THE CAUSE AND ANALYSIS OF BEARING AND SHAFT FAILURES IN ELECTRIC MOTORS

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ABSTRACT

The author presented Parts 1 and 2 of "The Cause and Analysis of AC Induction Motor Failures," which was co-authored by George Soukup, at EASA's 1997 convention in Denver, Colorado. This new paper presents Parts 3 and 4 on bearing and shaft failures. Although the focus is on AC induction motors, much of the material also applies to other rotating equipment. As with Parts 1 and 2, its purpose is to provide EASA service centers with a methodology for identifying the root cause of bearing and shaft failures in electric motors.

INTRODUCTION

Bearing failures account for the majority (50% to 65%) of all motor failures in industrial applications [6]. In the past few years with the wide use of PWM inverter drives, motor bearing failures have increased. The root cause of these failures is shaft-to-ground currents passing through the bearings. Although shaft failures are not as common, when they do occur, the results can be quite destructive and dangerous.

PART THREE—BEARING FAILURES

BEARING STRESS

For convenience of analysis, it is useful to categorize the known stresses acting upon a bearing as follows:

1. Dynamic and static loading
2. Thermal
3. Vibration and shock
4. Environmental
5. Electrical current
6. Shear stress
7. Mechanical

It should be noted that as long as these stresses are kept within the design capabilities of the bearing system, premature failure should not occur. However, if any combination of them exceeds the bearing capacity, then the life may be drastically diminished and a catastrophic failure could occur.

BEARING FUNDAMENTALS

The prediction of rating fatigue life, commonly referred to as L10 life, is predicated on the assumption that the primary cause of failure is *material fatigue*. The L10 is the estimated time for 10% of a large population to fail. This relationship is shown in Figure 1. Life on this chart is relative to the load relationship. If L10 is one year, then L50 or the average life (as many have survived, as have failed) is 5 times that, or 5 years. This means that for an application with a L10 life of 1 year, 10% of the bearings may fail within that first year, and that one-half of the bearings may fail after 5 years.

The life for ball bearings is approximately inversely proportional to the load raised to the third power and inversely proportional to the speed. These relationships are only valid within certain constraints relating to the bearing size, design, lubrication, temperature, load and speed:

$$L10 = \frac{10^6}{60n}\left(\frac{C}{P}\right)^a$$

a = 3 for ball bearings   n = Speed (RPM)

$a = \frac{10}{3}$ for roller bearings

C = Bearing dynamic load rating

P = Equivalent bearing load

Each bearing has a limiting speed determined by its physical characteristics, which relates to the basic size, type, configuration and the type of lubrication used. Exceeding the bearing speed limit can result in excessive temperatures, deterioration of lubricant, vibration, and loss of the effective internal clearance, hence, a reduction in bearing life.

It should also be pointed out that grease-lubricated bearings normally have lower speed limits than oil-lubricated bearings, especially on larger motors.

The material and quality of the bearing cage will also affect the speed limitation of the bearing. Improved bearing geometry will allow for increased speed and lower noise levels.

Figures 2 and 3 provide free-body diagrams of the bearing loading typically seen on horizontal and vertical motors.

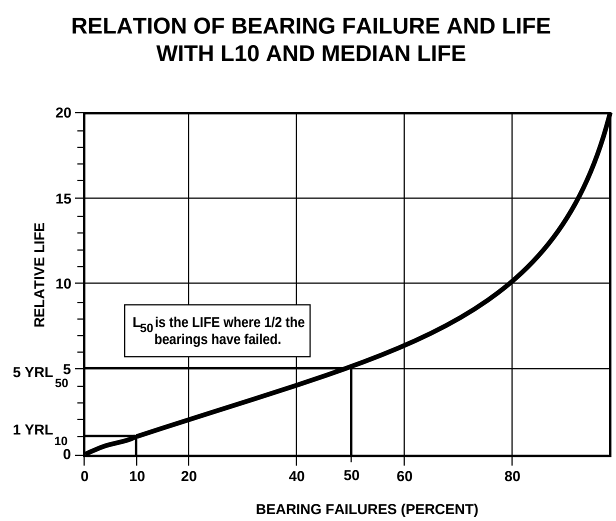

Figure 1

HORIZONTAL BEARING LOADING PRINCIPLES (ANTI-FRICTION)

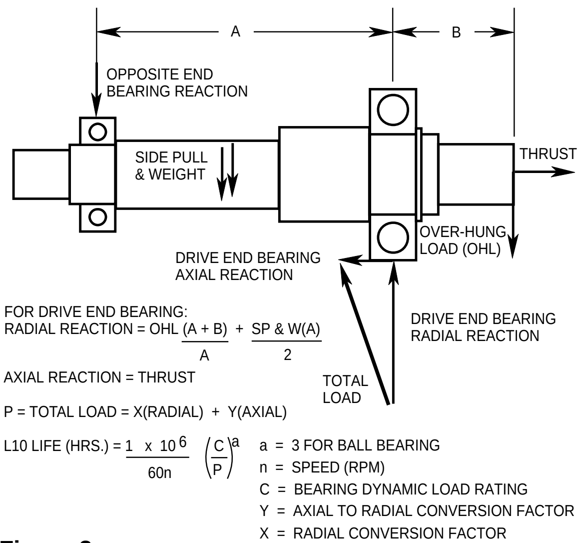

Figure 2

VERTICAL BEARING LOADING PRINCIPLES (ANTI-FRICTION)

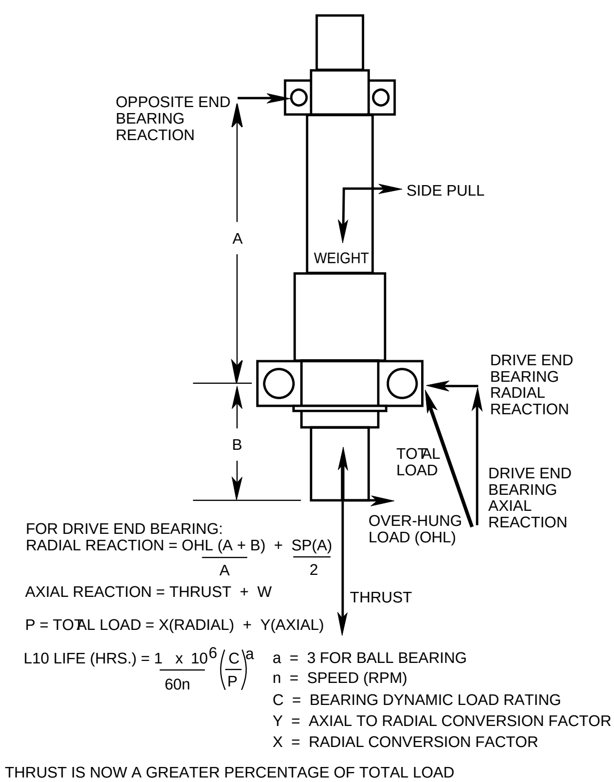

Figure 3

STEPS IN THE BEARING FATIGUE PROCESS

1. Microscopic subsurface fractures of metal due to cyclic loading stress produce thin layers of surface, which flake off and are the beginning of spalling.
2. Some increase in noise and vibration will occur.
3. A change in critical dimensions will start.
4. Noise, vibration, friction, heat and wear accompanied by more advanced spalling; it is no longer safe or prudent to operate the machine.
5. The final step is advanced spalling, usually followed by a catastrophic failure.

THERMAL LIMITS

For anti-friction bearings, normally used in electric motors, the bearing operating temperature should not normally exceed 100° C, assuming that the bearing is properly applied and lubricated. Exceeding this limit can result in a permanent change in the bearing size due to metallurgical changes of the steel and thermal expansion. Both of these conditions can cause loss or reduction of the radial internal clearances, which can generate excessive temperatures and reduced life. At excessive temperatures, hastened by rapid oxidation of the lubricant, softening of the steel will lower the bearing fatigue limit and shorten the bearing life.

BEARING TEMPERATURE

Factors that influence the bearing temperature include:

1. Winding temperature
2. Lubricant temperature
3. Motor thermal circuit (cooling path and method)
4. Oil and grease viscosity
5. Bearing seals, shields and lubricant type
6. The amount of grease in the bearing and cavity
7. Radial internal clearance
8. Ambient conditions, including contamination
9. Bearing load and speed
10. Bearing type and size

LUBRICATION OF ANTI-FRICTION BEARINGS

Proper lubrication of anti-friction bearings is critical for their successful performance. The major functions of the lubricant includes:

1. Providing a lubricant film for the various sliding and rolling contacts existing between the bearing elements.
2. Protecting the surface finish of the raceways and rolling elements from corrosion and rust.
3. Sealing the bearing from foreign materials.
4. Assisting in heat dissipation out of the bearing elements.

Grease lubrication is the method most commonly used on small and medium size electric motors in the range of 1 to 500 HP for horizontal machines. Sleeve bearings may be used in larger horsepower or 2 pole or high-speed applications. Vertical pump motors start to use oil-lubricated bearings at about 50 HP. Neither application is covered in this article. The lubricant used for grease applications is usually a mixture of oil impregnated into a soap base. The soap base keeps the oil in suspension until it is removed by the moving members of the bearing and adheres to the surfaces. It is obvious that the supply of oil is depleted with time, as it gradually

Place in Section 9 of your *EASA Technical Manual*; note its location in Section 15, "Future Tech Notes."

breaks down by oxidation. This process is a function of time, temperature, speed, load and environment.

Selection of the proper grease and its re-lubrication practices are critical for optimum bearing life.

Greases are usually made of a combination of soap or non-soap thickening materials mixed with mineral oil and additives. Soaps such as sodium, calcium, aluminum, lithium and barium are most commonly used. Polyurea is a synthetic organic thickener that has been widely used for electric motor bearings due to its elevated temperature properties. Polyurea is usually suitable for operating at temperatures in excess of 120° C, assuming the bearing material and clearance are sized properly. Rust and oxidation inhibitors and tackiness additives are included to enhance performance.

Present research is making it possible to predict bearing life more accurately. The use of Elasto Hydrodynamic Lubrication theory (EHL), introduced in the 1960s for calculating film thickness and pressure profiles, has been the key to many investigations and the base for understanding failure modes. Since the early 1970s, lubrication and film thickness have been recognized as a significant factor in the life equations. The AFBMA Standard 9/ANSI B3.15 and IS0 281 standards were modified in 1972 and 1977, respectively, to include this effect by the addition of the a_2(material) and a_3(operating conditions) life adjustment factors [7]. Typical factors that have been used are shown in Figure 4. The latest efforts have been in the area of particle contamination and lubricant cleanliness. These new studies are tending to reshape the life prediction equations. According to one bearing manufacturer [8], the true nature of the failure mode mechanism was hidden and not understood until recently for the following reasons:

1. The high loads used to accelerate testing resulted in insufficient time for wear to manifest itself.
2. Surface initiated cracks from particle indentation that penetrated into deeper areas of high stress and culminate in flaking could not be distinguished from flaking caused by cracks formed below the surface.

Based on these latest studies [9], bearing life theory has been further refined to use a family of curves to establish an adjustment factor to the unmodified life. Of primary importance is the "n" factor used to correct for contamination. An accurate assessment of the "n" factor requires an analysis on a computer with accurate knowledge of the application. Figure 5 is typical of the curves used to determine the life adjustment factor for contamination. These refinements along with similar actions taken by other manufacturers commonly lead to a more precise determination of bearing life.

In addition to new life prediction theories, new lubricants and lubrication methods are being devised which will extend the operating life. Synthetic greases are capable of extending grease life significantly as indicated by the oxidation characteristics depicted in Figure 6. Although grease life is a function of more than just oxidation life, it is a good indicator of the type of gain that can be made using synthetic grease. Synthetic greases can be formulated with a lower sensitivity to temperature variations and therefore have a larger useful temperature range and the potential for lower losses.

LIFE ADJUSTMENT FACTOR VS. VISCOSITY RATIO

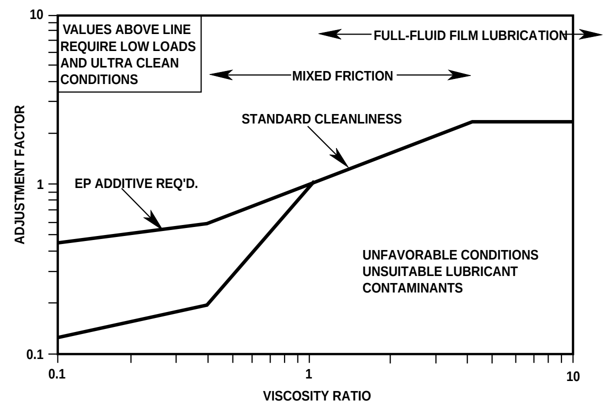

Figure 4

LIFE ADJUSTMENT FACTOR VS. CONTAMINATION LOAD FACTOR BASED ON A SKF FACTOR

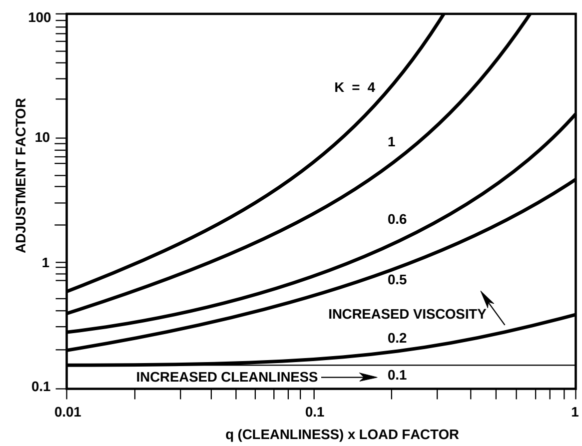

Figure 5

GREASE TEMPERATURE PROPERTIES TEMPERATURE VS. OXIDATION LIFE

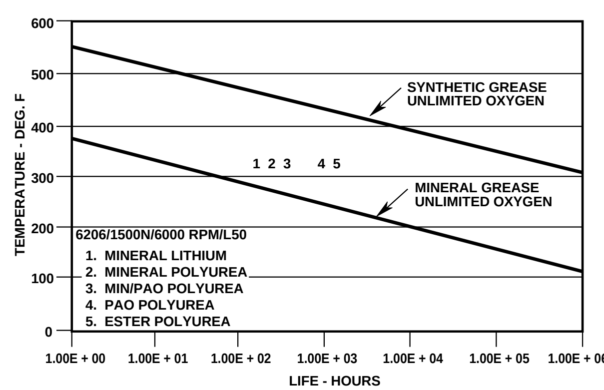

Figure 6

The question frequently asked about greases deals with the compatibility of them if mixed during the relubrication process. Table 1 is a guideline to assist in this process. If in doubt, do not mix without checking with the lubricant manufacturer.

TABLE 1. RESULTS OF GREASE INCOMPATIBILITY STUDY

	Aluminum Complex	Barium	Calcium	Calcium 12-hydroxy	Calcium Complex	Clay	Lithium	Lithium 12-hydroxy	Lithium Complex	Polyurea
Aluminum Complex	X	I	I	C	I	I	I	I	C	I
Barium	I	X	I	C	I	I	I	I	I	I
Calcium	I	I	X	C	I	C	C	B	C	I
Calcium 12-hydroxy	C	C	C	X	B	C	C	C	C	I
Calcium Complex	I	I	I	B	X	I	I	I	C	C
Clay	I	I	C	C	I	X	I	I	I	I
Lithium	I	I	C	C	I	I	X	C	C	I
Lithium 12-hydroxy	I	I	B	C	I	I	C	X	C	I
Lithium Complex	C	I	C	C	C	I	C	C	X	I
Polyurea	I	I	I	I	C	I	I	I	I	X

B = Borderline incompatibility C = Compatible
I = Incompatible

MOTOR BEARING LUBRICATION PRECAUTIONS

1. All motor housings, shafts, seals and relubrication paths must be kept thoroughly clean throughout the motor's life.
2. Avoid any dirt, moisture, chips or foreign matter contaminating the grease.
3. Identify the temperature range for the application and select a grease that will perform satisfactorily.
4. Over greasing may cause elevated bearing and/or winding temperatures, which can lead to premature failures. Be sure to properly purge excess grease.
5. When regreasing, be sure that the new grease is compatible with the existing grease and that it has the desired performance characteristics.
6. Be aware that synthetic grease may not be as suitable as petroleum greases in high-speed applications. Some applications may require an extreme pressure (EP) grease.
7. Be aware that some common greases are not desirable for motor applications. If they are too soft, whipping can occur. If too stiff, noise and poor bleeding characteristics can occur.

CAUSE OF FAILURE

The most common causes of bearing failures are:

1. Thermal overloads
2. Inadequate or excessive lubrication
3. Contamination
4. Excessive loading (axial/radial combined)
5. Vibration
6. Misalignment
7. Improper shaft and housing fits
8. Machinery defects
9. Shaft-to-ground currents
10. Incorrect handling or mounting
11. Load life and fatigue factors
12. Improper application
13. Damaged during transportation or storage

The challenge is to learn how to identify each type of failure with a high level of certainty and repeatability.

METHODOLOGY OF ANALYSIS

Five key areas that should be considered and related to one another in order to accurately diagnose the root cause of bearing failures are:

1. Failure mode
2. Failure pattern
3. Appearance
4. Application
5. Maintenance history

Brief discussions of each of these areas follow.

FAILURE MODE

The failure modes can be grouped into the following 12 categories which are usually the result of the combined stresses acting on the bearing to the point of damage or failure. This is arbitrarily referred to as the failure mode.

1. Fatigue spalling, flaking
2. Fretting
3. Smearing
4. Skidding
5. Scoring
6. Abrasive, abnormal wear
7. Corrosion
8. Lubrication failure
9. True or false brinelling
10. Electric pitting or fluting
11. Cracks
12. Seizures

These modes do not represent the cause of the bearing problem; instead, they are the result or way that the problem is manifested. This is arbitrarily referred to as the failure mode.

BEARING FAILURE PATTERNS

Each bearing failure has a certain pattern that is closely associated with, yet different from, the failure mode. These patterns can be grouped into some combination of these categories:

1. Temperature levels (discoloration)

2. Noise levels
3. Vibration levels
4. Lubrication quality
5. Condition of mounting fits
6. Internal clearances
7. Contamination
8. Mechanical or electrical damage
9. Load paths and patterns (alignment)

APPEARANCE OF MOTOR AND BEARING

When coupled with the mode and pattern of failure, the motor bearing and load appearance usually give a clue as to the possible cause of failure. The following checklist will be useful in the evaluation:

1. Are there signs of contamination in the area of the bearings? Any recent welding?
2. Are there signs of excessive temperature anywhere in the motor or driven equipment?
3. What is the quality of the bearing lubricant?
4. Are there signs of moisture or rust?
5. What is the condition of the coupling device used to connect the motor and the load?
6. What levels of noise or vibration were present prior to failure?
7. Are there any missing parts on the rotating member?
8. What is the condition of the bearing bore, shaft journal, seals, shaft extension and bearing cap?
9. What was the direction of rotation, overhung load and axial thrust? Are they supported by the bearing wear patterns?
10. Does the outer or inner face show signs of fretting?
11. Is the motor mounted, aligned and coupled correctly?

Do not destroy the failed bearing until it has been properly inspected. It is also important to save a sample of the bearing lubricant.

APPLICATION DATA

It usually is difficult to reconstruct the actual operating conditions at the time of failure. However, knowledge of the general operating conditions will be helpful. The following items should be considered:

1. What are the load characteristics of the driven equipment and the loading at time of failure?
2. Does the load cycle or pulsate?
3. How many other units are successfully operating?
4. How often is the unit started?
5. What type of bearing protection is provided?
6. Where is the unit located and what are the normal environmental conditions?
7. Is the motor enclosure adequate for the application?
8. What were the environmental conditions at time of failure?
9. Is the mounting base correct for proper support to the motor?
10. Is the belting or method of connection to the load correct for the application?

MAINTENANCE HISTORY

An understanding of the past performance of the motor can give a good indication as to the cause of the problem. Again, a checklist may be helpful.

1. How long has the motor been in service?
2. Have any other motor failures been recorded, and what was the nature of the failures?
3. What failures of the driven equipment have occurred? Was any welding done?
4. When was the last time any service or maintenance was performed?
5. What operating levels (temperature, vibration, noise, etc.) were observed prior to the failure? What tripped the motor off the line?
6. What comments were received from the equipment operator regarding the failure or past failures?
7. How long was the unit in storage or sitting idle prior to starting?
8. What were the storage conditions?
9. How often is the unit started? Were there shutdowns?
10. Were correct lubrication procedures utilized?
11. Have there been any changes made to surrounding equipment?
12. What procedures were used in adjusting belt tensions?
13. Are the pulleys positioned on the shaft correctly and as close to the motor bearing as possible?

SUMMARY AND CONCLUSIONS

There are numerous ways to go about failure analysis. The procedure proposed is a simple one that can be easily taught and communicated to employees with a wide range of skills and backgrounds. This type of analysis will usually lead to the quick elimination of those factors that are not contributing to the failure. When the problem is reduced to the one or two most likely culprits, thoughtful analysis will usually lead to the correct conclusion. It is not one's brilliance that leads to the truth; instead, it is the ability to sort that which is important from among all of the unrelated data available.

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[6] O.V. Thorsen and M. Dalva, “A Survey of Faults on Induction Motors. . . ,” IEEE Transaction on Industrial Applications, Vol. 31, No. 5, September/October, 1995.

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APPENDIX I: BEARING PROTECTION

Increased bearing operating temperatures, vibration or noise levels are possible indicators of impending problems or failure. It may be desirable to measure these variables on a routine or continuous basis. If the equipment is part of the motor, it may have gages, meters, alarms or shutdown features.

The following is a brief discussion of the methods commonly used to provide this protection.

BEARING TEMPERATURE PROTECTION

As a general guide, temperature limits for bearings are shown in Table 2.

TABLE 2

	LUBRICANTS	
	STANDARD	**SYNTHETIC**
Normal	80° C (176° F) or lower	110° C (230° F)
Alarm	90° C (194° F)	120° C (248° F)
Shutdown	100° C (212° F)	130° C (266° F)

Specific applications may require slightly different limits. For most applications, actual temperatures will usually be lower than those above. For maximum protection, the user should determine the “normal” bearing operating temperature for the application and adjust the “alarm” setpoint 10° C higher. (Do not exceed the “critical” temperature indicated above, except in extreme emergency).

The detectors are normally mounted with the temperature-sensitive probe in contact with the bearing outer race for grease or oil-lubed bearings. Where capillary bulb detectors are used, the bulb is placed in oil in contact with or close proximity to the bearing race. The probe is in contact with the bearing shell for Kingbury plate and sleeve bearings.

Selection of a particular type of equipment for indicating and monitoring the temperature of bearings depends upon the function the device is to perform. Table 3 summarizes some of the most commonly used devices.

TABLE 3

DETECTOR TYPE	ALARM	SHUTDOWN	TEMP. READING	OPERATE AUX. EQUIPMENT
Switch	Yes	Yes (1)	No	Yes
Indicator & Switch	Yes	Yes (1)	Yes	Yes
Thermometer	No	No	Yes	No
RTD	Yes (2)	Yes (2,1)	Yes (2)	Yes (2)
Thermocouple	Yes (2)	Yes (1, 2)	Yes (2)	Yes (2)
Thermistor	Yes	Yes (1)	Yes (2)	Yes (2)

(1) Requires connection to motor control relay.
(2) Requires auxiliary controller not normally supplied with motor.

MOTOR VIBRATION

The vibration limits for electric motors are usually expressed in displacement or velocity levels, and on some occasions acceleration levels are used. Figure 7 indicates the levels established by NEMA MG 1, Part 7, for new machines unloaded.

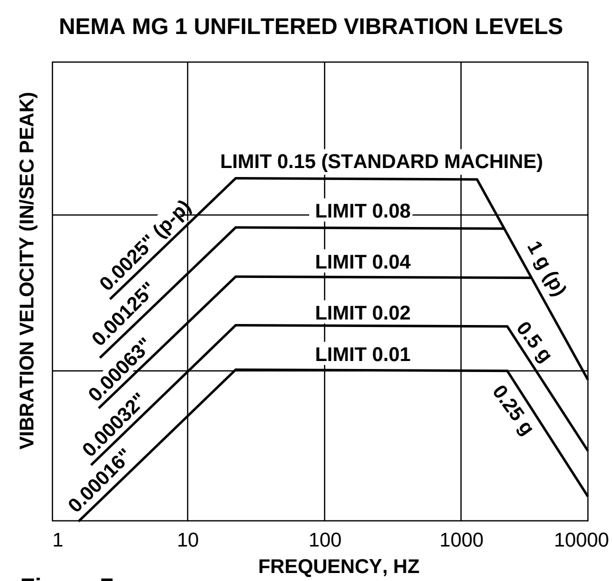


Figure 7

Numerous devices are available to measure vibration levels (either mechanically or electronically), some of which have shutdown capabilities. The size, application and location are factors in determining the best approach to monitor and protect the motor.

The mechanical vibration for medium horsepower alternating current and direct current machines built in a 143 and larger frame, when measured in accordance with MG1-12.06, shall not exceed a peak vibration velocity of 0.15 inches per second.

NOISE AND FAULT ANALYSIS

There are methods of analyzing acoustic emissions of ultra-high frequency bearing noise that may not be audible to the human ear. These methods generally measure bearing damage to the balls and raceways, such as spalling and pitting. They are usually employed as part of a predictive maintenance program. Some of the keys to success with these methods are proper selection of the time intervals between testing, location and measurement methods. Properly done, these methods can detect a flaw before any detectable change in vibration or temperature occurs.

There are several other methods available for bearing fault detection, such as acoustic emission, stress wave energy, fiber optics, outer race deflection, spectrum analysis, and lube oil analysis. Some of them can, if done properly, detect faults at very early stages. For more detailed information, see citation 10 in the Reference section.

UNUSUAL FAILURES

SHAFT CURRENTS

During the past few years, a significant increase in problems associated with shaft voltages and currents has been observed. In many cases, these currents have caused bearing failures, which are identified as fluting or pitting type failures. There are at least three known causes for the phenomena:

1. Electromagnetic dissymmetry, which is usually inherent in the design and manufacture of the motor.
2. Electrostatic charges (associated with friction) accumulated on the rotor assembly. Also, shaft couplings and air passage are known causes.
3. Electrostatic coupling caused by extreme power supplies such as PWM inverters.

Other abnormalities in sinewave power supply associated with grounding, unbalances, harmonic content and high common mode voltages may also result in induced shaft voltages.

In the case of motors used in conjunction with PWM inverters, it is theorized that the terminal motor voltage supplied by the drive is not balanced or symmetrical in some aspect.

Another possible source of this problem is electrostatic coupling, which induces a voltage into the shaft large enough to cause currents that damage the bearings. The high dv/dt's associated with the GTO and IGBT transistors are the major source of this problem. The amount of load, rotor speed, method of coupling and type of bearing lubricant can each aggravate the situation. In some cases, insulated bearings may not solve this type of problem.

Regardless of the cause of the induced shaft voltage, if its value exceeds .3 to .5 V_{RMS} sinewave, it may produce currents large enough to permanently damage the bearings. This problem has heretofore been limited to larger motors, usually 500 frame and up (where the stator outside lamination diameters exceeds 20"). In most cases, the current passes through both bearings. This condition can be corrected by insulating the outboard bearing on horizontal motors or top bearing on vertical motors.

This approach is usually not practical on smaller size motors, where it is now starting to appear when a PWM inverter with IBGTs is used.

Figure 22 shows a typical bearing when fluting has occurred. Depending upon the amount of running time on the bearing, the raceways may show signs of straight frosting all the way to spalling. Appendix II provides a more detailed summary of the various methods used to eliminate bearing currents.

APPENDIX II: METHODS OF REDUCING BEARING CURRENTS IN MOTORS OPERATED ON PWM DRIVES

An estimated 25 percent of all bearing failures on PWM applications are dv/dt- and carrier-frequency related, according to Dr. Tom Lipo of the University of Wisconsin. The following briefly summarizes the various methods that are being used or investigated to reduce or eliminate damaging bearing currents on AC industrial motors operated on low-voltage PWM drivers:

1. **Insulate shaft bearing journals**
   One or both ends; very effective on larger motors above 200 HP.
2. **Insulate bracket bore to bearing O.D. fit**
   One or both ends; use on vertical and horizontal motors; not as durable as shaft insulation at journal.
3. **Use bearing with insulated I.D. or O.D**
   Long lead time; not always available.
4. **Insulated balls or lubricants**
   In experimental stage only.
5. **Grounding brush between shaft and ground**
   Subject to contamination problems and expensive, but it does work in many cases.
6. **Clean up the VFD output waveform**
   Best overall solution and could include single output reactors, limit filters, or motor terminators; can be expensive.
7. **Reduce drive switching frequency to less than 5kHz**
   Will cause some noise and loss of efficiency.
8. **Reduce or eliminate common-mode voltage**
   Under investigation; can be done by use of filters and reactors.
9. **Improve grounding techniques**
   a. Proper cable selection.
   b. Optimize grounding location; eliminate floating grounds.
   c. Proper cable termination—use of current connectors.
10. **Other options**
   a. Resonant link, zero switching in development stage; high cost.
   b. Switched reluctance driver with slower waveforms; not yet ready.
   c. Mechanical driver or gear; a step backward!
   d. Faraday shields in prototype stage.

The motor manufacturers have done a good job of addressing the increased insulation stress on the winding and also offer insulated bearings on larger motors. However, there is no single, clear-cut solution that is economically feasible for 1-200 HP motors. When asked for recommended solutions on their smaller motors, the first choice is usually output filters at the drive; this seems to give the best results to date.

REFERENCE LIBRARY

One of the best methods to assist in the analysis of bearing failures is to develop a reference library of pictures of known causes of bearing failures. The following is a sample of some of the more typical types of failure.

Fatigue Failures
1. Incipient
2. Advance
3. Extreme

Misalignment
1. Load paths
2. Out-of-round
3. Skewed paths
4. Edge loading
5. Smearing

Defective Fits/Seats
1. Loss of internal clearance
2. Loose fits
3. Skidding
4. Creep
5. Fretting corrosion

Contamination
1. Chips in raceway
2. Damaged/faulty seals
3. Abrasion

Mechanical
1. Mounting
2. Parasite thrust
3. False brinelling
4. True brinelling
5. Fluting from rotational vibration

Excessive Temperature

Improper Lubrication

Overspeeding

Shaft Currents
1. Pitting
2. Fluting
3. Welding

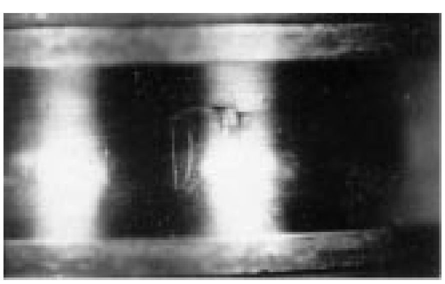
The following section provides pictures of some of the more common bearing failures listed above.

DEFECTIVE FITS/SEATS

Fretting corrosion caused by loose fit & vibration

Figure 8

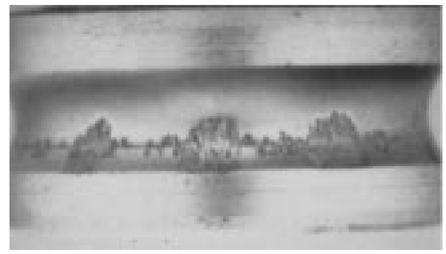
FATIGUE



Early stage of spalling caused by excessive preload.

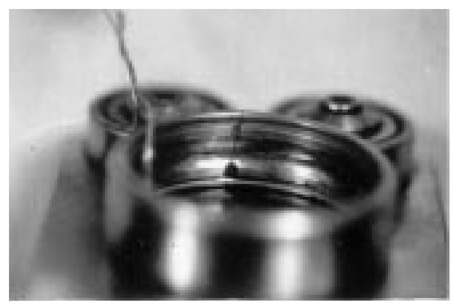
Figure 9

FATIGUE (CON'T.)



Advanced stages of spalling.

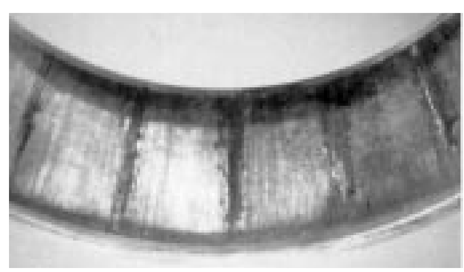
Figures 10 and 11



Fatigue fracture of outer ring caused by burrs in the housing bore.

Figure 12

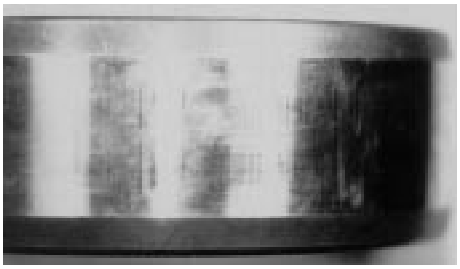
MECHANICAL



False brinelling and fretting caused by vibration in a non-operating condition.

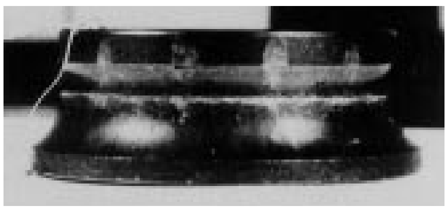
Figure 13

MECHANICAL—Continued



False brinelling and fretting caused by vibration in a non-operating condition.

Figure 14



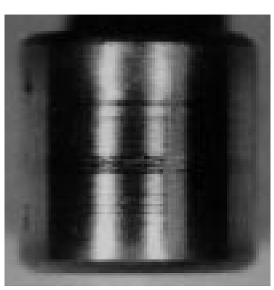
Thrust on low shoulder of angular contact bearing caused by improper installation.

Figure 15

Excessive thrust on a spherical roller bearing.

Figure 16

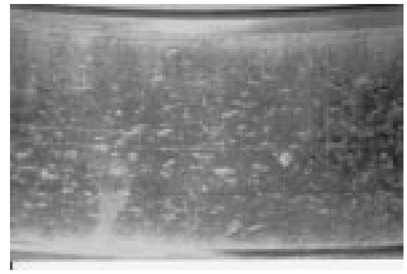
CONTAMINATION



Smear marks on roller caused by debris.

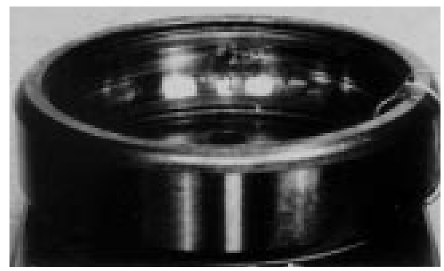
Figure 17

CONTAMINATION—Continued



Metallic contamination in raceway.

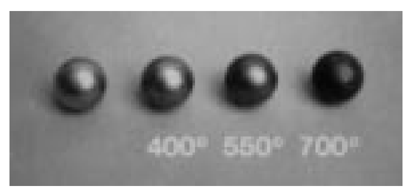
Figure 18



Damaged caused by water intrusion.

Figure 19

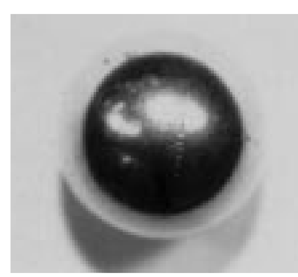
TEMPERATURE



Color variation due to excess temperature.

Figure 20

SHAFT CURRENTS



Pitting caused by electrical currents.

Figure 21

SHAFT CURRENTS—Continued

Fluting caused by internally generated current.

Figure 22

PART FOUR—SHAFT FAILURES*

THE CAUSE AND ANALYSIS OF SHAFT STRESS

The majority of all shaft failures are caused by a combination of various stresses that act upon the rotor assembly. As long as they are kept within the intended design and application limits, shaft failures should not occur during the expected life of the motor. These stresses can grouped as follows:

- **Mechanical**
  - Overhung load and bending
  - Torsional load
  - Axial load
- **Dynamic**
  - Cyclic
  - Shock
- **Residual**
  - Manufacturing processes
  - Repair processes
- **Thermal**
  - Temperature gradients
  - Rotor bowing
- **Environmental**
  - Corrosion
  - Moisture
  - Erosion
  - Wear
  - Cavitation
- **Electromagnetic**
  - Side loading
  - Out of phase reclosing

STRESS SYSTEMS ACTING ON SHAFTS

Before the causes of shaft failures can accurately be determined, it is necessary to clearly understand the loading and stress acting on the shaft. These stresses can best be illustrated by the use of simple free-body diagrams.

Figure 1 is taken from the *Metals Handbook*, Volume 10 [1], and illustrates how tension, compression and torsion act on the shaft for both ductile and brittle materials. In the case of motor shafts, the most common materials can be classified as ductile. It should be pointed out that failures caused by bending can be treated as a combination of tension and compression when the convex side is in tension and the concave side is in compression.

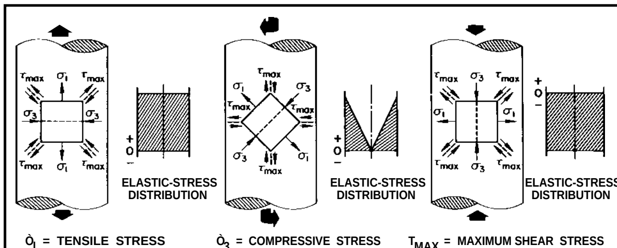


Figure 1. Free-body diagrams showing orientation of normal stresses and shear stresses in a shaft under simple tension, torsion and compression loading.

THE TOOLS OF SHAFT FAILURE ANALYSIS [1] [3] [4]

The ability to properly characterize the microstructure and the surface topology of a failed shaft are critical steps in analyzing failures. The most common tools available to do this can be categorized as follows:

- Visual
- Optical microscope
- Scanning electron microscope
- Transmission electron microscope
- Metallurgical analysis

The material presented in this paper assumes that it may be necessary to employ the services of a skilled metallurgical laboratory to obtain some of the required information. However, experience shows that a significant number of failures can be diagnosed with a fundamental knowledge of motor shaft failure causes and visual inspection. This may

* Numbering of figures, references, and tables in Part 4 begin again with Number 1.

then lead to seeking confirmation through a metallurgical laboratory. Regardless of who does the analysis, the material presented here will help lead to an accurate assessment of the root-cause and failure.

FAILURE ANALYSIS SEQUENCE

There is no specific sequence for determining the cause of failure. The order of steps may depend on the type of failure. However, the following may be a useful guideline [4]:

1. Describe failure situation
2. Visual examination
3. Stress analysis
4. Chemical analysis
5. Fractography
6. Metallographic examination
7. Material properties
8. Failure simulation

METHODOLOGY FOR ANALYSIS

To be consistent with the previous papers on stator, rotor and bearing failures [10] [11], and in combination with the above sequence, it is proposed that the analysis of shaft failures contain at least the following elements:

- Failure mode
- Failure pattern of shaft
- Appearance of machine
- Application
- Maintenance history

CAUSES OF FAILURE

Studies have been conducted to try to quantify the causes of shaft failures. One industry study [2] provided the results for rotating machines shown in Table 1.

TABLE 1

CAUSE OF SHAFT FAILURES	PERCENT
Corrosion	29%
Fatigue	25%
Brittle Fracture	16%
Overload	11%
High-Temperature Corrosion	7%
Stress Corrosion Fatigue/Hydrogen Embrittlement	6%
Creep	3%
Wear, Abrasion, and Erosion	3%

Source: Adapted Brooks and Choudhury [2].

Other informal studies [6] [8] suggest that the majority of all shaft failures are fatigue related (in the 80 - 90% range). For motor applications, it is at least the majority of all shaft failures. The number climbs into the 90% range when the result of corrosion and new stress raisers are added. Hence, the main focus of this paper is on failure associated with fatigue.

Figures 2 and 3 show typical free-body diagrams for typical motor shaft loading.

TYPICAL MOTOR SHAFT LOADING [11]

HORIZONTAL BEARING LOADING PRINCIPLES (ANTI-FRICTION)

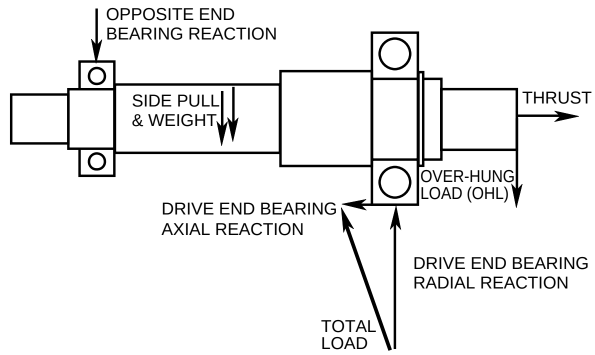


Figure 2

VERTICAL BEARING LOADING PRINCIPLES (ANTI-FRICTION)

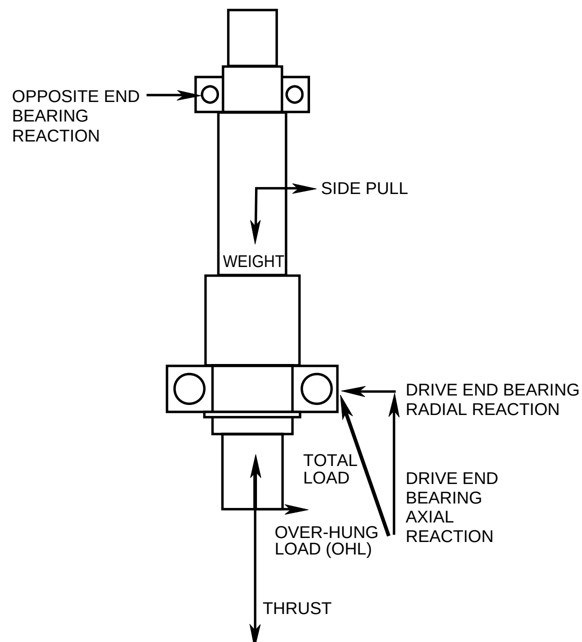
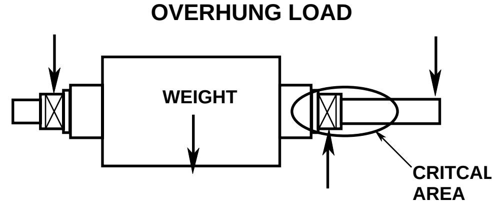


Figure 3

The following three cases (Figures 4, 5, and 6) provide the most common types of motor shaft loading that can lead to fatigue types of failures.

OVERHUNG LOAD



Failure Mode: Bending Fatigue & Shaft Rub

Figure 4

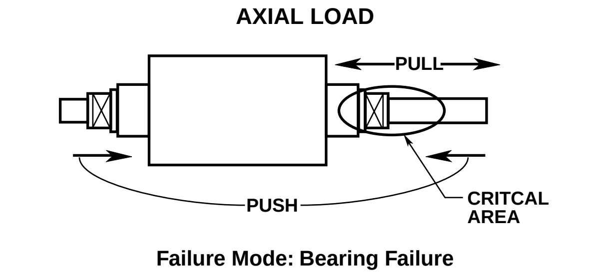


Figure 5

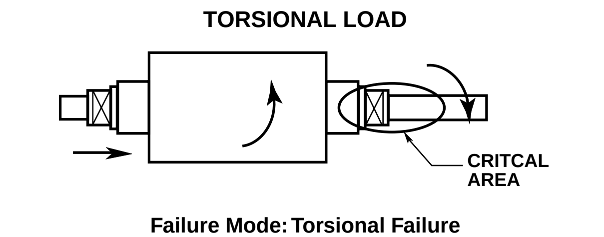
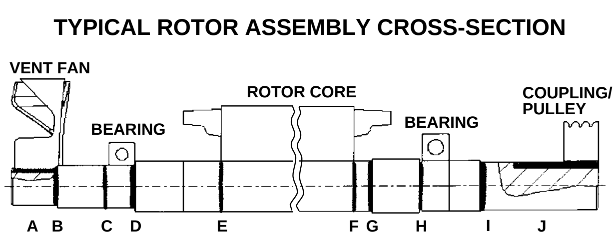


Figure 6

AREAS OF HIGHEST CONCENTRATION

Figure 7 illustrates areas on a normal motor shaft where design stress concentrations (raisers) will exist. A stress raiser will exist wherever there is a surface discontinuity—e.g., bearing shoulders, snap ring grooves, keyways, shaft threads or holes. Shaft damage or corrosion can also create stress raisers. Fatigue cracks and failure will usually occur in these regions. For motors, the two most common places are at the shoulder on the bearing journal (Point H) or in the coupling keyway region (Point J). The most common area for shaft damage is on the part of the shaft outboard of the bearing. In most cases, an axial load will result first in a bearing failure. There are numerous examples, however, where the shaft is damaged before shutdown is achieved.



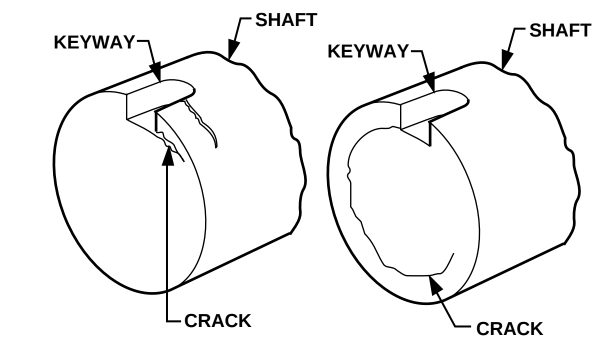
All of the highlighted areas create stress raisers. Points F, H, I and J are usually the most vulnerable areas because of the shaft load at these points. It is hard for a shaft to fracture at points A, B, C, D or E.

Figure 7

SHAFT KEYWAYS [4] [12]

Keyways are used commonly to secure fans, rotor cores and couplings to the shaft. All of these cause stress raisers. However, the keyway on the take-off end or driven end of the shaft is the one of most concern because it is located in the area where the highest shaft loading occurs. When this loading has a high torsional component, fatigue cracks usually start in the fillets or roots of the keyway.

Keyways that end with a sharp step have a higher level of stress concentration than "sled-runner" types of keyways. In the case of heavy shaft loading, cracks frequently emanate at this sharp step. Figures 8 and 9 illustrate this type of failure. It is important to have an adequate radius on the edges of the keyway.



Peeling-type cracks in shafts usually originate at the keyway [4]**.**

Figure 8

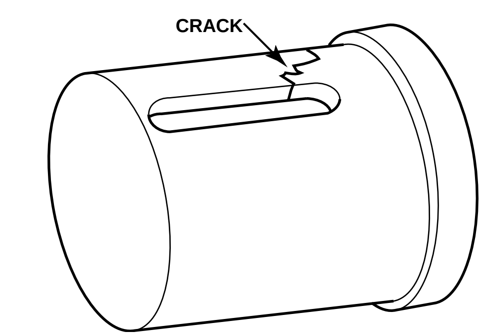


Figure 9

FAILURE MODE

As stated previously, for motor shafts, 90% of all failures can be placed into the fatigue modes shown in Table 3 [2]. If the shaft is not designed, built, applied or used properly, a premature failure can occur with any of the failure modes.

TABLE 3. COMMON CAUSES OF SHAFT FAILURES FOR MOTORS

FAILURE MODE	CAUSE
Overload	High impact loading (quick stop or jam).
Fatigue	Excessive rotary bending, such as overhung load, high torsional load or damage causing stress raisers.
Corrosion	Wear pitting, fretting, and/or cavitation can result in a fatigue failure if severe enough.

The appendix provides a more complete breakdown of failure modes [7].

As stated previously, shaft fatigue failures can be classified as bending fatigue, torsional fatigue and axial fatigue. In the case of axial fatigue for motors, the bearing carrying the load will fatigue (contact fatigue) before the shaft does. Spalling of the bearing raceways usually evidences this. In the bending mode, almost all failures are considered "rotational," with the stress fluctuating or alternating between tension and compression. This is a cycling condition that is a function of the shaft speed. Torsional fatigue is associated with the amount of shaft torque present and transmitted load.

Since most shaft failures are related to fatigue, which is failure under repeated cyclic load, it is important to understand fatigue strength and endurance limits. One way to establish the strength and limits is to develop an S-N diagram as shown in Figure 10 for a typical 1040 steel.

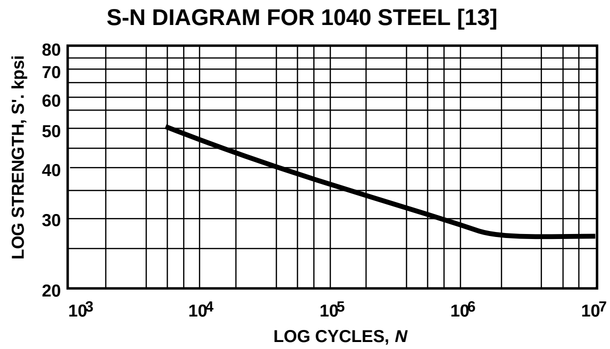


Figure 10

For steel, these plots become horizontal after a certain number of cycles. In this case, a failure will not occur as long as the stress is below 27 kpsi, no matter how many cycles are applied. However, at 10^5 cycles, it will fail if the load is increased to 40 kpsi. The horizontal line in Figure 10 is known as the fatigue or endurance limit. For the types of steels commonly used for motors, good design practice dictates staying well below the limit. Problems arise when the applied load exceeds its limits or there is damage to the shaft that causes a stress raiser.

DEFINING THE FATIGUE PROCESS [4]

Fatigue fractures or damage occur in repeated cyclic stresses, each of which can be below the yield strength of the shaft material. Usually, as the fatigue cracks progress, they create what is known as "beach marks."

The failure process consists of the following: first, the fatigue leads to an initial crack on the surface of the part; second, the crack or cracks propagate until the remaining shaft cross-section is too weak to carry the load. Finally, a sudden fracture of the remaining area occurs.

Fatigue failures usually follow the weak-link theory. That is, the cracks form at the point of maximum stress or minimum strength. This is usually at a shaft discontinuity between the edge of the rotor core shaft step and the shaft coupling.

APPEARANCE OF FATIGUE FRACTURES

The appearance of the shaft is influenced by various types of cracks, beach marks, conchoidal marks, radial marks, chevron marks, ratchet marks, cup and cone shapes, shear lip and a whole host of other topologies. Some of the most common ones associated with motor shafts that have failed are due to rotational, bending fatigue. The surface of a fatigue fracture will usually display two distinct regions as shown in Figure 14. Region A includes the point of origin of the failure and evolves at a relatively slow rate (seconds through years), depending on the running and starting cycle and, of course, the load. Region B is the instantaneous or rapid growth area (cycles through seconds) and exhibits very little plastic deformation. If the conchoidal marks were eccentric that would indicate an unbalanced load.

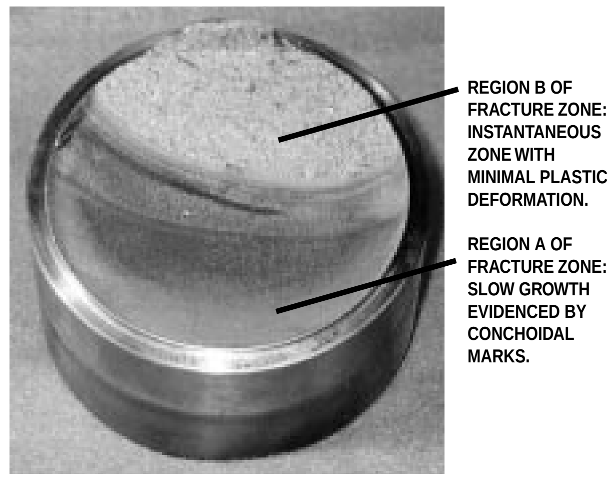


Figure 11

In Figure 12, both the slow growth region and instantaneous regions can be seen. This shaft fractured at the snap ring groove, which is a high stress raiser area. Note: the presence of ratchet marks on the periphery of the shaft; they point to the origin of the cracks.

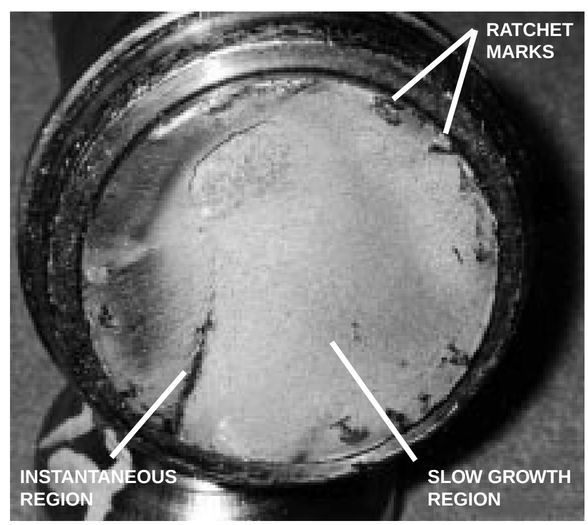


Figure 12

In Figures 13 and 14, the initiation sites originated at the root of the keyway. Both the slow growth and instantaneous areas are present. In Figure 14, the initiation sites are well defined.

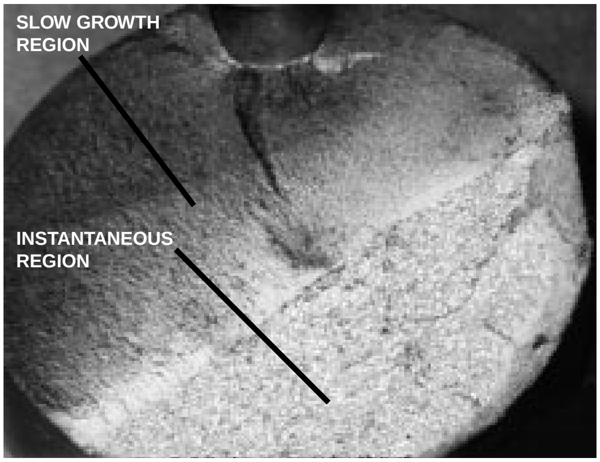


Figure 13

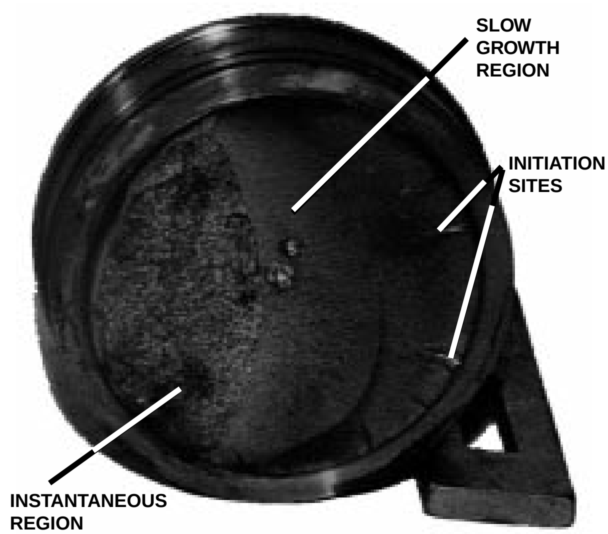


Figure 14

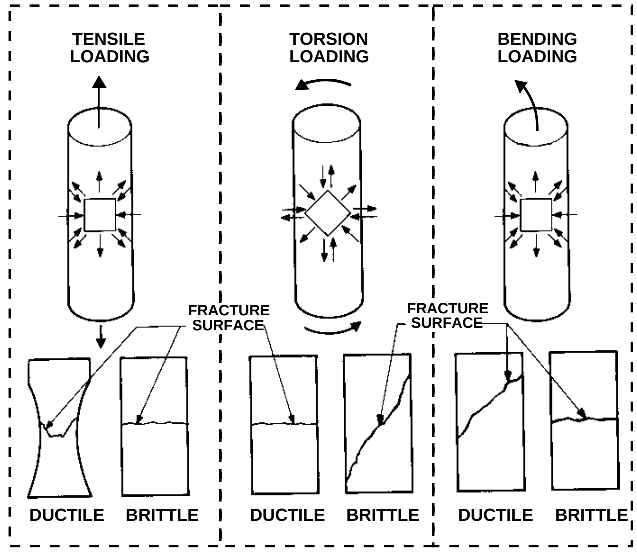


Figure 15A Figure 15B Figure 15C

FAILURE PATTERNS

Failure patterns can be associated with how the shaft "looks" at the time of failure. Depending upon the type of material, shaft fractures can be identified by classifying them as ductile or brittle.

Plastic deformation is always associated with ductile fractures, since only part of the energy is absorbed as the shaft is deformed. In brittle fractures, most of the energy goes into the fracture, and most of the broken pieces fit together quiet well. Ductile failures have rough surfaces, and brittle failures have smooth surfaces, as shown in Figures 15A, 15B and 15C [1] [2] [8]. These are an expansion of Figure 2, where the stresses are shown.

SURFACE FINISH EFFECTS

In most applications, the maximum shaft stress occurs on the surface. Hence, the surface finish can have a significant impact on fatigue life. During the manufacturing process and future handling and repairs, it is important not to perform operations that would result in a coarser shaft. The impact of surface finish and fatigue life in cycles can be seen in Table 4.

TABLE 4

FINISHING OPERATION	SURFACE FINISH (μ in.)	FATIGUE LIFE (cycles)
Lathe	105	24,000
Partly Hand Polished	6	91,000
Hand Polished	5	137,000
Ground	7	217,000
Ground and Polished	2	234,000

Information taken from Colangelo and Heiser [3].

CORROSION FAILURES

In corrosion failures, the stress is the environment and the reaction it has on the shaft material. At the core of this problem is an electrochemical reaction that weakens the shaft. Pitting is one of the most common types of corrosion, which is usually confined to a number of small cavities on the shaft surface. Only a small amount of material loss can cause perforation, with a resulting failure without warning in a relatively short period of time. On occasion, the pitting has caused stress raisers that result in fatigue cracks.

RESIDUAL STRESS FAILURES

These stresses are independent of external loading on the shaft. A wide variety of manufacturing or repair operations can affect the amount of residual stress. They include [1]:

- Drawing
- Bending
- Straightening
- Machining

- Grinding
- Short blasting or peening
- Surface rolling
- Polishing

All of these operations can produce residual stresses by plastic deformation. In addition to the above mechanical processes, thermal processes that introduce residual stress include:

- Hot rolling
- Torch cutting
- Welding
- Heat treating

All residual stress may not be detrimental. If the stress is parallel to the load stress and in an opposite direction, it may be beneficial. Proper heat treatment can reduce these stresses if they are of excessive levels.

SHAFT FRETTING [4]

Shaft fretting can cause serious damage to the shaft and the mating part. Typical locations are points on the shaft where a "press" or "slip" fit exists. Keyed hubs, bearings, couplings, shaft sleeves and splines are examples. Taper fits seem to be an exception to this rule and experience little or no fretting. The presence of ferric oxide (rust) between the mating surfaces, which is reddish-brown in color, is strong confirmation that fretting did occur. The cause of this condition is some amount of movement between the two mating parts and oxygen. Once fretting occurs, the shaft is very sensitive to fatigue cracking; this eventually leads to a fatigue mode failure. Shaft vibration can worsen this situation if it is not corrected.

CAVITATION [4] [9]

In pumping applications where a liquid rapidly passes over the shaft, a phenomena known as cavitation can occur. Cavities, bubbles or voids are created in the fluid for short durations. As they collapse, they produce shock waves that ultimately cause craters on the shaft surface. The shaft can be weakened and fail in a relatively short period of time. A common approach to minimizing this condition is to use a stainless steel shaft, which has a much enhanced abrasion resistance and wear quality. There are also some elastomeric coatings that often increase resistance to erosion.

SURFACE COATING

Metallic coatings to protect or restore a shaft can cause harmful residual stresses, which can reduce the fatigue strength of the base metal. In most cases, there are enough safety factors to handle this additional stress. However, if the shaft is being stressed to its design limits, then such processes as electroplating, metal spray or catalytic deposition could be a source of fatigue failures.

During some plating processes, it is possible to introduce hydrogen into the base metal. If it is not removed by the appropriate heat treatment process, severe hydrogen embrittlement may occur, which can greatly reduce the tensile strength of the shaft.

Shafts repaired by welding are beyond the scope of this paper. However, caution must be used in this process. The selection of the proper weld material, method of application, stress relieving, surface finish, and diameter transition are all critical to a successful repair. Not all shaft materials are good candidates for repair by welding.

The *Metals Handbook*, Volume 10 [1], Pages 395-396, provides additional information on this subject.

MISCELLANEOUS NON-FRACTURE TYPES OF SHAFT FAILURES

There is a broad category of shaft failures or motor failures that do not result in the shaft breaking. The following is a list of the more common causes. Fatigue failures that are caught in the early stages would also fit in the non-fracture category:

- Bending or deflection, causing interference with stationary parts.
- Incorrect shaft size causing, interference, run out or incorrect fits.
- Residual stress, causing a change in shaft geometry.
- Material problems.
- Excessive corrosion and wear.
- Excessive vibration caused by electrical or mechanical imbalance.

In many cases, bearing failures that are catastrophic will cause serious shaft damage but usually will not result in a fracture.

CHECKLIST

The following section provides a checklist for use in gathering critical information pertaining to the appearance, application and maintenance history of the motor and other related equipment. Some of these questions overlap.

APPEARANCE OF MOTOR AND SYSTEM

When coupled with the class and pattern of failure, the general appearance of the motor usually gives a clue as to the possible cause of failure. The following checklist will be useful in evaluating assembly conditions:

- Does the motor exhibit any foreign material?
- Are there any signs of blocked ventilation passages?
- Are there signs of overheating exhibited by insulation, lamination, bars, bearings, lubricant, painted surfaces, etc.
- Has the rotor lamination or shaft rubbed? Record all locations of rotor and stator contact.
- Are the topsticks, coils, or coil bracing loose?
- Are the motor cooling passages free and clear of clogging debris?
- What is the physical location of the winding failure? Is it on the connection end or end opposite the connection? If the motor is mounted horizontally, where is the failure with respect to the clock? Which phase or phases failed? Which group of coils failed? Was the failure in the first turn or first coil?
- Are the bearings free to rotate and operating as intended?
- Are there any signs of moisture on the stator or rotating assembly, contamination of the bearing lubricant, or corrosion on the shaft?
- Are there any signs of movement between rotor or and shaft or bar and lamination?

- Is the lubrication system as intended or has there been lubricant leakage or deterioration?
- Are there any signs of stalled or locked rotor?
- Was the rotor turning during the failure?
- What was the direction of rotation and does it agree with fan arrangement?
- Are any mechanical parts missing (such as balance weights, bolts, rotor teeth, fan blades, etc.) or has any contact occurred?
- What is the condition of the coupling device, driven equipment, mounting base and other related equipment?
- What is the condition of the bearing bore, shaft journal, seals, shaft extension, keyways and bearing caps.
- Is the motor mounted, aligned and coupled correctly?
- What is the shaft loading, axial and radial?
- Is the ambient usual or unusual?
- Do the stress raisers show signs of weakness or cracking? (The driven end shaft keyway is a weak link.)

When analyzing motor failures, it is helpful to draw a sketch of the motor and indicate the point where the failure occurred, as well as the relationship of the failures to both the rotating and stationary parts (such as shaft keyway, etc.).

APPLICATION CONSIDERATIONS

It usually is difficult to reconstruct conditions at time of failure. However, knowledge of the general operating conditions will be helpful. Consider the following items:

- What are the load characteristics of the driven equipment and the loading at time of failure?
- What is the operating sequence during starting?
- Does the load cycle or pulsate?
- What is the voltage during starting and operation; is there a potential for transients? Was the voltage balanced between phases?
- How long does it take for the unit to accelerate to speed?
- Have any other motors or equipment failed on this application?
- How many other units are successfully running?
- How long has the unit been in service?
- Did the unit fail on starting or while operating?
- How often is the unit starting and is this a manual or automatic operation? Part winding, wye/delta, or ASD or across the line?
- What type of protection is provided?
- What removed or tripped unit from the line?
- Where is the unit located and what are the normal environmental conditions?
- What was the ambient temperature around the motor at time of failure? Any recirculation of air?
- What were the environmental conditions at time of failure?
- Is the mounting base correct for proper support to the motor?
- Was power supplied by a variable-frequency drive? How far away is it?
- How would you describe the driven load method of coupling and mounting and exchange of cooling air?

MAINTENANCE HISTORY

An understanding of the past performance of the motor can give a good indication as to the cause of the problem. Again, a checklist may be helpful:

- How long has the motor been in service?
- Have any other motor failures been recorded, and what was the nature of the failures?
- What failures of the driven equipment have occurred? Was any welding done?
- When was the last time any service or maintenance was performed?
- What operating levels (temperature, vibration, noise, insulation, resistance, etc.) were observed prior to the failure?
- What comments were received from the equipment operator regarding the failure or past failures?
- How long was the unit in storage or sitting idle prior to starting?
- What were the storage conditions?
- How often is the unit started? Were there shutdowns?
- Were correct lubrication procedures utilized?
- Have there been any changes made to surrounding equipment?
- What procedures were used in adjusting belt tensions?
- Are the pulleys positioned on the shaft correctly and as close to the motor bearing as possible?

PREVENTION

In general terms, a number of practices can be used to minimize the probability that a premature shaft failure might occur. The following are some of the more critical steps.

1. Be sure that the application and the possible loading on the motor are well understood and communicated. It is imperative to know if there is an overhung load. The environmental conditions are also critical.
2. The motor manufacturer must be sure that proper materials are selected. For the most part, steel with the properties of hot rolled 1045 steel is adequate.
3. The manufacturing processes are critical. During the processing of the shaft, care must be taken not to introduce stress raisers and to achieve the required shaft finish.
4. The installation phase and operation phases are also critical. Care must be taken not to damage the shaft when coupling it to the driven equipment. For belt driven loads, remember the <u>MOMENT</u> principle (force x distance) in placement of the pulley.

ACKNOWLEDGEMENTS

The author wishes to express appreciation to the following companies for their contribution of material and pictures for this project: Weyerhaeuser, Inc.; Goulds Pumps, Inc.; Buckeye Pumps, Inc.; Longo Industries; Brithinee Electric; and Darby Electric.

SUMMARY AND CONCLUSIONS

All too often when a motor fails, the major (and sometimes only) focus is the repair or replacement and getting it "up and running again." Without down playing the importance of this goal, time should be spent collecting valuable information that will assist in a root-cause analysis that can be conducted after the fact. This paper, along with the previous ones [10] [11], provides the methodology to analyze and properly identify failures, so that, hopefully, the necessary steps can be taken to eliminate them.

One of the best methods to assist in the analysis of shaft failures is to develop a reference library of pictures of known causes of shaft failures. The following is a sample of some of the more typical types of failures.

TABLE 4

1. Loading • Impact loading • Rotational bending • Torsional loading
2. Environment • Wear • Pitting • Cavitation • Fretting • Temperature
3. Manufacture • Excessive stress raisers • Residual stress • Surface coatings • Surface finish
4. Design • Improper material selection • Lack of application knowledge • Design strength
5. Repair • Welding • Machining

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APPENDIX

The following pictures show some of the more common shaft failures.

Figures 16 and 17 are of a 1045 series carbon steel motor shaft that failed due to rotational bending fatigue over time. The point of failure was at the shoulder of the customer take-off end.

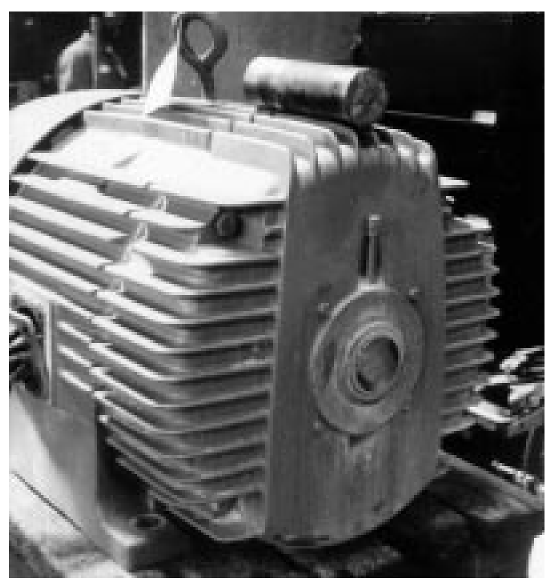

Figure 16

APPENDIX—Continued

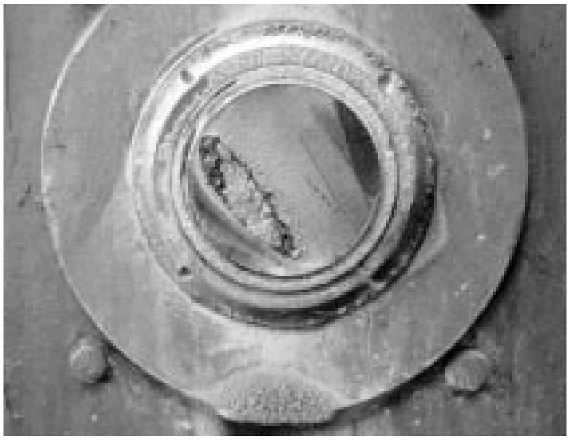

Figure 17

Figures 18 and 19 are of a 1040 series carbon steel motor shaft that failed due to rotational bending fatigue over time. The point of failure was at the bearing journal shoulder.

Figure 18

Figure 19

Figures 20 and 21 are of a 1045 hot rolled steel motor shaft that failed due to rotational bending fatigue. It was a heavy belting application. The failure originated at the end of the keyway.

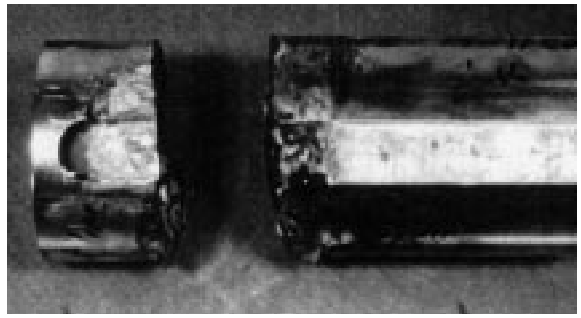

Figure 20

Figure 21

Figures 22 and 23 are of a 4140 alloy steel pump shaft that failed due to rotational bending fatigue, initiating in the root of the shaft keyway. The most likely cause was a combination of misalignment and vibration. The coupling may also have been a contributing factor. A number of beach marks were present.

Figure 22

APPENDIX—Continued

Figure 23

Figures 24, 25 and 26 are of a stainless steel (316L Austenitic) pump shaft that failed due to rotational bending fatigue over time. The failure originated at a large fillet radius. This particular steel is not a good material for shafts because it work-hardens under cyclic loading.

Figure 24

Figure 25

Figure 26

Figures 27 and 28 are of a 4340 alloy steel pump shaft that failed due to high-cycle fatigue initiating at the root of the keyway radius. The fatigue cracks, which were spread over 90% of the surface, caused an increase in vibration prior to failure. There were signs of beach marks. The cause of this failure was an inadequate keyway radius.

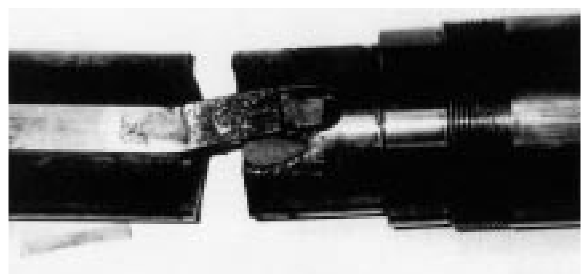

Figure 27

Figure 28

Place this *Tech Note* in Section 9 of your *EASA Technical Manual* for future reference. Note its location in Section 15, "Future Tech Notes."

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