common causes of



Installation and shaft alignment report

Company: ______________________________
Equipment name: ________________________
Location: ______________________________
Equipment identification #: _________________

Static piping stress checks
Date: ____________
Dial indicators wee located on the ...
O motor O pump
With piping attached and after loosening the pump foot bolts, the dial indicators read the following values ...
________ mils vertical
________ mils lateral/horizontal

Shaft and coupling hub runout checks
motor shaft Date: _______ pump shaft
key key

Soft foot checks and corrections
Indicate where any 'soft foot' corrections were made, the shape and thickness of the shims or custom 'wedges', and indicate how the corrections are oriented under each of the machinery feet.

Shaft alignment information
Indicate how the shaft positions were measured with the machinery off-line.
O Reverse indicator O Face-peripheral
O Shaft to coupling spool O Face–face
O Double radial O Laser O Other ________
amount of bracket sag ________ mils
Desired/shoot-for dial indicator readings
0 T B 0 T B
Final readings
0 T B 0 T B

Piping stress test by: _______________
Runout checks by: _______________
Soft foot checks by: _______________
Final alignment readings by: ___________

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FIGURE 1.16 Sample alignment recording form.

alignment shifts can be traced back to unstable foundations or baseplates, piping stress (both static and operational stresses), and inconsistent OL2R machinery movement. These problems are not easy to find and equally difficult to fix. All of the effort expended getting rotating machinery within acceptable alignment tolerances is worthless if the machinery cannot maintain its position over long periods of time.

1.12 ALIGNMENT RECORD KEEPING

I was once told, "If something is important enough to measure, then it's important enough to write it down and save it." Keeping historical records of the soft foot conditions, runout on the shafts and coupling hubs, piping stress checks, as-found and final off-line shaft alignment position measurements, and machinery dimensions can take some time and effort to compile and record but there is a good chance that this information might save you or one of your coworkers as much and possibly more time than it took to generate the records in the first place. Figure 1.16 illustrates an example of what type of information might be kept in the historical record file for a motor and pump.

REFERENCES

Guidebook for Maintenance Proficiency Testing, Electric Power Research Institute, December 1989, EPRI NP-6679.

Handbook for Evaluating the Proficiency of Maintenance Personnel, Electric Power Research Institute, March 1988, EPRI NP-5710.

2 Detecting Misalignment on Rotating Machinery

It has long been known that one of the principal causes of damage to rotating machinery can be directly attributed to misalignment conditions. The primary cause of this damage can be traced back to excessive forces impinging on the rotors, bearings, seals, and housings. As there seems to be a direct link between how long the rotating machinery will operate and the presence of undesirable forces on the machinery, it seems prudent to reduce or eliminate as many of these forces as possible.

The capacity to detect and then correct misalignment on rotating machinery is directly related to the knowledge, skills, and desire of the personnel responsible for the equipment. If it is understood that accurate alignment is paramount for the long-term survival of rotating machinery, then it is somewhat of a dilemma trying to explain why misalignment continues to be a major source of damage to rotating machinery. The principal reason for this can be traced back to the fact that there are major philosophical differences on how people operate and maintain their equipment. For a moment, let us examine the different approaches organizations apply when operating and maintaining their industrial machinery.

2.1 THE FOUR MAINTENANCE PHILOSOPHIES

If you work long enough in the industry, you may get an opportunity to observe all the different "styles" of maintenance. How maintenance organizations operate their equipments usually fall into four different categories:

1. Breakdown or run-to-failure maintenance
2. Preventive or time-based maintenance
3. Predictive or condition-based maintenance
4. Proactive or prevention maintenance

2.1.1 Breakdown or Run-to-Failure Maintenance

The basic philosophy of this type of maintenance is to allow the machinery to run to failure and only repair or replace the damaged equipment when obvious problems occur. Studies have shown that the costs to operate in this fashion are about $18 per horsepower per year. The advantage of this approach is that it works well if equipment shutdowns do not affect production and if labor and material costs do not matter. Where would this apply?

The disadvantages are that the maintenance department perpetually operates in unplanned and "crisis management" maintenance activities with unexpected production interruptions and the plant must have a high inventory of spare parts to react quickly. Without a doubt, it is the most inefficient way to maintain a facility. Futile attempts are made to reduce costs by purchasing cheap parts and hiring cheap labor, further aggravating the problem. Frequently the personnel are overworked and the department is understaffed, and the workers arrive at work each day to be confronted with a long list of unfinished work and a half dozen new emergency jobs that occurred while they were at home in the evening. It is not uncommon to send someone out to work on an emergency job first thing in the morning and by ten o'clock, half way through the job, stop their progress and send them on a new higher priority emergency job.

Despite the wonders of modern life in the new millennium, I see many places like this. I hope you are not in one of them.

2.1.2 Preventive or Time-Based Maintenance

This maintenance philosophy consists of scheduling maintenance activities at predetermined time intervals where you repair or replace damaged equipment before obvious problems occur. If such maintenance is carried out correctly, studies have shown that the costs to operate in this fashion are about $13 per horsepower per year. The advantage of this approach is that it works well for equipment that does not run continuously and the personnel have enough knowledge, skill, and time to perform the preventive maintenance work.

The disadvantages are that the scheduled maintenance may be done too early or too late. It is quite possible that there may be a drop in production due to unnecessary maintenance work. In many cases there is a possibility of diminished performance through incorrect repair methods. I have witnessed perfectly good machines disassembled, good parts removed and discarded, and then new parts improperly installed. For some, squirting grease into bearings every month is their idea of a preventive maintenance program.

2.1.3 Predictive or Condition-Based Maintenance

This philosophy of maintenance consists of scheduling maintenance activities only if and when mechanical or operational conditions warrant by periodically monitoring the machinery for excessive vibration, temperature, lubrication degradation, or observing any other unhealthy trends that occur over time. When the condition gets to a predetermined unacceptable level then the equipment is shut down to repair or replace damaged components in the equipment to prevent a more costly failure from occurring. In other words, "do not fix what is not broke." If this kind of maintenance is performed correctly, studies have shown that the costs to operate in this fashion are about $9 per horsepower per year. The advantage of this approach is that it works very well if personnel have enough knowledge, skill, and time to perform the predictive maintenance work. The repairs to equipment can be scheduled in an orderly fashion and it allows some lead time to purchase materials for the necessary repairs, reducing the need for a high parts inventory. As maintenance work is only performed when it is needed, there is a likely increase in production capacity.

The disadvantages are that maintenance work may actually increase if the personnel improperly assess the level of degradation in the equipment. Observing the unhealthy trends in vibration, temperature, or lubrication requires the facility to procure equipment to monitor these parameters and provide training to in-house personnel. The alternative is to outsource this work to a knowledgeable contractor to perform predictive or condition-based duties. If an organization had been running in the breakdown or run-to-failure mode or the preventive maintenance style, the production and maintenance management must conform to this new philosophy, which can be problematic if the maintenance department is not allowed to purchase the necessary equipment, provide adequate training to the people to learn the new techniques, not given the time to collect the data, or not permitted to shutdown the machinery when problems are identified.

2.1.4 Proactive or Prevention Maintenance

This maintenance philosophy utilizes all of the predictive or preventive maintenance techniques discussed above in concert with root cause failure analysis to not only detect and pinpoint the precise problems that occur but also to insure that advanced installation and repair techniques are performed including potential equipment redesign or modification to avoid or eliminate problems from occurring. If this kind of maintenance is done correctly, studies have shown that the costs to operate in this fashion are about $6 per horsepower per year. The advantages of this approach are that it works extremely well if personnel have enough knowledge, skill, and time to perform all of the required activities. As in the prediction-based program, repairs to equipment can be scheduled in an orderly fashion but then additional efforts are made to provide improvements to reduce or eliminate potential problems from repetitively occurring. Again, repairs to equipment can be scheduled in an orderly fashion and it allows lead time to purchase materials for the necessary repairs, reducing the need for a high parts inventory. As maintenance work is only performed when it is needed, and extra efforts are put forth to thoroughly investigate the cause of the failure and then determine ways to improve the reliability of the machinery, there can be a substantial increase in production capacity.

The disadvantages are that this requires extremely knowledgeable employees in preventive, predictive, and prevention or proactive maintenance practices or to outsource this work to a knowledgeable contractor who works closely with the maintenance personnel in the root cause failure analysis phase and then assists in the repairs or design modifications. This also requires procurement of equipment and properly training personnel to perform these duties. If an organization had been running in the breakdown or run-to-failure mode or the preventive maintenance style, the production and maintenance management must conform to this new philosophy, which again can be problematic if the maintenance department is not allowed to purchase the necessary equipment, provide adequate training to the people to learn the new techniques, not given the time to collect the data, not permitted to shutdown the machinery when problems are identified, not given the time and resources to conduct the failure analysis, and then do not modify the component or procedure to increase the reliability.

2.1.5 Industrial Maintenance Philosophy Survey Results

Over the past few decades, surveys have shown the level of participation in each of the above-mentioned maintenance approaches or styles as shown in Figure 2.1. Despite the proven benefits of predictive or condition-based maintenance and proactive or prevention maintenance programs, 50% of the industries surveyed still allow their machinery to run to failure.

2.2 TYPES OF FORCES THAT OCCUR ON ROTATING MACHINERY

As mentioned earlier, the majority of failures in rotating machinery are caused by undesirable forces. Machinery shafts want to rotate freely with little or no external forces impinging on the rotors, bearings, couplings, and seals. When moderate or excessive static or dynamic forces are present, the components begin to slowly degrade, eventually leading to mechanical failure. The performance of the equipment relating to its designed operating conditions such as output horsepower, discharge pressure, flow, speed, etc., may all be optimum, but if excessive amounts of force and vibration are present, it is definitely not going to be running for very long.

There are two basic forces that act on the rotating machinery: static forces and dynamic forces as shown in Figure 2.2. Static forces are forces that always act in one direction.

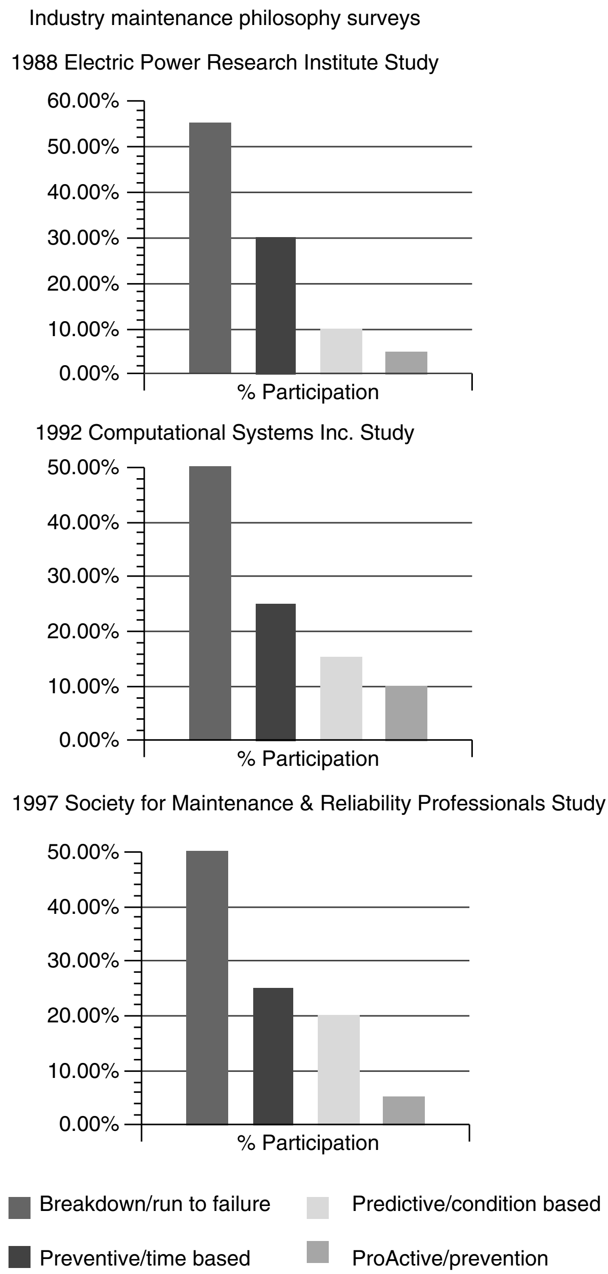


FIGURE 2.1 Industry survey showing how maintenance departments classify their maintenance approach.

Dynamic forces are forces that change their direction or periodically fluctuate for some reason. It is very important to understand that only dynamic forces can cause vibration to occur in machinery.

We will examine two different analysis methods commonly used in the industry to determine if rotating machinery is misaligned—vibration analysis and infrared thermography. Many of the generalizations made by vibration and infrared thermographic equipment vendors concerning detection of misalignment are not always true.

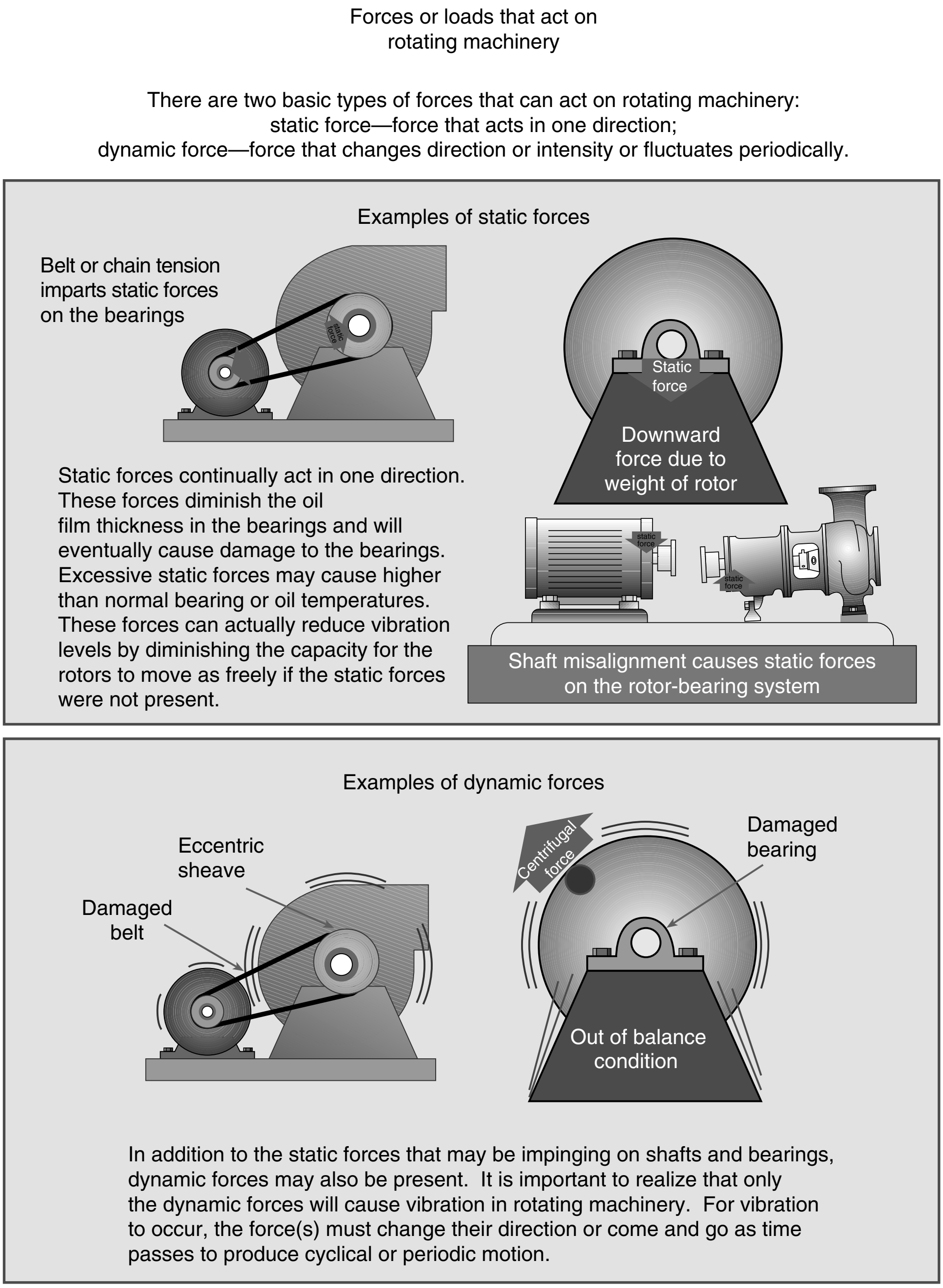


FIGURE 2.2 Forces in rotating machinery.

2.2.1 How Mass, Stiffness, and Damping Affect the Vibration Response of Machinery

One of the most overlooked aspects of vibration analysis is the effect of mass, stiffness, and damping of rotating machinery. As force is the major factor for stress and eventually cause damage to rotating machinery, it is important to understand what effect the mass, stiffness, and damping of this equipment has on the level of vibration that is measured.

Mass is frequently, but incorrectly, referred to as the weight of an object. More precisely, it is the amount of material present in an object. Newton's second law of motion states that

$$F = ma$$

or

$$\text{force} = \text{mass} \times \text{acceleration}$$

At the Earth's surface, our planet exerts a gravitational pull of 32.174 ft/s^2 or 386.088 in./s^2 and is designated as 1 g. On the Moon, the gravitational pull is much less so you may "weigh" less but your mass remains the same. The accepted unit for mass is a slug [1 lbf (one pound of force) = 0.03108 slug]. Therefore 1 lbm (one pound of mass) = 0.00259 lbf s^2/in.).

Stiffness refers to the flexibility, rigidity, or "springiness" of an object. Stiffness is expressed in lbf/in. or how much force does it take to stretch or compress an object 1 in. in length.

Damping refers to the resistance to motion. Frequently rubber vibration isolators or dampers are installed between machinery and the floor of a building to prevent the transmission of vibration in the machine to the floor. The accepted unit for damping is lbf s/in.

The equation below describes force as a function of time:

$$F(t) = (K \times \text{displacement}) + (C \times \text{velocity}) + (M \times \text{acceleration})$$

where K represents the stiffness (lbf/in.), C the damping (lbf s/in.), and M the mass (lbf s^2/in.).

All of this may seem very boring but it explains why vibration analysis is so very difficult. Remember, vibration sensors measure motion, not force. As vibration amplitude is often used to describe the severity of a problem, the dynamic forces that generate the amount of motion of an object will change if the mass, stiffness, or damping is altered.

2.2.2 How Vibration Is Measured

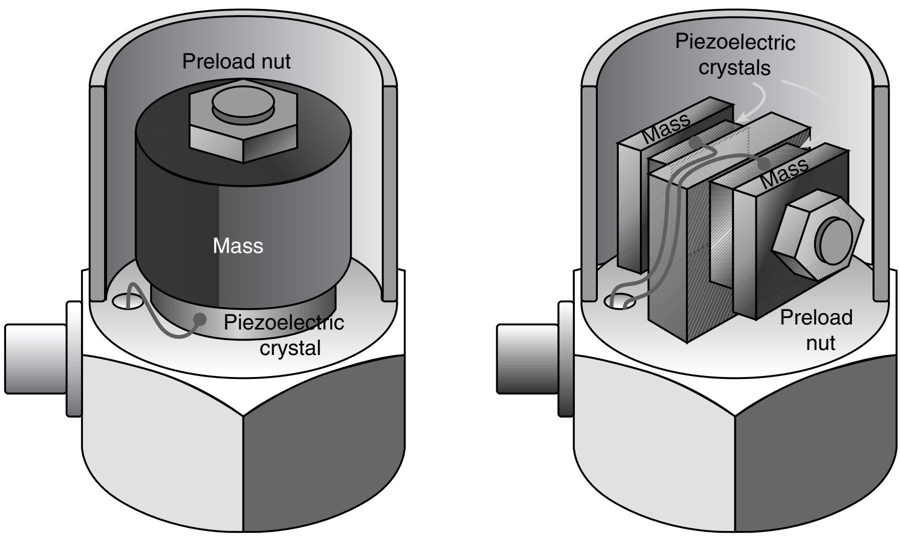
There are three types of vibration sensors: accelerometers as shown in Figure 2.3, seismometers (velocity pickups) as shown in Figure 2.4, and proximity probes as shown in Figure 2.5. Accelerometers and seismometers are typically used to take casing–bearing cap measurements. Proximity probes are permanently mounted to the bearing housing and are typically used to measure motion of a shaft supported in a sliding type bearing to observe shaft motion with respect to the machine case. Proximity probes can also be used to measure axial position of a shaft, commonly referred to as thrust probes, and they can be used to capture rotational timing information as explained below. Figure 2.6 shows the useful frequency range of each of these sensors. The typical units of measure for acceleration is *g* s; for velocity, inches or millimeters per second (in./s or mm/s); and for displacement mils (1 mil = 0.001 in.) or millimeters. You can convert from one unit to another as shown in Figure 2.7.

On each two bearing machines, a total of five vibration readings are typically measured: four radial vibration measurements and one axial vibration measurement. A radial vibration measurement is taken at a 90° angle to the centerline of rotation of the shaft and an axial vibration reading is taken in line with the centerline of rotation. Radial vibration measurements taken from the outside of the machine case or bearing housing with accelerometers or seismometers on machinery where the shafts are in a horizontal orientation are usually taken at the top (i.e., twelve o'clock) and side (i.e., three o'clock or nine o'clock) positions at both the inboard (coupling end) and outboard bearings as shown in Figure 2.8. The axial vibration measurement is taken at either the inboard or outboard end of the machine. The accelerometer

Accelerometers

Accelerometers are perhaps the most popular vibration sensor today for capturing bearing cap or casing measurements. The piezoelectric material used to generate the signal in these sensors is usually quartz or a ceramic called lead zirconate titanate (PZT). This type of material produces anelectrical charge if force is applied to it. There are several different configurations but they are typically manufactured to be compression or shear type of sensors. The piezoelectric material must be placed under a strain (preloaded force) in order to measure either tension orcompression forces. Permanently mounting these sensors must be done carefully as to prevent distortion of the housing.

Compression type | Shear type



Advantages
¥ Wide frequency response (up to 3,000,000 cpm).
¥ Lightweight and physically small.
¥ Good ambient temperature range. Special sensors can be placed in environments up to 1000°F.
¥ Moderate pricing.

Disadvantages
¥ Sensitive to stresses induced when permanently mounted.
¥ Requires a power supply and amplification circuitry (some sensors have amplification circuits built into the sensor housing).

FIGURE 2.3 Operating principles of accelerometers.

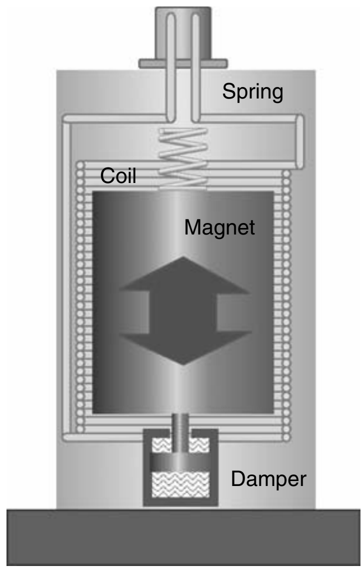
is held in position by hand, or with a magnetic base, or with a quick release connector, or it may be permanently attached to the housing using epoxy or a threaded rod drilled and tapped into the machine case.

Another useful piece of information that can be gathered to assist in understanding the vibration on machinery is a rotational timing reference signal commonly known as the "phase angle." There are four different ways to gather phase angle data as shown in Figure 2.9:

1. A strobe light viewing a reference mark on the rotating shaft with a stationary protractor positioned around the circumference of the shaft

Velocity sensors

Velocity sensors are also known as seismic probes. Effectively they are linear voltage generators. As the permanent magnet moves back and forth inside the housing, the magnetic flux lines cut through the windings of the coil surrounding the magnet producing an alternating current. The faster the magnet moves, more flux lines are cut through the windings and the voltage increases. These probes are excellent for measuring casing or bearing housing movement. They have also been employed with shaft riders that physically touch the shaft as it



Advantages
¥ Strong signal generated by coil which can be transmitted over fairly long distances (up to 100 ft).
¥ Self-generated signal requires no special power supply or circuitry.
¥ Rugged construction can be mounted virtually in any position.
¥ Frequency response is good to 300,000 cpm.

Disadvantages
¥ Physically large and heavy compared to proximity probes and accelerometers.
¥ Output signal decays exponentially below 600 cpm.
¥ Relativey expensive and not manufactured by many companies.

FIGURE 2.4 Operating principles of seismometers.

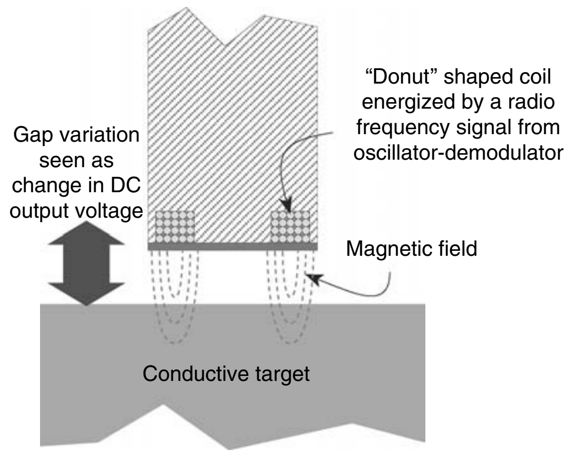
2. A strobe light viewing a rotating protractor marked on the circumference or end of a shaft with a stationary reference mark positioned around the circumference of the shaft
3. A photo tachometer, which consists of a piece of reflective tape attached to the rotating shaft and a fiber optic cable with one set of fibers shining a light onto the shaft and another set of fibers sensing the piece of reflective tape as it passes by
4. A proximity probe positioned over a keyway or hole in the rotating shaft

Bear in mind that the phase angle signal is somewhat meaningless unless the phase angle sensor (strobe light, phototach, or prox probe) is controlled (triggered) by the same analyzer that is also used to measure the vibration signal. Also be cognizant of the fact that the phase

Proximity probes

Proximity probes can effectively be considered as noncontacting, electronic dial indicators. The measure displacement or distance directly. A small pancake coil located in the tip of the probe induces an electromagnetic field. When an electrically conductive surface (e.g., a steel shaft) is placed near the magnetic field, eddy currents are induced in the surface. As the probe tip is moved toward the surface, the circuit voltage drops; as the tip is moved away from the surface, the circuit voltage increases. These probes are excellent for use in monitoring shaft vibration where the rotor is supported in sliding type bearings where the AC component of the signal measures radial vibration. These probes are also used to monitor the axial/thrust position of a rotor to ascertain wear on a thrust bearing by monitoring the DC component of the signal.

Typical probe sensitivity is 100 or 200 mv/mil



Advantages

¥ Small in physical size and lightweight. Probes diameters typically used for monitoring radial vibration range between 1/4 to 3/8 and can be made in just about any length. Special probes can accurately measure up to 1/2 of distance.
¥ Relatively inexpensive at around $400.00 for probe and oscillator-demodulator (aka proximitor). Power supplies (usually either −18 or −24 VDC) and visual readout devices add significantly to the cost.
¥ Measurements are virtually unaffected by lubricants or gases that pass between the probe tip and the shaft surface.
¥ Senses actual shaft motion relative to bearing housing and when used in an *X–Y* configuration (i.e., two probes set 90° apart) with a dual channel analyzer can display orbital shaft motion inside the bearing.
¥ Frequency response ranges from 0 to 300,000 cpm making it very usable for rotating machinery applications.
¥ Proximity probes can also be used to measure distance and are frequently used to monitor sliding type thrust bearing wear physical position of a shaft inside the bearing, casing movement or expansion measuring off-line to running machinery movement surveys for hot and cold shaft alignment studies. Probes are also used to measure once-per-rev positions
(usually at the keyway) to provide phase angle reference.
¥ Satisfactory service in environments up to 250°F. Higher temperatures can cause a shift in the DC voltage and linearity loss at extremes of range.
¥ The output signal from the oscillator-demodulator can be transmitted over a significant distance (up to 1000 ft).

Disadvantages

¥ Probes are usually permanently attached to bearing housings requiring special mounting fixtures and careful placement.
¥ Surface imperfections in the shaft (i.e., scratches, grinding marks) will also be observed by the probe and can significantly affect the signal making it confusing as to how much of the overall signal is actual shaft motion and how much is due to surface imperfections.
¥ Damaged shaft journal areas that have been reworked by chrome plating are particularly troublesome as the probe will ignore the chrome plated surface and see the rough surface beneath the chrome.
¥ Requires a power supply and impedance matched circuitry (i.e., you may not be able to mix different probes, cables, and oscillator-demodulators).
¥ Susceptible to induced voltages if sensor wiring is run in conduct with other higher voltage wires (e.g., 110 VAC, 60 Hz).

FIGURE 2.5 Operating principles of proximity probes.

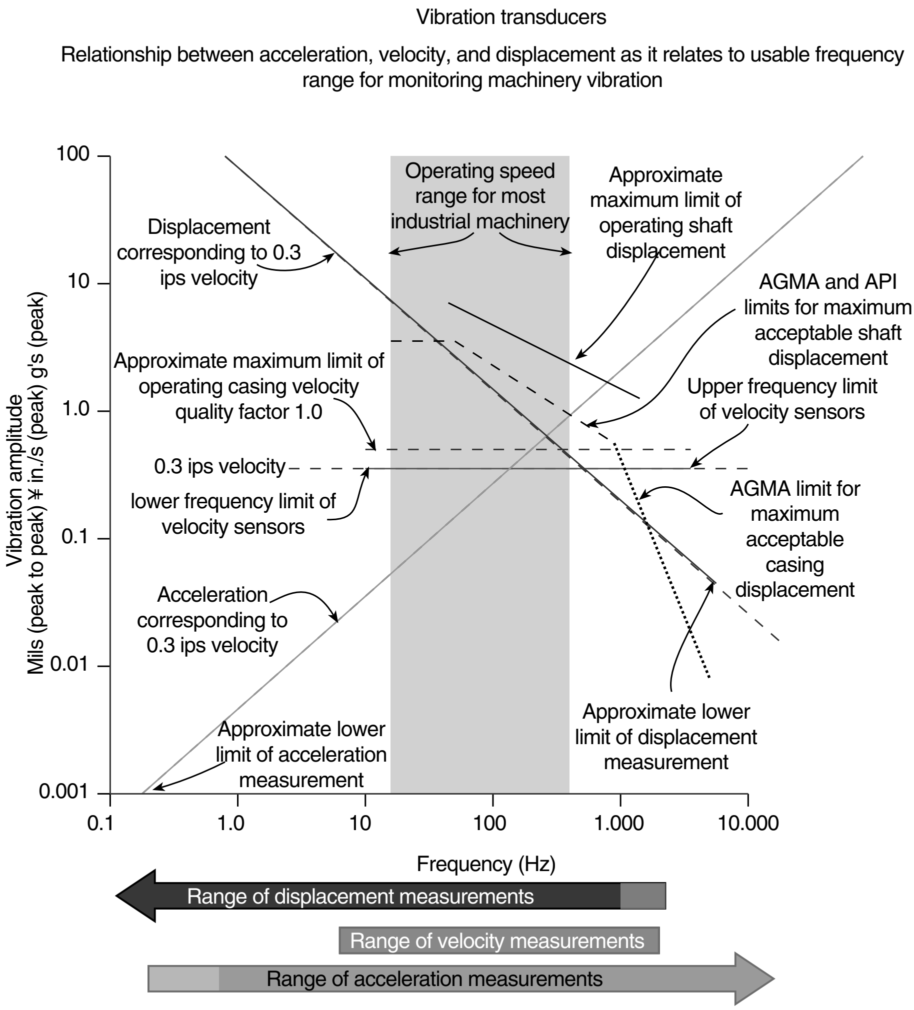


FIGURE 2.6 Frequency range of accelerometers, seismometers, and proximity probes.

angle data is directly related to the running speed of the machine and is only useful if the majority of the vibration is occurring at running speed. Not all of the vibration that exists in rotating machinery occurs at the machine's running speed as explained below.

The two most commonly used parameters in vibration analysis are amplitude and frequency. Amplitude, as shown in Figure 2.10, is an indicator of the severity of vibration. Frequency, as shown in Figure 2.11, is an indicator of the source of the vibration. If overall vibration amplitude levels are relatively high at any of the sensor locations, a more detailed survey should be taken with a spectrum (fast Fourier transform, FFT) analyzer to aid in determining the vibration signature of the machinery.

2.2.3 Time and Frequency Domain Vibration Information

Vibration information is typically displayed in two different ways: in the time domain and in the frequency (spectral) domain as shown in Figure 2.12. Actual examples of time and frequency domain information are shown in Figure 2.13.

Converting from one vibration unit to another

Finding acceleration (g s) if frequency (cpm) and velocity (in./s) or displacement (mils) is known . . .

acceleration = 0.0000000142 × frequency^2 × displacement [A=0.0000000142 F^2 D]

acceleration = 0.00027144 × velocity × frequency [A=0.00027 VF]

Finding velocity (in./s) if frequency (cpm) and acceleration (g s) or displacement (mils) is known . . .

velocity = 0.00005236 × frequency × displacement [V=0.00005236 FD]

velocity = 3684 × (acceleration/frequency) [V=3684 (G/F)]

Finding displacement (mils) if frequency (cpm) and acceleration (g s) or velocity (in./s) is known . . .

displacement = 19108.3 × (velocity/frequency) [D=19108.3 (V/F)]

displacement = 70400000 × (acceleration/(frequency)^2) [D=70400000 (G/F^2)]

Vibration parameter	*Symbol*	*Common units of measurement*
Frequency	F	Cycles per minute (cpm)
Displacement	D	Mils peak to peak
Velocity	V	in./s peak
Acceleration	A	G peak

Example A

F = 600 cpm
D = 15 mils peak to peak
A = 0.0000000142 F^2 D
A = (0.0000000142)×(600)^2 × 10
A = 0.0767 g s

Example B

F = 600 cpm
V= 0.5 in./s. peak
A = 0.00027 VF
A= 0.00027 × 0.5 × 600
A= 0.0814 g s

Example C

F = 600,000 cpm
A = 50 g s
V = 3684 (G/F)
V = 3684 (30/600,000)
V = 0.307 in./s peak

Example D

F = 600,000 cpm
A = 50 g s
D = 70400000 (G/F^2)
D = 70400000 (50/600,000^2)
D = 0.0098 mils peak to peak

Notice in example A how a considerable amount of displacement (15 mils) at 600 cpm has a small corresponding amount of acceleration (0.0767 g s). Also notice that a tremendous amount of acceleration (50 g s) at 600,000 cpm produces an extremely small amount of displacement (0.0098 mils peak to peak). Finally notice how the velocity in examples B (0.5 in./s peak) and C (0.307 in./s peak) would be of much concern regardless of the frequency (600 cpm in B and 600,000 cpm in C). That is why velocity is typically chosen as the unit of choice for measuring casing vibration on machinery, it is somewhat frequency independent. By reviewing the equation for force, notice that at low frequencies, displacement and stiffness are the predominant factors but at high frequencies, acceleration and mass are the predominant factors. Velocity across a much broader frequency range represents the damaging effects of dynamic force better than displacement or acceleration.

FIGURE 2.7 Converting one vibration unit to another.

Discerning what a vibration sensor is telling you happens to be one of the most difficult tasks the machinery diagnostician is faced with. However with the use of an FFT signal analyzer, vibration "signatures" can be taken that split the complex overall vibration signal and enable one to look at various frequencies of the sensor output. Many rules of thumb have emerged that attempt to classify specific machinery problems with specific types of vibration signatures. The experienced vibration analyst quickly learns that these rules of thumb are to be used as guidelines on arriving at the source of the problem. Quite often, more than one problem exist on

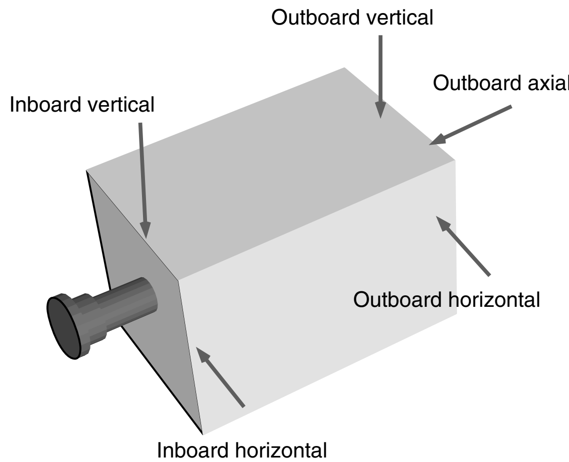


FIGURE 2.8 The area/position in which the vibration measurements on bearing caps of rotating machinery are typically gathered.

a piece of rotating machinery such as a combination of imbalance, misalignment, and damaged bearings that will all appear on the vibration spectrum.

If the source of the problem is misalignment, what will the vibration spectrum look like? Does the signal look the same for all different types of machinery with different kinds of couplings, bearings, and rotors?

2.2.4 Using Vibration Analysis to Detect Misalignment

One goal of this chapter is to examine the types of vibration signatures misaligned rotating equipment exhibit and the forcing mechanisms involved to generate this signal. Many people who work in the field of vibration analysis feel that shaft misalignment can be detected by the following symptoms:

- High one or two times running speed frequency components
- High axial vibration levels
- A 180° phase shift will occur across the coupling

The above symptoms can happen during shaft misalignment, but not always. There are four general statements that can be made from a number of controlled tests where rotating machinery was purposely misaligned and also from many field observations that have been made on equipment that was operating under misalignment conditions.

1. You cannot detect the severity of misalignment using vibration analysis. In other words, there is no relation between the amount of misalignment and the level or amplitude of vibration.
2. The vibration signature of misaligned rotating machinery will be different with different flexible coupling designs. For example, a misaligned gear coupling will not show the same vibration pattern as a misaligned rubber tire-type coupling.
3. Misalignment vibration characteristics of machinery rotors supported in sliding type bearings are typically different than the vibration characteristics of machinery rotors supported in antifriction type bearings.

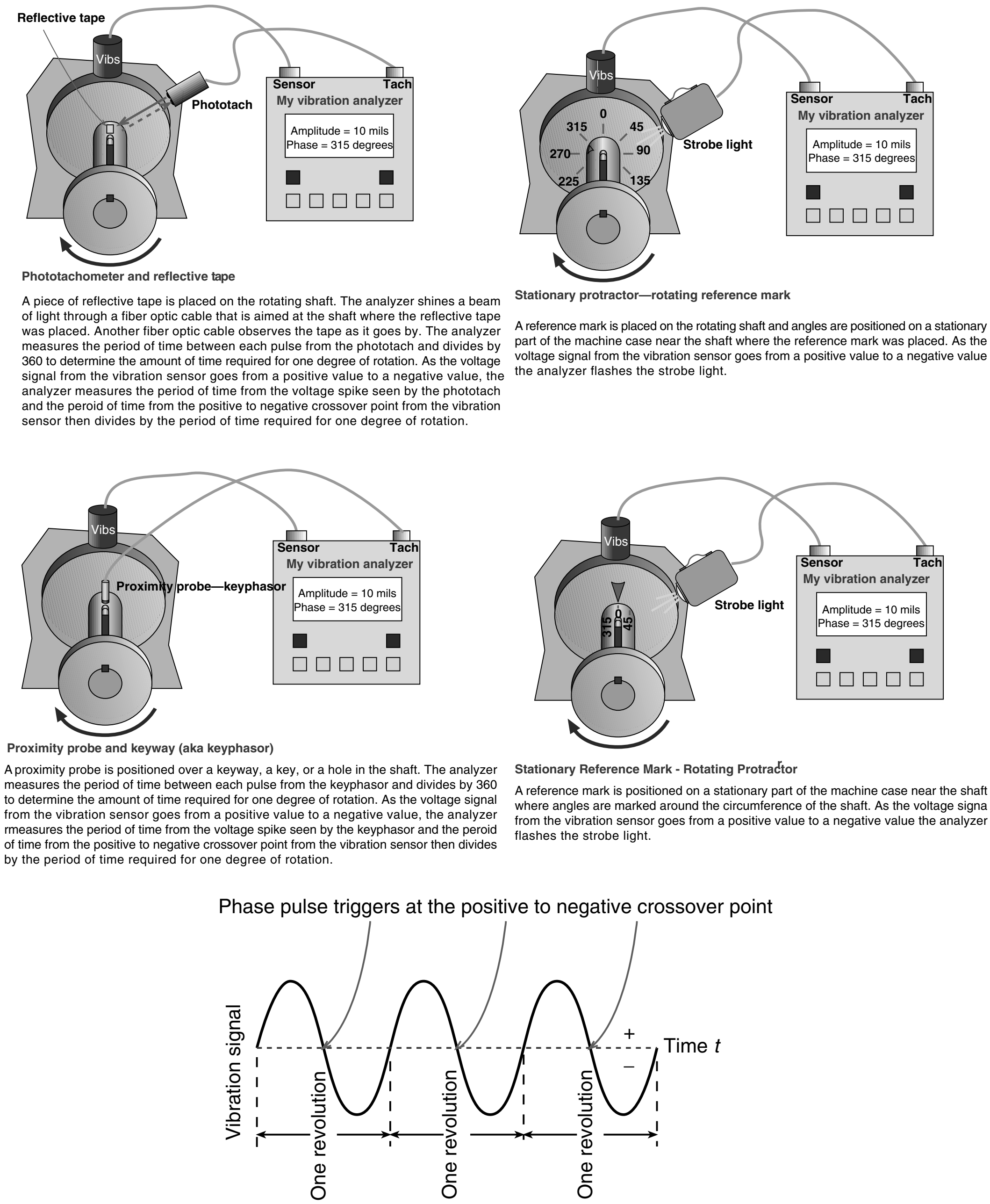
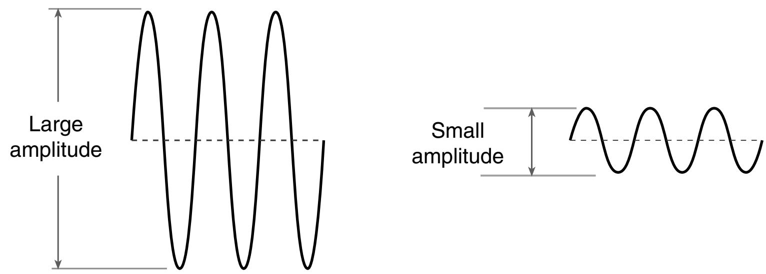


FIGURE 2.9 The four different methods to capture phase angle information.

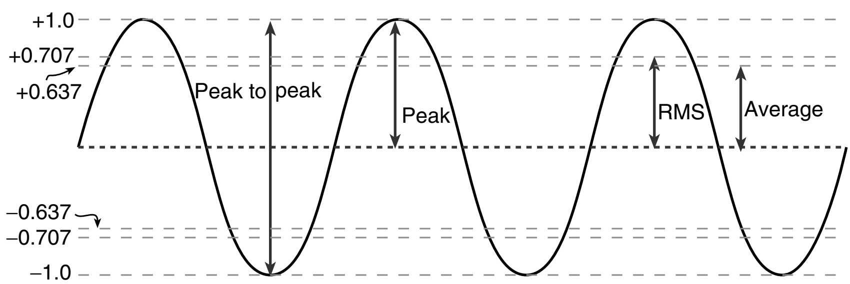
4. Vibration signatures from misaligned flexible couplings frequently have components at multiples of running speed. As previously mentioned, phase angle information only makes sense if the primary vibration is occurring at running speed. If the majority of vibration is principally occurring at frequencies other than running speed, phase angle data is somewhat meaningless.

Amplitude

Vibration amplitude is defined as the strength or size of the signal. In vibration analysis, it is usually the predominant factor in determining the severity of a problem.



Vibration amplitude is expressed in four different ways: peak to peak, peak, RMS (root mean squared), and average.



In the United States, vibration displacement amplitude when using proximity probes is usually expressed in peak-to-peak values, velocity amplitude is usually expressed in peak values when using velocity sensors or accelerometers (integrated to read in velocity), and acceleration amplitude is also usually expressed in peak values. In Europe, velocity and acceleration are usually expressed in RMS values.

If you are comparing vibration amplitude measurements on machinery taken at different time intervals (e.g., once a month) to determine if the vibration is changing, or if you are comparing your measurement to another persons measurements, it is important to insure that the amplitude values remain the same.

FIGURE 2.10 Vibration amplitude.

2.2.5 Relationship between Vibration Amplitude and Misalignment Severity

If two pieces of rotating machinery are coupled together and misaligned by 5 mils/in. and vibration readings are taken on the bearing caps and then the unit is shutdown and misaligned to 10 mils/in. (double the initial amount), started back up and vibration readings taken on the bearing caps again, the overall vibration amplitudes measured will not be twice the amount compared to the first set of data collected at misalignment conditions of 5 mils/in.

Increasing misalignment may actually decrease vibration levels. Conversely, if a drive train that has been running misaligned for a period of time was shutdown and realigned more accurately, the vibration levels may increase after it is restarted. Many drive trains may be slightly to moderately misaligned and vibration analysis will not be able to detect the misalignment condition. Surprising facts, but true! To verify these statements, let us review some experimental tests and actual field data taken on misaligned rotating machinery.

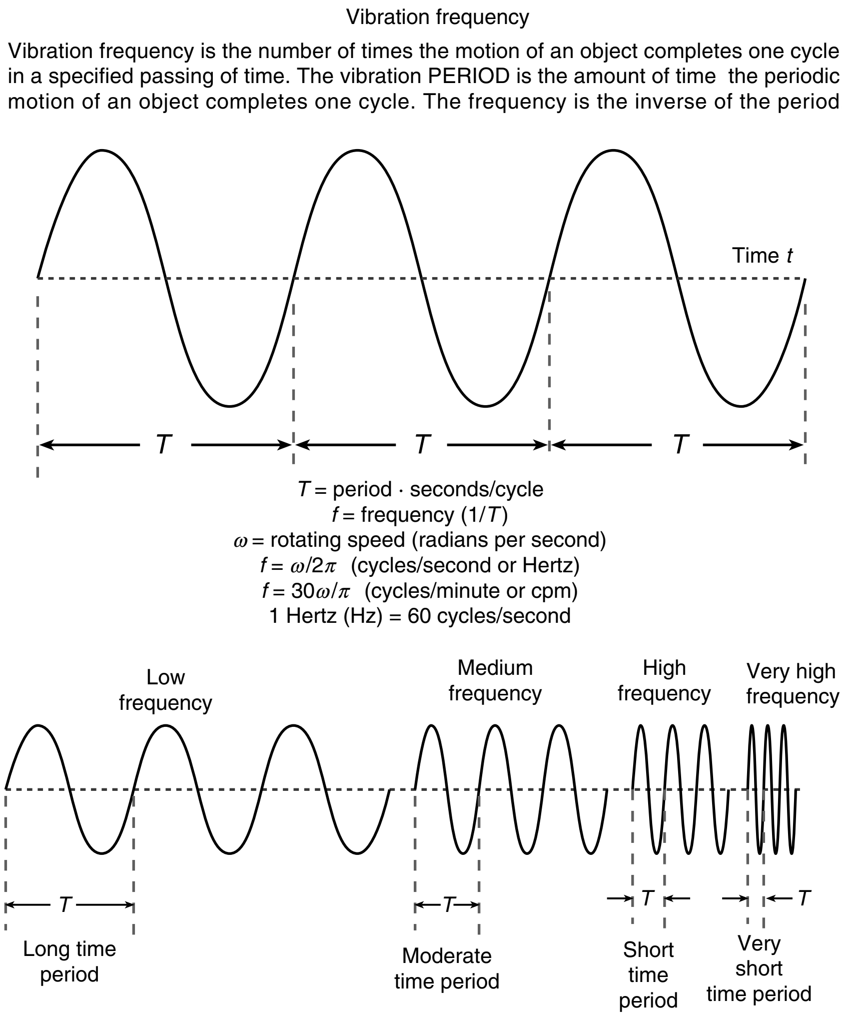


FIGURE 2.11 Vibration frequency.

2.2.6 Vibration Results from a Controlled Misalignment Test on a Training Demonstrator

Figure 2.14 shows a 1/2 hp, 1775 rpm motor driving a center shaft with two balance disks coupled to another outer shaft with one overhung balance disk. A steel bar was attached to both bearing housings that support the center shaft. Two proximity probes were positioned on this bar to monitor the distance between the two balance disks and the probe tips to measure the amount of shaft distortion that occurred on the center shaft. The three shafts (motor, center, and outer) were connected together using flexible disk-type couplings. The unit was near perfectly aligned, operated at running speed, and overall vibration measurements taken on all six bearings. The demonstrator was then shutdown, the bolts holding the middle shaft to the frame were loosened, and the middle shaft was misaligned 31 mils sideways, locked in that position, started back up, and vibration, proximity probe gap readings, and amperage measurements were taken. The demonstrator was again shutdown, the bolts holding the middle shaft to the frame were loosened, and the middle shaft was

Periodic vibration and the Fourier transform

The vibration that comes from rotating machinery is typically not simple, harmonic vibration but can be comprised of several varying forces emanating at different frequencies. When two or more forces occurring at different frequencies develop on rotating machinery, they add together to produce a more complex waveform. Around 1790, Jean Baptiste Fourier, a French physicist and mathematician, discovered a mathematical relationship that showed any complex waveform comprised of several different harmonic components emanating at different frequencies can be resolved into their distinct frequencies. This mathematical relationship is known as the Fourier series or Fourier transform. Today, with the use of computers, this mathematical formula can be done at a very fast rate of speed aptly named as the fast Fourier transform or FFT.

$$f(t) = A_0 + A_1 \sin(\omega t+\varphi 1) + A_2 \sin(2\omega t+\varphi 2) + A_3 \sin(3\omega t+\varphi 3) + \cdots$$

where f(t), complex waveform; A1, A2, etc., amplitudes of each wave; $\varphi 1$, $\varphi 2$ are the phase "lags" between each waveform

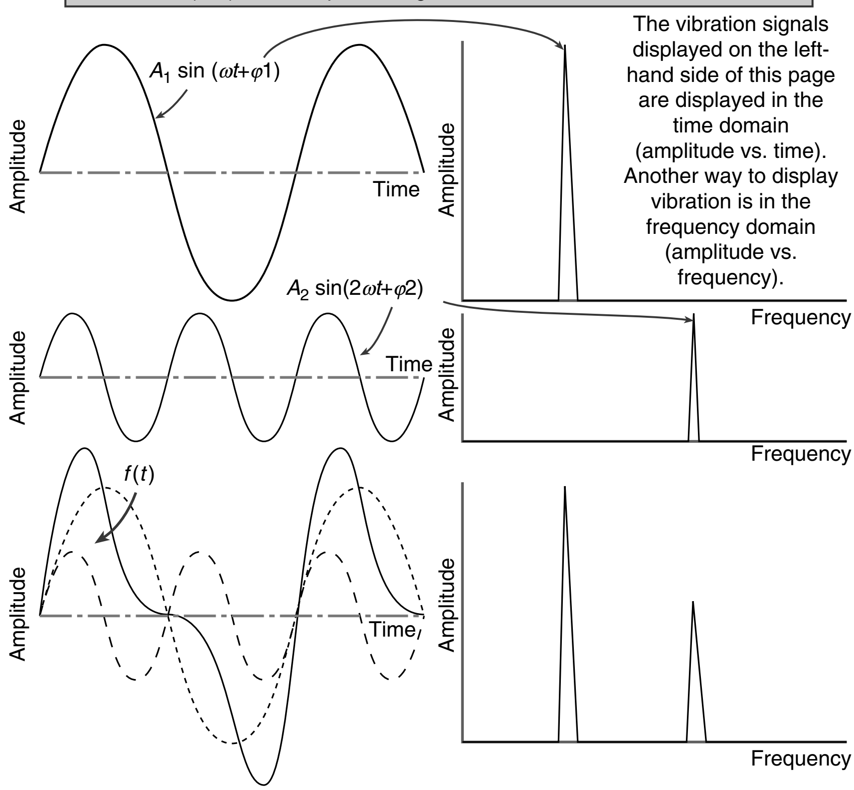


FIGURE 2.12 Spectral information and the Fourier transform.

misaligned another 31 mils sideways (now a total of 62 mils sideways), locked in that position, started back up, and vibration measurements were taken for a final time.

Figure 2.15 shows the results of the vibration measurements, the proximity probe gap readings, and the amperage draw.

Notice that in virtually every case, the vibration levels dropped as the misalignment increased. The amperage draw showed very little change across each of the runs. However notice that the distance between the proximity probes and the balance disks increased just

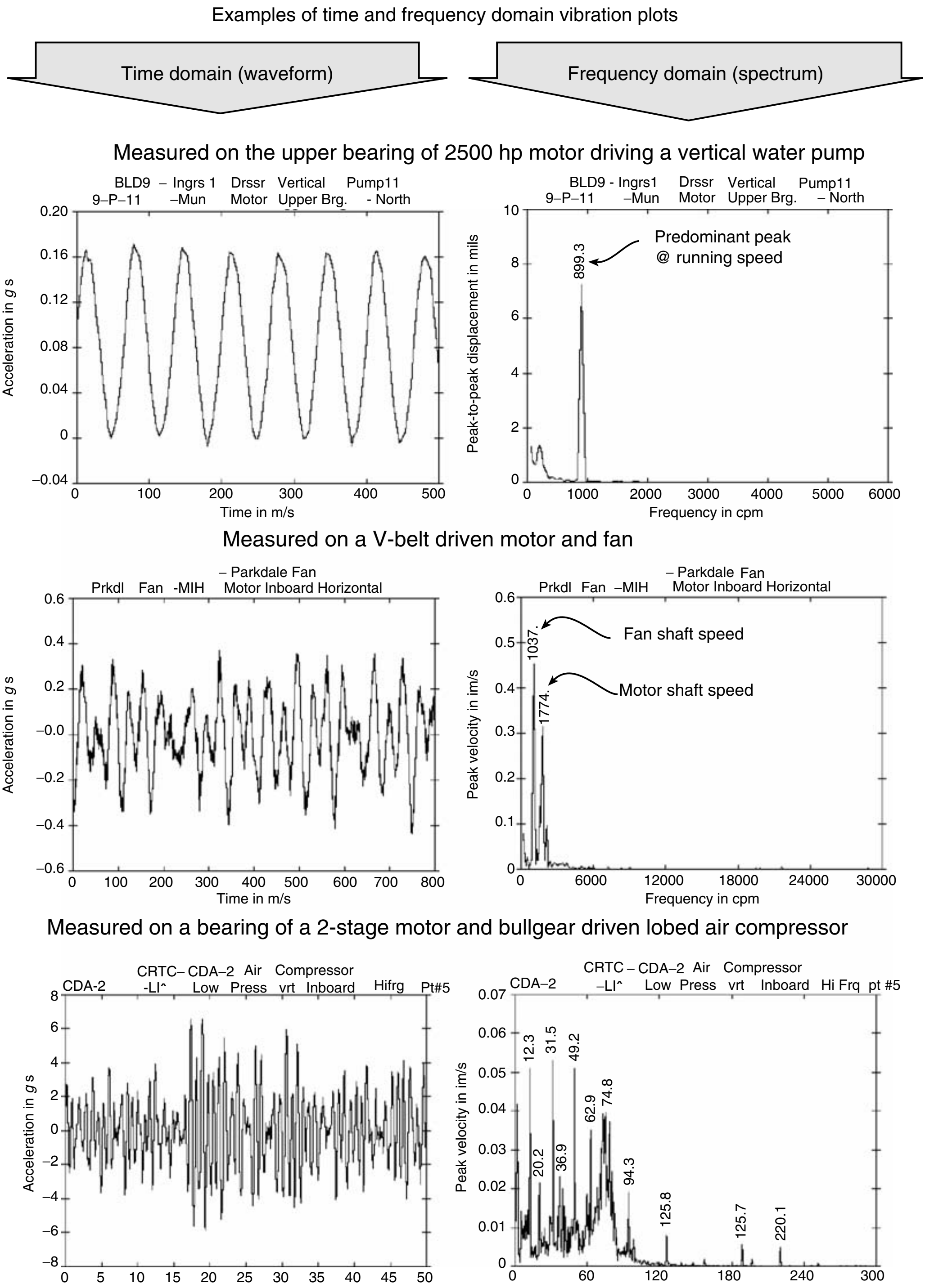


FIGURE 2.13 Actual time and frequency plots.

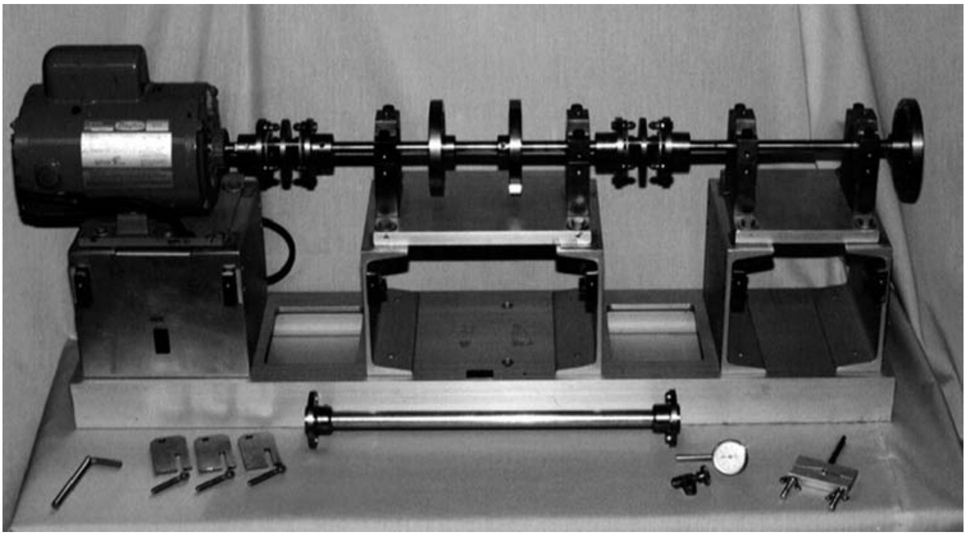


FIGURE 2.14 Training demonstrator used for misalignment vibration test.

about proportionally with the amount of misalignment. This verifies that elastic bending of the shafts does indeed occur similar to what was shown in Figure 1.3.

2.2.7 Vibration Results from a Controlled Misalignment Test on a Motor and Pump

Figure 2.16 shows a 60 hp, 1775 rpm motor and circulating water pump, connected by a metal ribbon-type coupling as shown in Figure 2.17 that was purposely misaligned by 21 and 36 mils sideways (laterally) and 55 and 65 mils vertically. A total of seven test runs were made under various alignment conditions. The vibration analysis equipment used for the test is shown in Figure 2.18. Vibration data was taken at five points on each unit using a hand-held vibration meter with an accelerometer sensor to record overall readings on the bearing housings. A seismometer with a magnetic base was also attached at each sensor location and the signals were fed into an analyzer and an X–Y plotter to record the vibration signature. As the motor housing was aluminum construction, ¼ in. thick carbon steel plates were epoxied to the motor in the horizontal and vertical planes at both bearings and another plate was attached on the inboard end bell to capture the axial vibration levels.

The reverse-indicator shaft alignment method was used to determine the relative shaft positions for all test runs. The nomenclature used to identify each run indicates the maximum amount of motor shaft deviation with respect to the pump shaft at the point of grid contact in the coupling. In Run #2 M2W, for instance, the maximum amount of shaft deviation occurred in the lateral (i.e., side-to-side) position of the shafts. The motor coupling hub contact point is 0.002 in. to the west of the contact point on the pump coupling hub and is so designated as M2W or Motor-2 mils-west.

Run #1 (Motor uncoupled and running solo). The first run was conducted with the motor uncoupled to determine whether the motor had an unbalance condition, damaged bearings, or some other problem that could affect the vibration response when coupled to the pump.

Run #2 M2W (Motor-2 mils-west). The pump and motor were initially aligned well within acceptable alignment tolerances.

Run #3 M21W (Motor-21 mils-west). The motor was positioned 0.021 in. to the west with no shims being added or removed from the pump or the motor from the second run.

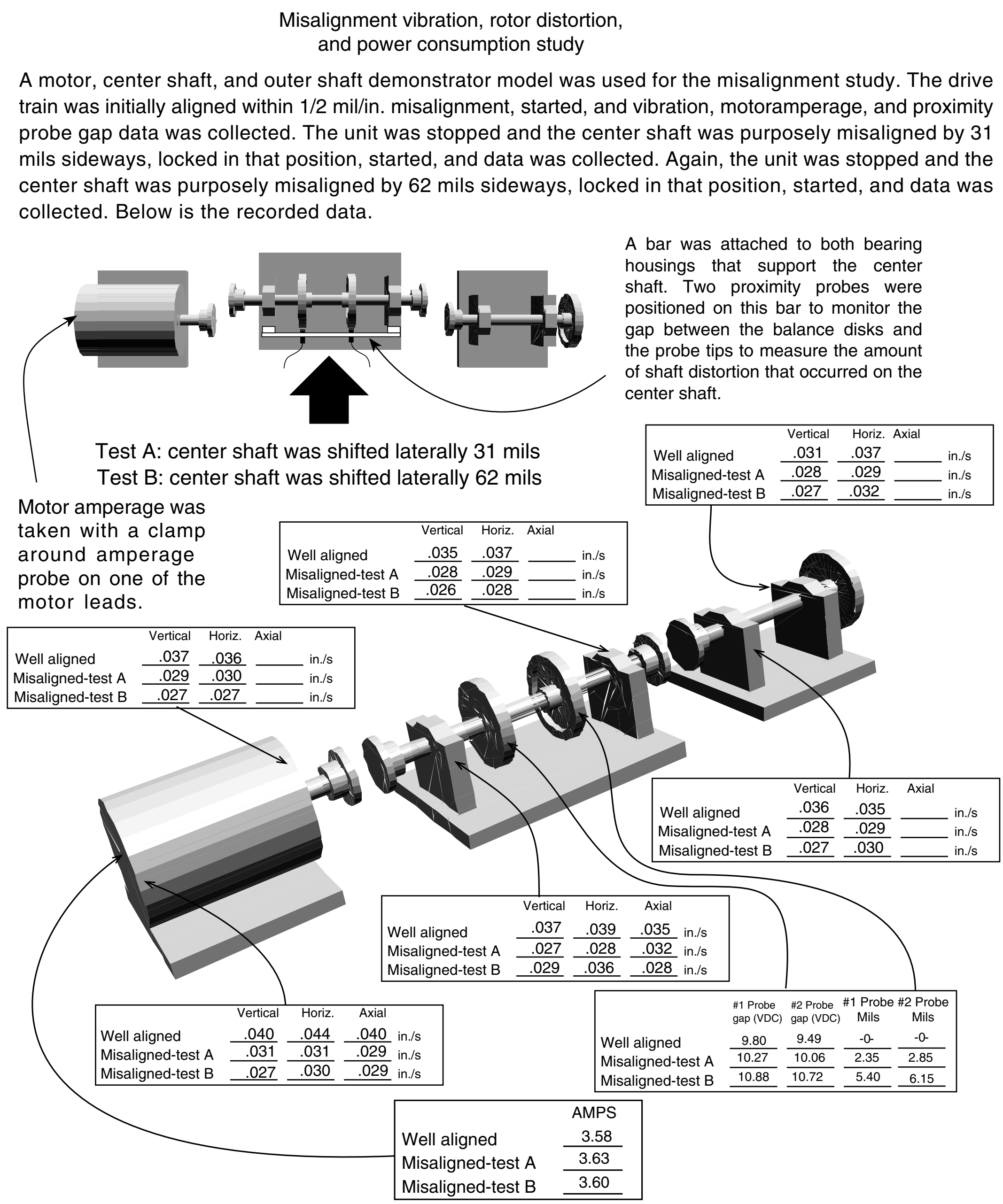


FIGURE 2.15 Results of misalignment vibration test on demonstrator.

Run #4 M36W (Motor-36 mils-west). The attempt was made in this run to slide the motor further to the west. The motor however became bolt bound and was unable to be moved any further sideways.

Run #5 M65H (Motor-65 mils-high). The motor is now positioned well from side to side, but is 0.065 in. higher than the pump shaft centerline.

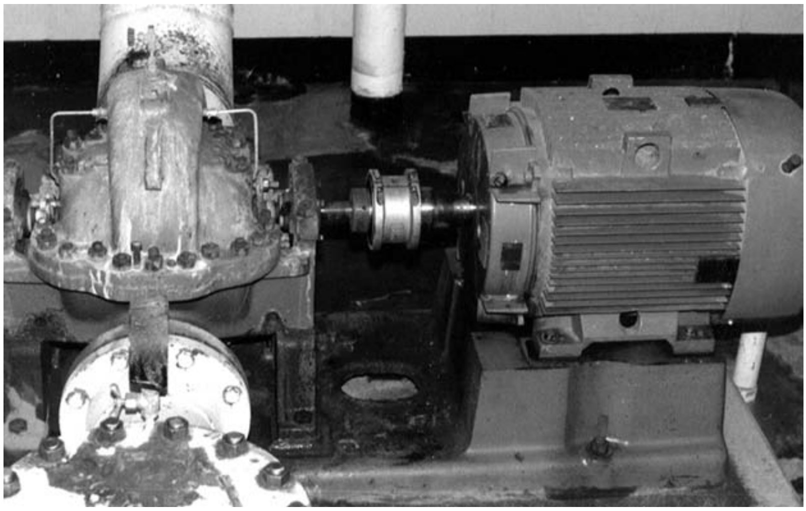


FIGURE 2.16 Pump and motor used for misalignment vibration test.

Run #6 M55L (Motor-55 mils-low). In this test run, the motor shaft centerline is set considerably below the pump shaft centerline while still maintaining good side-to-side alignment.

Run #7 M6W (Motor-6 mils-west). The pump and motor were again aligned well within acceptable alignment tolerances (similar to Run #2 M2W) to determine if the vibration response at the bearings would repeat.

FIGURE 2.17 Metal ribbon coupling connecting pump and motor shafts.

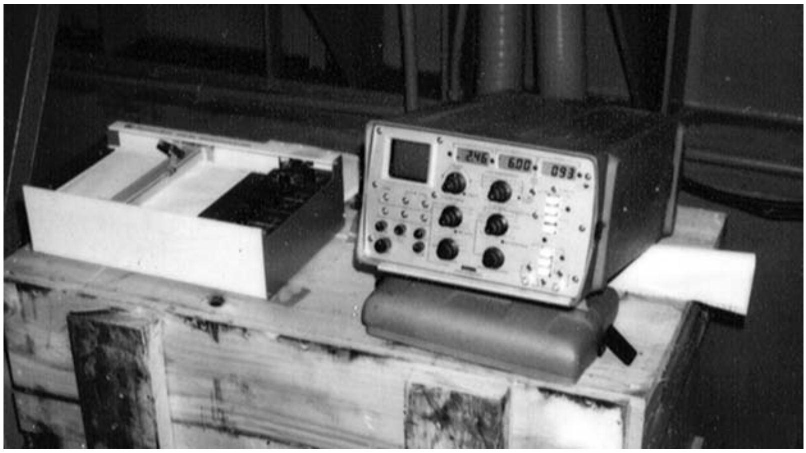


FIGURE 2.18 Vibration equipment used for the test.

The overall vibration results of the seven test runs are shown in Figure 2.19. Figure 2.20 through Figure 2.29 show the vibration spectral data collected at each measurement point during these induced misalignment conditions and were arranged to observe the vibration signature changes during each test run at each of the sensor locations on the motor and the pump.

Notice in every trend that the overall vibration only slightly increased, and in some cases, slightly decreased, as the equipment was misaligned by 21 and 36 mils. In some cases, when the equipment was at the greatest misalignment condition (65 mils), the vibration decreased from the levels seen at 55 mils.

Below are some observations and comments on the vibration data collected:

- The largest change in overall vibration levels occurred at the inboard bearings of both the pump and the motor.
- The axial vibration level on the motor attained its highest value when its shaft was higher (above) the pump shaft. Likewise the axial vibration level on the pump attained its highest value when its shaft was higher than the motor shaft.
- The highest horizontal amplitude readings on both the pump and the motor occurred when the motor shaft was low with respect to the pump shaft centerline (M55L) even though the amount of misalignment was not as severe as in the M65H case.
- The pump bearings increased in amplitude when the motor shaft was higher than the pump shaft (from Run #5 to Run #6) whereas the motor bearings decreased or stayed the same.
- The outboard bearing of the pump experienced a greater increase in overall vibration levels compared to the outboard bearing of the motor.
- The pump experienced a decrease in overall vibration levels on both bearings when the motor was misaligned laterally (notice Run #2 and Run #3).
- The horizontal and axial amplitude levels of the inboard pump bearing increased as the amount of the misalignment increased. The vertical levels however changed only slightly during all the different shaft configurations.
- The overall vibration levels on the pump and motor taken during Run #7 were, for the most part, the same as the levels taken during Run #2 where the alignment conditions

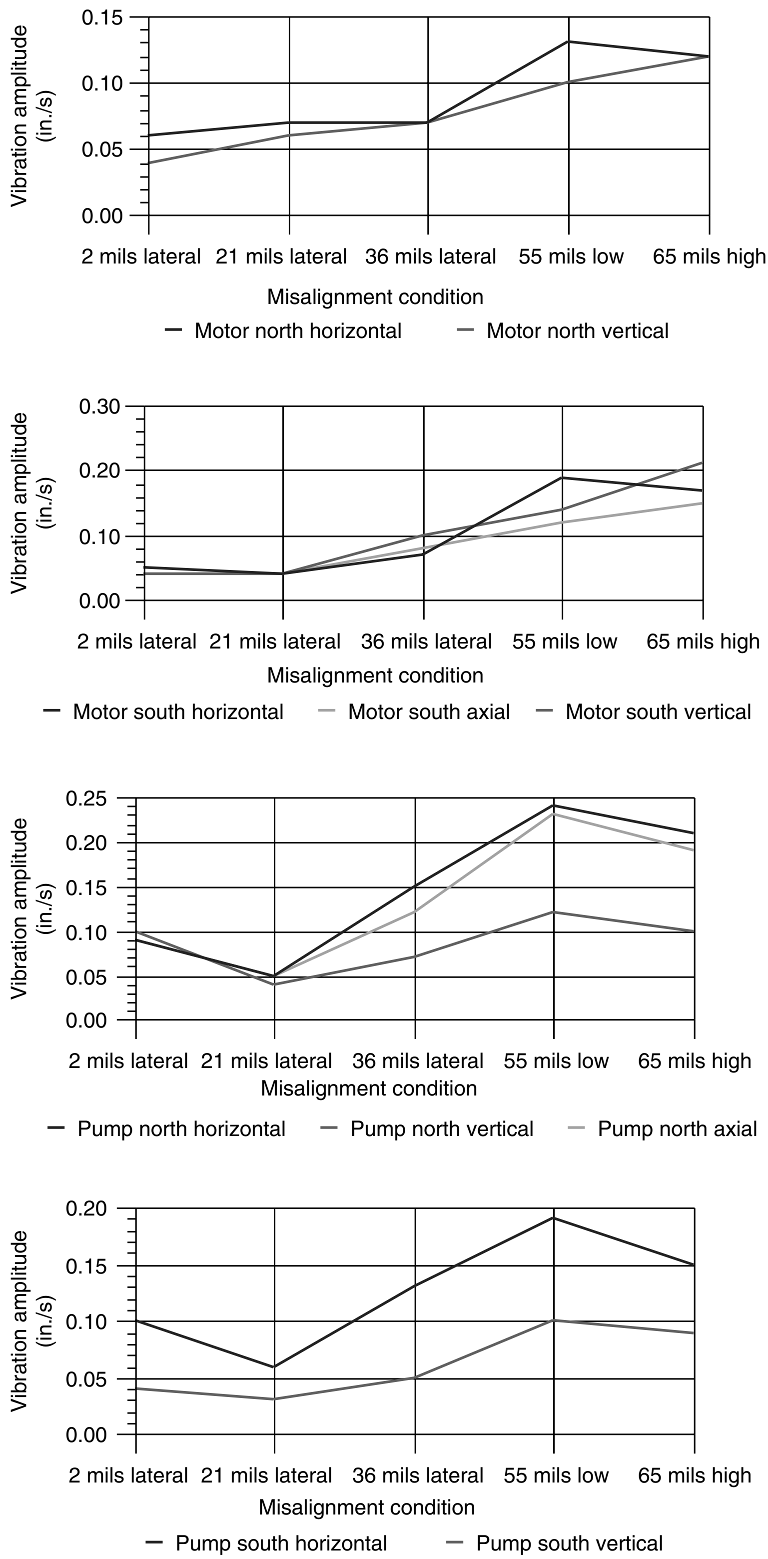


FIGURE 2.19 Overall vibration amplitude levels on bearing housings.