Troubleshooting Induction Motors

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Abstract: **The keys to successful motor operation include a total understanding of the application, then choosing the proper type of motor for the application. This must then be followed by the proper installation – mounting, coupling, and a total understanding of the motor surroundings or environment. Of course, for continued success proper maintenance of the motor must also be performed. Many problems could be avoided if the application and environment were understood, while others may be caused by a changing environment in which the motor operates. In addition, some are due to choosing the wrong motor for the application or defects within the motor itself. This paper examines the most common mechanically or electrically originated motor problems and their preventative action.**

I. INTRODUCTION

TROUBLE with a motor, like trouble with any rotating machinery, ranges – depending on the situation – from aggravation to crisis. Certain problems seem to reoccur more frequently than others. Some problems could be avoided if the application and environment were understood, while others may be caused by a changing environment in which the motor operates, and, of course, some are due to the motor itself. These problems include the following.

- Improper Voltage.
- Motor has inadequate torque to drive the load.
- Motor takes too long to start.
- Overload or instantaneous trip.
- Overload relays take the motor off during full load operation.
- Unsatisfactory vibration.
- Bearing problems.

II. VOLTAGE VARIATION

Many problems are a result of high or low voltage, unbalanced voltage, ungrounded power systems, or voltage spikes. The following are examples of the most common of these types of problems seen.

A. Low Voltage

Low voltage is normally not the direct cause of motor overheating since the overload relays will kick the motor off line when the current exceeds rated amps. As a result, the motor will not generate rated HP. The motor slip also increases proportionally to the square of the voltage drop. As a result, the motor will be running slower with a lower output and the process would not be producing as expected. Low voltage during start can create additional problems. When specifying the motor, it is important to understand what the true voltage at the motor terminals is during starting. This is not the power system voltage, or the tap on the autotransformer. To determine this voltage, one must take into account the total line drop to the motor terminals during the high current draw, which is present while the motor is starting.

On designs which are subject to reduced voltage start and have a high risk of not properly starting, it is recommended that the voltage at the motor terminals be measured on the first couple of starts, after this motor or any other machinery is added to the power system, to eliminate concerns or problems in the future.

B. Overvoltage

It is normally true that motors tend to run cooler at rated horsepower at voltages exceeding rated voltage by up to 10%, but the current draw is only controlled by the load and at rated current and 10% overvoltage the motor will be overloaded by approximately 10%. The core loss is 20 to 30% greater than normal and could cause the machine to overheat. If it is verified that the motor will see an overvoltage, the overload current relay must be adjusted downward to compensate, or stator temperature detectors should be used to monitor the temperature.

C. Ungrounded Power Systems

An ungrounded power system is a serious concern that, if not properly addressed, can lead to premature motor insulation failure. Other than the possible higher voltage stress on the insulation system, this voltage condition will have little effect on the motor performance. On a well balanced grounded power system, the voltage line to neutral (V_{L-N}) will equal the voltage line to ground, but this is not necessarily true on an ungrounded system. (See Fig. 1.)

On an ungrounded system, it is not unusual to see voltage swings in the power supply to the motor, causing the voltage line to ground to approach the magnitude of line to line voltage. For example, on a 4000 volt system the line to ground voltage should be $4000/\sqrt{3} = 2300$ volts. The voltage swing can increase the voltage seen across the ground wall insulation to as much as 4000 volts. The voltage may be even higher, depending on the power supply and possible fault conditions. A standard 4 kV motor has an insulation from coil to ground, which is only good for 2400 volts $\pm$ 10%. In the condition where the line to ground voltage is 4000 volts, the motor must be provided with an insulation system suitable for a $4000 \times \sqrt{3} = 6800$ volts L-L.

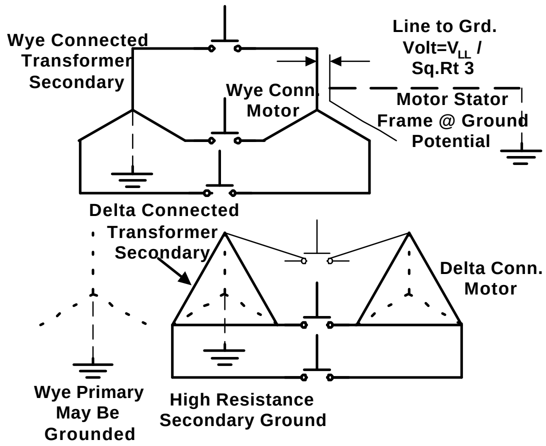


Fig. 1 – Ungrounded Power System

This condition is even more common and severe when operating on a variable frequency power supply. Conditions have been seen where the voltage line to ground can exceed the line to line voltage by 20% or more.

Motors can typically withstand short infrequent durations of high line to ground voltage, such as would be seen in clearing a ground fault, but support equipment such as capacitors or other electronic equipment can be quickly and easily damaged. NEMA MG1 and IEC 34-1 added this above-mentioned warning to the Standards. This will alert users to this concern.

If an application does exist in which a motor will be subjected to high line to ground voltage, the motor manufacturers must be alerted to provide a motor and other equipment suitable for this overvoltage condition. Alternately, one may wish to provide phase to ground overvoltage protection. Note that phase to phase overvoltage protection will not identify the problem since phase to phase voltage may not change significantly with a ground fault or as a result of a voltage swing on an ungrounded system.

D. Unbalanced Voltages

Unbalanced voltage will produce negative sequence currents that will produce excess heating in the stator winding and rotor bars, but will not produce useful power output. Derating of the

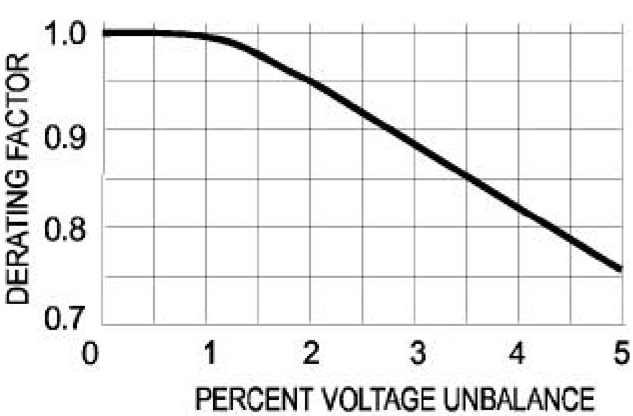


Fig. 2 – Derating Factor from NEMA MG1

motor is necessary when unbalanced voltages exceed 1% as defined by Fig. 2. This condition which produced increased heating, increased energy consumption and lower efficiency. Note, a 2% voltage unbalance can produce as much as 10% increased losses in the machine.

III. MOTOR STARTING

A. Torque Requirement Misconception

There is a common misconception that high locked rotor torque (LRT) will ensure successful starting of the motor and its driven equipment. In the majority of applications, successful starting has little to do with the LRT. In fact, requiring a high LRT and considering nothing else could be quite detrimental to a motor's starting performance and may do exactly the opposite of what was intended.

The majority of applications require very low LRT, and they have very similar load torque curves. Loads such as fans, pumps, and most compressors have a torque requirement approaching zero at zero speed, increasing as the square of the speed up to 100% torque or some lesser required torque at 100% speed. Typical curves are shown in Fig. 3. As a result, successful starting depends on having adequate torque at a point where the load torque becomes significant and approaches the output capability of the motor. This normally occurs around 70-80% speed. Very little torque is normally required at 0 speed. (See Fig. 4.)

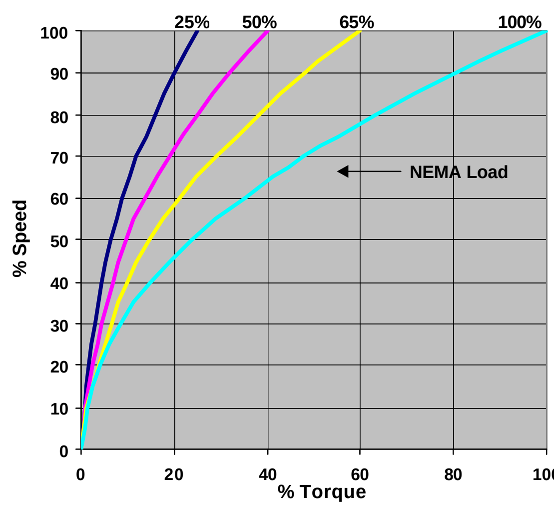


Fig. 3 – Load Speed-Torque Curve

A motor having high LRT, such as defined by the National Electrical Manufacturer's Association (NEMA) for Design C on small motors, or large motors with less exaggerated high torque curves, will normally have a large dip in torque in the 50-80% speed range. This design has a reduction in torque where it is needed the most. (See Fig. 5.) This curve shows a motor that would clearly not accelerate at 90% voltage even though the motor has greater LRT than the design presented in Fig. 4.

Choosing to specify a motor with high LRT may only result in a motor that runs hotter with poorer efficiency, or one that is on a larger frame size due to the construction features required to achieve high torque. As a point of clarification, it needs to be stated that there are special applications that do require high LRT, but these represent a very small percentage of the above NEMA business. Also, in most of the discussions in this paper, it is assumed that the locked rotor current is restricted to 650% of rated current. It is possible, in many motors, to increase the flux densities, thereby increasing the locked rotor torque and

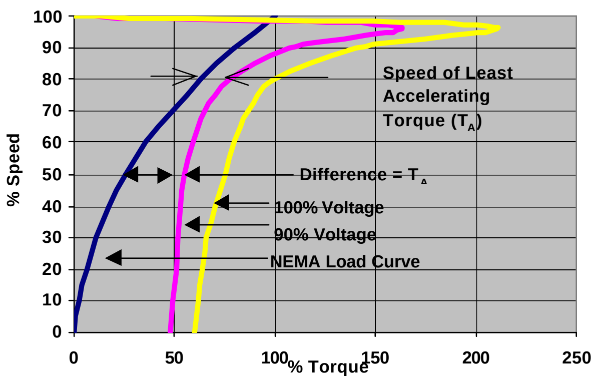


Fig. 4 – Typical Load and Motor Torque Curves

current without detrimental effects to the heating or other performance characteristics if the increase in locked rotor current (LRA) is acceptable. As a point of interest, International Electrotechnical Commission (IEC) standards permit higher LRA than NEMA or what normally is accepted in the United States.

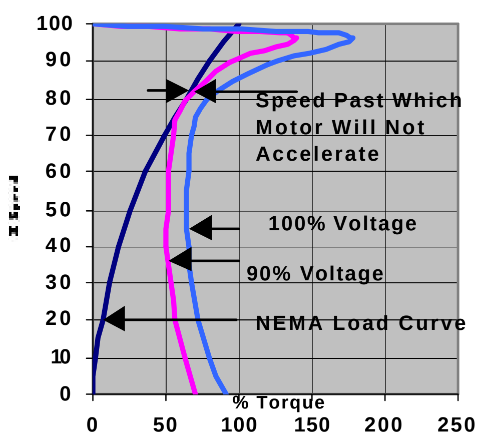


Fig. 5 – Motor with Higher Locked Rotor Torque

B. Reduced Voltage Start

NEMA requires that a standard motor has adequate torque at 90 and 100% rated voltage to start a fully loaded pump, fan, or compressor, which has a 100% load curve as shown in Fig. 3. All United States motor manufacturers produce motors to the requirement as standard. As a result, there normally are very few problems in starting unless the load curve exceed those shown in Fig. 3, and this information is not properly relayed to the motor manufacturer.

The real concern exists when it is required to start equipment with a reduced voltage of 65 or 50%, due to an autotransformer, reactor starter, or solid state starter. Also, a Wye-Delta start is similar in its effect on torque as would be seen on a 65% voltage start.

First of all, starting a fully loaded machine with 65 or 50% rated voltage or a Wye-Delta start should be strongly avoided. Although it may be possible to design a very special motor for

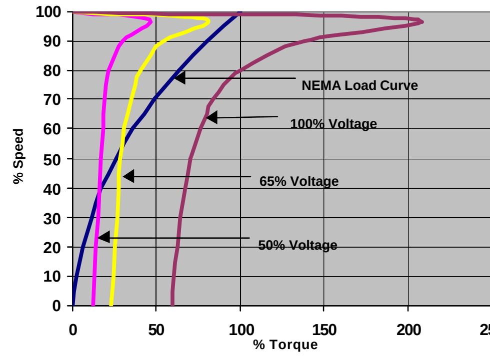


Fig. 6 – 50 and 65% Reduced Voltage Start

this severe requirement, it would require a considerable increase in frame size, and a decrease in efficiency and/or a large increase in LRA to achieve the torque. (See Fig. 6.) This load curve, using a standard motor design starting at 50 or 65% voltage against a full load start, will clearly hang up and will not accelerate past 40% speed at 50% voltage. Fig. 7 shows the same motor at 50 and 65% voltage, but with a greatly reduced load curve. It may appear that this motor will start, but if there is any additional voltage drop as would normally be seen in most applications, this motor would hang up or take too long to accelerate. (See Fig. 7.)

The most common cause of a motor not starting at reduced voltage is due to poor communication among user, motor manufacturer, and process equipment manufacturer (fan, pump, compressor, etc.). Experience has proven that the following are not normally communicated very well:

- actual voltage delivered to motor terminals
- load torque
- load wk2.

C. Actual Voltage at Motor Terminal

Actual motor terminal voltage is probably the most poorly communicated. Load torque and Wk 2 are at times very difficult to obtain, but at least when they are communicated, they are normally correct and clear. This is not always true about voltages. The greatest confusion is in the specification of 50 or 65% reduced voltage start (RVS). It is normally specified that the motor be suitable for starting at 65 or 50% of rated voltage. This is almost always incorrect. The typical reason for RVS is due to a weak power system requiring the current to be low on startup to minimize line voltage drop. To minimize the voltage drop is the key. Voltage drop will never be eliminated. As an example, a 50% RVS on an autotransformer would supply 50% of rated voltage out of the secondary tap, minus whatever power system drop is seen between the transformer and the motor terminals. It is not unusual to see voltages at the motor terminals at 42-45% of rated voltage with a 50% tap on an autotransformer. This can be very serious, and would most likely cause the equipment not to start.

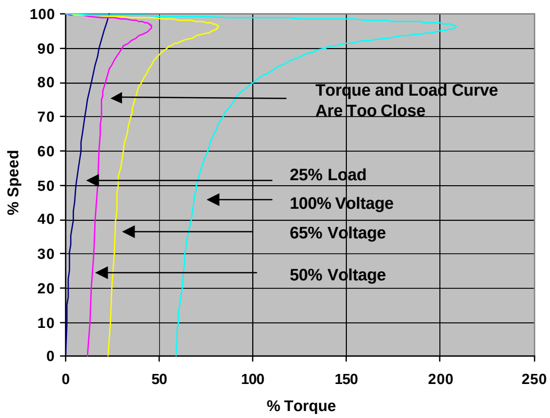


Fig. 7 – Reduced Load Curve

NEMA makes recommendations for standard motors to which all U.S. motor manufacturers design. NEMA recommends that a standard motor be capable of starting a 90% of rates voltage, which is assumed to be a typical line drop, but this is not always recognized for RVS. Due to this, it is always important that the true voltage at the motor terminals be given to the motor manufacturer in one form or another. To say the motor must be suitable for 50% reduced voltage start is very dangerous. It should be stated as suitable for 50% RVS or autotransformer tap plus a 10% voltage drop. This would result in 45% voltage at motor terminals. (See Fig. 8.)

D. Load Torque

Many times, the motor manufacturer is just told that the valve will be closed (pump), dampers closed (fan), or that the vanes are closed (compressor). This supplies some information, but not enough to guarantee proper starting all of the time. The following table gives typical full speed torques on start-up, seen on various types of equipment.

TABLE OF STARTING CONDITIONS
(TORQUE AND CURVE SHAPES MAY VARY)

	Starting Condition	Torque at Full Speed at Start
Pump (Centrifugal)	Valve Closed	25 – 40%
Fan	Dampers Closed	40 – 90%
Compressor (Centrifugal)	Vanes Closed	25 – 60%

The above table does not include screw compressors or vacuum pumps, which have very high torque requirements at very low speeds. These require special considerations by motor manufacturers. (See Fig. 9.) Special applications such as this will require that a motor be designed around the load curve. These are a small percentage of the applications, but they will cause considerable problems if not properly designed.

Since the torque requirements for fans/pumps and centrifugal compressor vary considerably and compressor torque curve shapes vary so greatly, it is important that the load torque curve be available.

As can be seen here, it is very dangerous to assume any type of load or load curve without specific information from the equipment manufacturer.

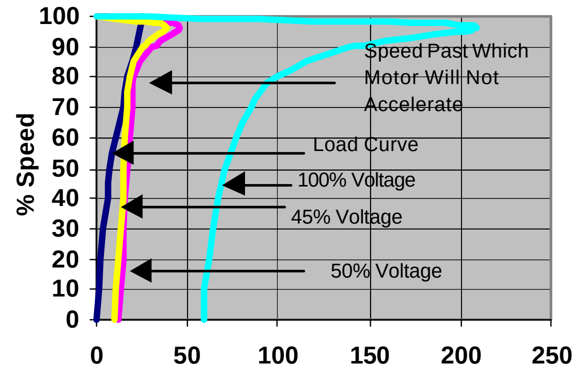


Fig. 8 – 45% Voltage

E. Load Wk^2

This requirement and concern is totally separate from the load torque requirement. The difference between the load and motor torque determines the amount of torque available for

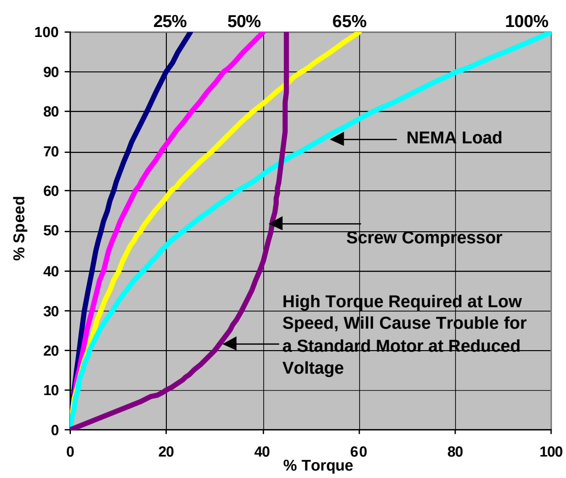


Fig. 9 – Screw Compressor Core

acceleration (T_A), and whether the equipment will accelerate at all or hang up at some subsynchronous speed. (See Fig. 4.) The load Wk^2 determines how long it takes to accelerate and how much heat is generated in the rotor bars, and connectors, and stator winding. Heating and acceleration time is directly proportional to Wk^2.

$$t = \frac{Wk^2 x RPM}{308 x T_A} = \text{acceleration time} \quad (1)$$

Heating during acceleration is proportional to I^2T.

High Wk^2 requirements normally require that the active motor material be increased to act as a heat sink, reducing the temperature rise during acceleration rather than increasing the torque.

It is relatively easy to get Wk^2 requirements from fan and compressor manufacturers since they normally understand the concern due to high inertias frequently seen. NEMA publishes recommended standard levels for all motors. Fans and compressors can, at times, exceed three-four times the Wk^2 recommended by NEMA. Levels on centrifugal pumps are normally very low.

At times, it is very difficult to get this information from the pump manufacturer. Many times, this delays the motor design until the motor manufacturer feels comfortable with the application. The motor manufacturer must be sure that the pump manufacturer is not talking about a vacuum pump, which can have a high Wk^2 and thus would create a serious problem. In any case, the load torque curve and Wk^2 must be known and the motor designed to ensure successful motor starting.

IV. DIFFICULTIES IN STARTING

There may be times when the user believes that he has taken all starting requirements into account, but the equipment still will not start, or it takes too long and the overload relay takes the motor off line. In general, during starting, the overload relays will take a motor off line in about 7-10 seconds at full voltage if the motor is not up to speed, or 25-35 seconds at 50% RVS. High inertia applications, such as fans and some compressors, will require that the overload relay be bypassed or delayed during start-up. If this has been checked, or the acceleration should not take that long, other areas will have to be reviewed.

In many of the cases where the equipment would not accelerate to full speed, it was found that the motor did not actually hang up, but was just taking too long. In these cases, a test can be performed to verify or check the load torque. Find out how long the motor can be accelerated from a cold condition without damage. For a one-start acceleration from cold, the motor manufacturer can normally permit a much longer acceleration time. The motor manufacturer can also supply the line amps, which will be seen at various load conditions at full speed. If the motor is allowed to accelerate for the longer period of time by manually bypassing the overloads, the motor amps at full speed can be recorded and the loading established based on the load information provided by the motor manufacturer. If the load is greater than expected, it is normally possible to reduce the load during starting by adjusting the vanes or valve on the compressor. Or, this can be done by locating air leaks around dampers on fan applications, or by closing the valves further on pump applications. This is the best way the loading can be determined and corrected without returning the equipment to the factory for special testing.

During the above-mentioned acceleration, the voltage at the motor terminals should have been monitored. This information could point out an unsuspected drop of motor voltage. It is important to note that the voltage of concern is the voltage at the motor terminals during start-up, not after or before start, and not at the control panels. It is common to see an additional 2-5% voltage drop between controller and motor during start-up.

If the voltage is low, the cause of the low voltage should be located. Sometimes, the voltage tap on the transformer can be stepped up 2-5%. At times, it does not take much of a voltage increase to eliminate the problem since torque varies as the square of the voltage. In addition, the motor manufacturer may allow a longer acceleration time at this lower voltage since the heating in the motor is a function of the I^2t and the current is proportional to the voltage.

The majority of the problems with these applications have been solved by the above steps. A small number of cases that cannot be solved in this manner may require more drastic steps, such as a new rotor or even a new motor to produce greater torque during starting. Before anything is done, it is important to go through the above steps to verify the terminal voltage and load torque, and compare it to the design motor torque at the terminal voltage to determine the true cause of the problem. Decide if the motor is not accelerating, or is just taking longer than expected. Keep in mind, as stated previously, that the overload will take a motor off line on long accelerations if they are not delayed. This is one of the biggest causes of nuisance trips during initial start-ups.

V. MOTOR INSTANTANEOUSLY TAKEN OFF LINE

This is one of the most common problems seen in the application of motors today. In the past, the National Electric Code (NEC) permitted a maximum instantaneous trip current at 13 times the full load rated current. This is a very misleading setting. A typical motor with 650% locked rotor current (LRA) will have a peak instantaneous current of 6.5 times the square root of 2, equal to 9.19 times rated. This is not the current that will be seen the moment the breaker is closed. At start, when the power is first applied to the motor, there will be a dc offset due to at least two of the three phases being energized out of phase with the field in the motor. At equilibrium when the motor is idle, all three phases are at zero potential. When the power is applied to the motor, one of the power lines may be at its peak negative or positive potential, as shown in Fig. 10 (a) or (d) for phase A. In the best possible condition, as shown in Fig. 10(b) or (c), the power is energized 30° from its peak to 0.86 times its peak potential for phases B and C. In the worst case condition where the power is energized at its peak potential, the maximum possible peak current is equal to the peak LRA of 9.19 plus the dc offset. This resulting peak current is equal to 2 times 9.19 minus the exponential decay. The dc time constant and instantaneous current can be calculated by the following formula:

$$Ta = \left(\frac{Xs}{2 * 3.14 * f * r1\left(1 + \frac{LLs}{kW_1}\right)} \right) \tag{2}$$

$$i \text{ instaneous} = 9.19 \ (e^{\frac{-t}{Ta}} - \cos wt) \text{ p.u. current}$$

where

t = time in seconds

w = $2pf$ radians/second

Xs = total starting reactance per phase at zero speed and locked rotor current

LLs = fundamental-frequency component of stray load loss in kW at rated current.

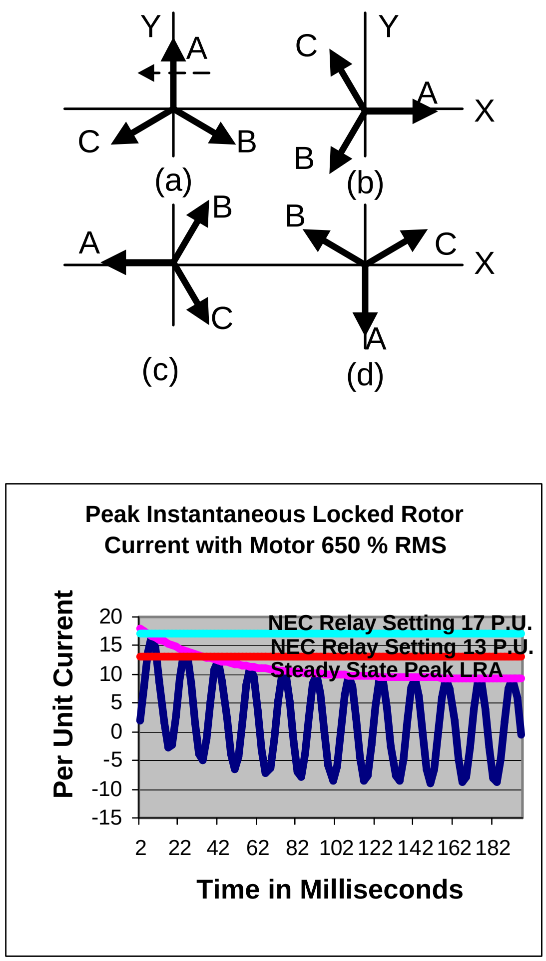
f = rated frequency

kW_1 = stator $I2r$ loss in kW at rated current and operating current

r1 = stator dc resistance per phase corrected to operating temperature.

As can be seen in Fig. 10 (e), the peak instantaneous current starts at 18.38 times rated current, which is well above the NEC setting of 13 p.u. The NEC has recently changed this to 17 p.u. on energy-efficient motors. The first peak will actually occur 1/2 cycle after the instant the motor was energized (0.5*1/60) = 0.00833 s. As shown in the example in Fig. 10 (e), for a typical motor, the peak instantaneous current will still be above 16 p.u.

Even if the phases were lined up in the best condition, 30^o off its peak, resulting in a peak approximately 0.866 times 16 p.u. equal to 13.8 p.u. with the 13 p.u. setting for non energy-efficient motors, the breaker will still trip most of the time. Only if the motor had lower than 650% LRA, or a very significant voltage drop, would the instantaneous relay not take the motor off line. An alternate would be to dampen the trip beyond the first 1/2 cycle. At the second 1/2 cycle peak, as shown in Fig. 10 (e), the peak current will be near or below 13 p.u. With this



(e)

Fig. 10 – Instantaneous Current

condition, we have found that most motors will start with a l/2 cycle damping with very few nuisance trips with the 13 p.u. setting. Even though some motor designs may still be slightly above the 13 p.u. at 0.025 s, the power system will usually have a small voltage drop, be energized slightly away from its peak, or the motor starting current may be lower than the 650% limit which will allow it to start. It has been reported that high efficiency motors tend to have more difficulty in starting. This may be due to the normal tendency to design them closer to the upper LRA limit in an attempt to get higher efficiency, in addition to reducing the losses by reducing stator resistance (r). As can be seen in the above formula for the dc time constant, reducing r will extend the open circuit time constant, resulting in a slower decay.

This change to 17 p.u. on energy efficient motors is the result of years of work of NEMA with the National Fire Protection Agency (NFPA) to change the National Electrical Code (NEC) to values of FLA and LRA that were more compatible with motor designs. Now, it may not be quite as important since the difficulty in starting has been addressed with the introduction of instantaneous trip damping. However, non energy-efficient motors may still see some nuisance tripping with the 13 p.u. setting. If you are experiencing this problem in starting, consider going to a relay which has trip damping.

VI. OVERLOADS SHUT DOWN MOTOR

If the motor is drawing more than rated current at full load, the most likely cause is excessive load or undervoltage. The full load amps on motors with efficiencies in the high 90's can be predicted very accurately, and normally are within 2% of the required amp draw for the load, whereas the load equipment which may have efficiencies less than 50% can easily be off by 5-10%. The voltage also plays an important part. If the voltage were down by 10%, it would require 10% overcurrent to provide rated torque. Also, the load will vary as the material being processed changes temperature. Liquid and air handling equipment requires more horsepower to process cold material than it does when the material reaches its designed operating temperature.

So, if you experience a problem with overcurrent, 1) check the voltage at the motor terminals, 2) review the specifications on the load equipment and verify the proper design temperature of the material being processed, and then 3) verify the amp rating with the motor vendor.

VII. MOTOR OVERHEATING

The most common cause of overheating is improper ventilation or high ambient temperature. A typical compressor room or pump house will heat up quickly if the room is not properly ventilated. A room that houses (4) 600 hp motors and pumps or compressors may only be 40 x 60 x 30 ft high. Four motors that size will intake and exhaust 6000 CFM of air at approximately 40^oC above inlet temperature. If the room is not ventilated, all the air in the room will be exchanged within 12 min., potentially raising the ambient temperature 40^oC above, the original ambient temperature. The temperature in the room will continue to rise until it reaches an equilibrium with the heat radiating out through the walls. This may seem a little ridiculous, and one may assume that everyone would know to avoid this condition, but rooms such as this have existed in various plants around the world, and motors were failing repeatedly until fans were installed in the walls to exchange the necessary amount of air.

There are other conditions, which are not quite as obvious, but are still very detrimental to the motor performance. The maximum ambient temperature permitted at the motor is normally 40^oC. This is the maximum temperature allowed at the inlet to the motor. There may be pockets of hot air in a room due to improper ventilation, obstructions, or being close to another heat source such as a compressor. A common problem is the location of the motor control panel. There are many applications where the panel is placed beside the motor. Although it is far enough away from the motor to allow the air to exhaust, the control panel deflects the air back into the inlet. This is more common on smaller motors with the air entrance into the bearing housings and exhaust directly out the sides of the yoke enclosure structure. Thermocouples should be placed at the air inlet at start-up of a new facility to confirm that this condition does not exist. If there are obstructions on the sides of the motors, a motor design can be supplied which has a top air discharge, discharging the air up and away from the motor. See Fig. 11.

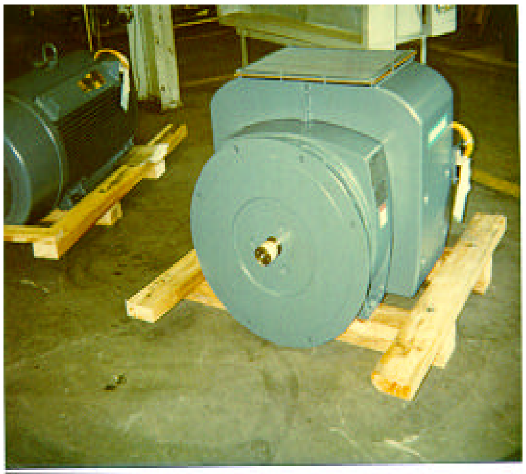


Fig. 11 – Motor with Top Air Discharge

If the motor is to be located in a sound enclosure, it is necessary that the air be ducted out of the enclosure.

Installing noise reduction in the top covers where space allows, and/or the introduction of baffles or a second enclosure, will reduce windage noise significantly. It is not unusual to be able to reduce the noise level by as much as 10 dB without increasing the motor temperature.

When using baffles or sound insulation, caution must be taken to avoid restricting the airflow. To accomplish this, the airflow requirement must be known and baffles located in such a way that the air speed and pressure drop is not excessive. A general rule for the maximum air velocity in a short run of ducts is given in the following formulas. The CFM required to cool a motor can be measured on an existing motor or estimated by the following:

$$CFM = P\,(kW_{loss}) \qquad (3)$$

where

P = 60-100;

$$KW_{Loss} = \frac{(0.746\,hp)}{efficiency} - 0.746\ hp \qquad (4)$$

maximum air velocity = $(A)(D_F)(3.14)(r/min)$

where

D_F = diameter of fan or rotor in feet

velocity = feet per minute

A = 0.15 for a short run of straight ducts

A = 0.10 if bends exist in ducts or if air changes direction entering duct.

Motors with top air discharge are easily adaptable to duct work. (See Fig. 11.) It is important to note that if a motor is placed in an enclosure with the load equipment, all the heat generated in the enclosure by both the motor and driven equipment will only be exhausted through the motor. This additional heating of the cooling air can be a serious problem. It can be resolved in several ways. First, on some motors, a blower can be added to help exhaust the air out through the motor ducts if the volume of air being discharged is increased to an adequate level to ventilate the enclosure. This will vary depending on the size of the enclosure and amount of heat being generated. The motor vendor should assist in the design, and special precaution should be taken with sleeve-bearing motors to avoid sucking the oil out of the bearings. An alternative is to design an enclosure with an auxiliary blower and good cross ventilation to avoid hot spots in the enclosure.

VIII. VIBRATION

Ordinarily, a rotating machine has a certain vibration level, which remains relatively stable for years after installation. But a rotating machine may exhibit excessive vibration at installation or after repairs, or vibration may increase either suddenly or gradually, causing undue wear to the machinery, ultimately resulting in machine failure.

COMPARISON OF DISPLACEMENT IN MILS, VELOCITY IN INCHES PER SECOND, AND VELOCITY IN mm/second

Cycles Per Minute	Displacement (mils P-P)	Velocity (Peak) (inches/second)	Velocity (RMS) (mm/second)
720	1	0.038	0.682
900	1	0.047	0.844
1200	1	0.063	1.131
1800	1	0.094	1.688
3600	1	0.188	3.376
7200	1	0.376	6.753

Spotting the causes of excessive vibration through an effective plant maintenance program is not difficult, and once the causes have been reviewed, the rotating machinery can easily be restored to running order. The basis of such a program is periodic checking and recording, at a recommended frequency of two-three months, plus a detailed check after major repair or service. During a check of the machine, amplitudes and frequencies of vibrations should be recorded. Frequencies of particular interest are those at rotational speed, line frequency, and multiples of each. Some like to record vibration using velocity measurements, in inches per second, while others use displacement, in mils (thousandth of an inch), peak to peak.

Causes of vibration may be in the motor, such as: unbalance of the rotating element, rubbing parts, loose parts, oil film instabilities, anti-friction bearing problems, electrical design, and resonant parts. Causes of vibration may also be external to the motor, such as: foundation, installation, misalignment, adjacent parts in resonance, poor air circulation, and changing conditions after installation and start-up.

To begin analyzing a vibration problem, determine and record operating conditions such as load, rotational speed, if variable, and bearing and machine temperatures as available. Also determine whether vibration conditions change significantly with a change of operating conditions. The rotating part, such as an exposed portion of the shaft, should be visibly marked with a series of numbers around the circumference, or attach a target for a phasor to determine the high side of vibration during operation.

Vibration readings should be made precisely at the operating conditions already chosen and recorded. Because vibratory characteristics often change when operating conditions change, it is important to keep consistent conditions of operation throughout a vibration analysis.

The most productive next step is checking external items, such as the following.

1. Are all foundation bolts tight? Are the shims between the motor feet and mounting surface tight? Try to move them with pliers or hammer, or insert a feeler gauge between the motor feet and support. If any looseness or space is found, the motor needs to be realigned, properly shimmed, and hold-down bolts tightened so that the motor is equally and solidly supported by all supporting surfaces.

2. Check visible fasteners on the motor for tightness', such as bearing housing bolts. Tighten any found loose. When the load produces impacts, such as by a hammermill bolts may work loose if they are not locked.

3. Check the horizontal vibration of the motor feet or, for vertical motors, the base ring. If the vibration exceeds 30% of the horizontal vibration of the motor bearings at the shaft centerline, the motor mounting arrangement may be weak or resonant. An analysis may be made by measuring and plotting horizontal vibration at intervals, such as each 6 in, from ground or floor level to the top of the motor. Results of such an analysis are illustrated in Fig. 12, which shows the mounting structure to have problems-perhaps a gap between base and ground, or a resonant or weak base. This analysis is equally effective on vertical machines.

One way to determine whether vibration is caused by resonance, rather than electrical disturbance or simple unbalance, is to observe the vibration closely at the instant the machine is deenergized. If the vibration disappears instantly when power is cut, the trouble may be electrical in origin. If the foundation structure is resonant at or near operating speed, the vibration also disappears rapidly when power is cut off, but not instantly as for electrical vibration. Because a motor decelerates rapidly when power is cut off, vibration due to simple unbalance also diminishes. Thus, only very careful observations ensure that a reduction of vibration is not due strictly to the reduction in speed.

When a resonant condition is suspected as the cause of vibration, it is recommended that vibration amplitude and phase angle versus speed be plotted. Resonance, electrical disturbance and simple unbalance each produce a characteristic plot of vibration amplitude with a reduction in speed when power is cut off. (See Fig. 13.)

If resonant frequency of the support coincides with the operating speed of the machine, or with half or twice rotational speed, it will be nearly impossible to maintain a smooth running machine. Just a slight imbalance will cause noticeable, sometimes violent vibration at the resonant frequency. Unless the machine can be precision-balanced and so maintained throughout its life, changing of the support resonant frequency usually is recommended.

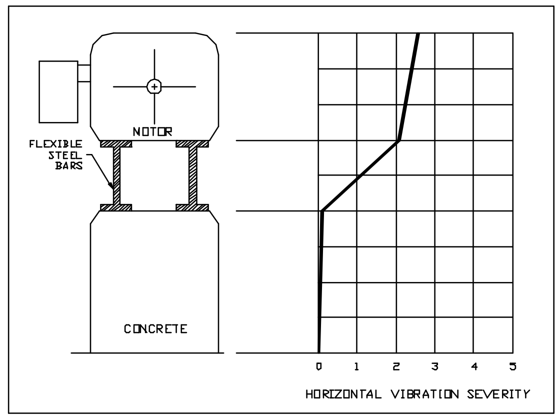


Fig. 12 – Example of Weak Base

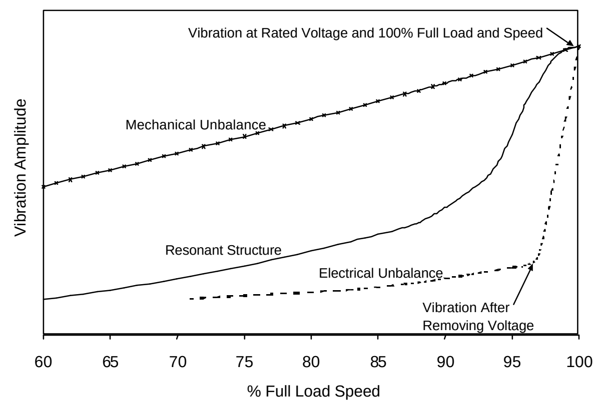


Fig. 13 – Characteristic conditions of vibration amplitude versus speed following removal of voltage

Support resonance (Fig. 14) peaks at natural frequency. The curve is for a 3600 rpm machine, support resonance 1810 cpm.

If the motor and driven loads are mounted on a common base, see if the base is in more than one piece, with a bolted joint between the motor portion and driven load portion of the base assembly. If so, examine carefully at the joint to see if bolts are tight and if the base under the motor has shifted relative to the base under the load. If so, the shaft alignment has also shifted.

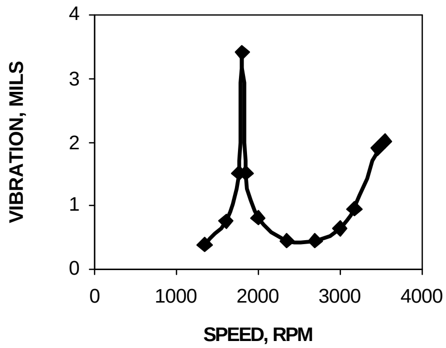


Fig. 14

Sometimes the "sympathetic" vibration of a part attached to the motor will cause increased vibration amplitudes at the motor bearing housings. Parts attached to the motor include lube oil piping, air housings, etc. Considering that the resonant frequency of any part is related to its gravitational sag by the formula resonance frequency in cycles per minutes it is apparent

$$\text{Resonant Frequency} = 187.7 \sqrt{\frac{1}{\vee \text{ gravitational sag in inches}}} \quad (5)$$

for instance, that if a pipe sags 0.0027 in between supports, its natural frequency will be 3600 cycles/min. If attached to a 3600 rpm motor, it would be excited at its natural apparent for instance, that if a pipe sags 0.0027 in between supports, its natural frequency will be 3600 cycles/min. If attached to a 3600 rpm motor, it would be excited at its natural frequency and would probably vibrate excessively. The solution is easy; just add a pipe clamp in between the others. If the parts vibrating are portions of the air housing, mounting the air housing on a gasket instead of directly on the metal portions of the motor will often reduce vibration, as the gasket will reduce the vibration energy transmitted to the air housing.

THE RELATIONSHIP OF GRAVITATIONAL SAG OR DEFLECTION AND RESONANT FREOUENCY

Gravitational Deflection (inches)	Resonant Frequency (cycles/minute)
0.098	600
0.024	1200
0.011	1800
0.0027	3600
0.0012	5400
0.00068	7200

Shaft alignment should be checked. Bases and foundations sometimes shift, and machines sometimes shift on their bases. An extreme case which comes to mind was an installation of a 3000 HP motor driving a car-shredding hammermill. The hammermill would chop complete automobiles into clean, fist-sized chunks, at the rate of 30 autos/hour. The first hour of each working day was utilized in tightening the hammermill fastenings and realigning the shafts, which moved as much as 1/8 in a day's operation.

Misalignment manifests itself in various ways, often in a twice-rotational frequency vibration of particularly large magnitude in the axial direction. It should be noted that it is the shafts when turning in their respective bearings that must be aligned, not the coupling surfaces. In the absence of a company or manufacturer's tolerance for alignment of motor shaft to driven equipment shaft, 0.002 in is a useful tolerance.

When in doubt as to whether the vibration originates in the motor or the driven machine, the coupling halves may be loosened, one half and its associated machine shaft rotated 180^o, and the halves recoupled. If under the same running conditions as before the vibration high side is the same, then the source of vibration is in the machine on which the phasor target or angle numbers are marked. Conversely, if the high side shifts 180^0, the cause is in the other machine.

When the source of vibration is found to originate in the motor, a solution can be achieved. If the frequency of vibration is exactly at rotational speed and amplitude of vibration and phase angle or high side remains constant, the problem is probably one of simple unbalance. This can be corrected by standard balancing procedures. A simple unbalance may be caused by nonsymmetrical rotating parts, a slightly bowed shaft, or a nonconcentric or improperly assembled coupling.

Add balance weights to an external element, such as a coupling or belt pulley first. This usually is the most accessible spot to add balancing weight. Also, the effect of a given weight is greater then added here than between bearing centers, as a given unbalance has a greater effect here. When an insufficient or incorrect balancing effect is obtained, the machine must be opened and weights added to the rotor body.

If vibration frequency is at rotational speed, but amplitude and/or phase angle initially wander and either stabilize or continue to wander with time, the problem may be one of the rotor rubbing a stationary part, such as a shaft seal. If wandering of amplitude and/or phase angle stabilizes or tends toward stabilization, the seal probably was installed incorrectly and “wore itself in.” When vibrational wandering does not stabilize, the seal or other rubbing part should be investigated and corrected. Typical clearance of seals is shown in Fig. 15.

A frequency of vibration of twice rotational speed may indicate a poorly shaped sleeve-bearing journal, misalignment, or looseness and movement between parts. "Poorly shaped journal" means a shaft sufficiently bent to show nonconcentricity in the journal or an out-of-round journal surface. Severity of this nonround surface varies from several ten-thousandths of an inch for 3600 rpm machines to 0.001 in for slow speed machines.

Looseness or movement of rotor parts, indicated by a vibration at twice rotational speed, may be thought of, for example, as a fan with an oblong bore which rocks about its tight diameter once per revolution. Because of large centrifugal forces on larger diameter machines at higher speeds, rotor parts which may be extremely tight when installed, may become loose when not properly designed, or altered during repairs.

A frequency of vibration at about half rotational speed suggests bearing oil film disturbances, in which the journal is not stable at one location in the bearing during operation; instead, if whirls about a center in the bearing. This condition usually appears in high-speed machines and indicates either that the oil is too heavy or bearing clearance insufficient (assuming proper bearing design and previous successful operation). The operator should check to make certain the proper oil is used in the bearings. When the grade and type are found to be correct, the clearance of the bearing should be checked. This may be done by micrometer, feeler gauges, measuring the thick-ness of soft lead pressed between shaft and bearing or by plastigauge.

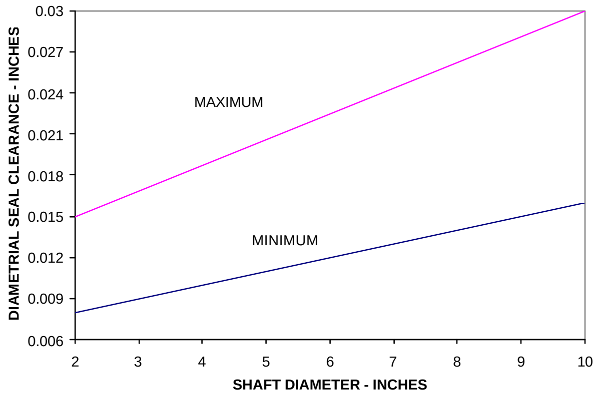


Fig. 15 – Diametrical Seal Clearance

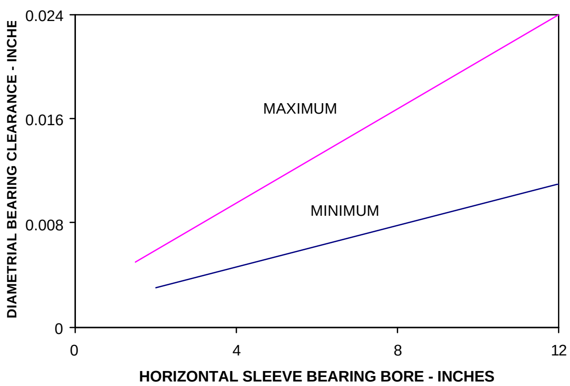


Fig. 16 – Diametrical Bearing Clearance

Vibration dampening is obtained from the bearing oil film, so bearing clearance should not be so great as to lose this benefit. However, bearing clearance should not be unduly reduced because too small a clearance promotes oil whirl and hot bearing operation. The operator should strive to maintain bearing clearances as specified by the manufacturer. Fig. 16 shows normal bearing clearances for horizontal bearings. Oil film whirl or subharmonic vibration, at approximately half rotational speed, can also occur in bearings utilizing a circulating oil system, if the oil entering the bearing is too cold, as this has the same effect as using too heavy an oil. Normal inlet oil tempera-ture should be 35-45^{o}C.

If vibration frequency is exactly at rotational speed but amplitude and/or phase angle change rapidly after start-up and tend to stabilize within 30 mm or so, the problem probably is one of thermal unbalance; that is, heat in the rotor affects shaft straightness or rotor parts location. Solutions to this problem are as varied as the types of rotors, but usually require work on the rotor to eliminate the changing unbalance.

Electrical causes of vibration generally exhibit one of two conditions. The simplest to find is a fixed 120 Hz vibration, which is a transformer-type vibration of the stator due to the impressed 60 Hz voltage. In certain types of machines, this vibration is transmitted readily through the machine structure to the bearings. Usually, the entire machine will vibrate at this frequency, but will stop with removal of voltage. Often, strengthening the motor supports or securing the machine more rigidly to its foundation will reduce this vibration to an acceptable level.

The other common form of electrically induced vibration is a "slip-beat vibration" at rotational frequency, with the amplitude varying periodically at exactly the slip speed times number of poles. For example, an induction motor operating at 1783 rpm (four-pole, 1800 rpm synchronous speed) will have a slip-beat vibration of 68 cpm. This vibration is due to the flux level in the laminated cores of the motor and minor dissymmetry in the magnetic circuits. In most cases, it is not discernible or barely discernible. This noise is often heard in motor rooms where two or more machines are operating at essentially the same speed, in the same way that a "beat" is heard in multiengine airplanes or boats with unsynchronized engines.

When a slip beat frequency noise or vibration suddenly appears in a motor, the machine should be checked, particularly when the associated vibration amplitude fluctuation is large. Possible causes are broken rotor rods or end connector, bent shaft, or unbalanced stator voltage. The cause can be found by operating the motor at no load. If the trouble is in the rotor cage, the vibration fluctuations diminish at no load because it is a function of current. However, if it is a bent shaft, the vibration fluctuations remain (at a lower frequency due to less slip at no load) because they are related to machine voltage. See Fig. 17. Vibration wave shapes (Fig. 17) help to isolate cause of vibration. Such waves are of three types.

A rough anti-friction bearing gives a relatively high frequency vibration, several times the frequency of rotor speed, but not necessarily a direct multiple. This problem is indicated by an unsteady frequency and, sometimes, amplitude as well. The vibration continues when an operating machine is deenergized and coasts to a stop. The solution is to repair or replace the bearing.

Vertical machines with sleeve guide bearings may have a unique vibration problem. Sleeve bearings on vertical machines do not have the same type of load carrying hydrodynamic oil film as horizontal sleeve bearings since horizontal sleeve bearings support the weight of the rotor. To prevent shaft whirl or shaft floating in the bearings, causing random frequency of vibration, the diametrical clearance of vertical sleeve bearings is less than for horizontal bearings of the same diameter. Fig. 18 gives typical diametrical clearances of vertical sleeve bearings.

Torsional vibration is seldom a problem with induction motors, but may be a problem with synchronous motors during starting if not provided for in design of the motor and shaft system.

Likewise, a load which routinely gives torsional impacts, like a pulverizer or hammermill, or an accidental shock, like a log going into an operating pump, may be a problem if not foreseen and provisions made for the special application.

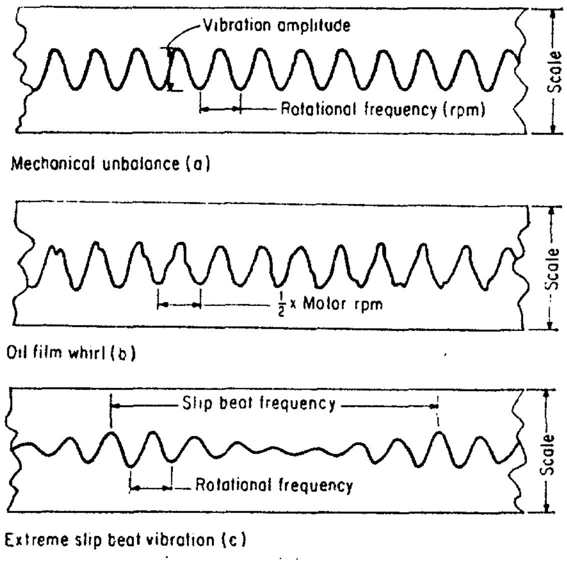


Fig. 7 – Vibration Wave Shapes

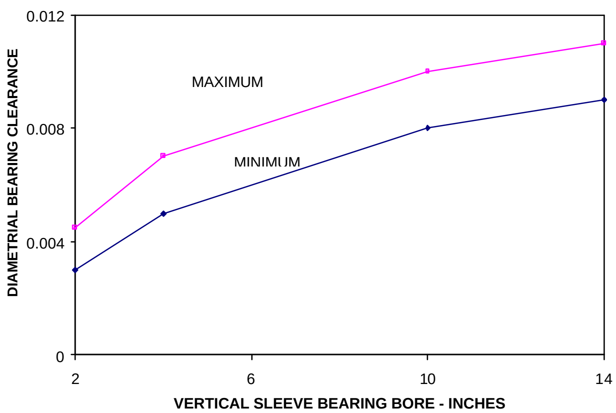


Fig. 18 – Diametrical Bearing Clearance

In almost all cases, the result is a twisted drive shaft extension, and/or an offset coupling key, and/or a damaged coupling. See reference paper [5] for a diagnostic chart and more information on solving vibration problems.

IX. ANTI-FRICTION BEARINGS

Problems with anti-friction bearings are most often analyzed as due to poor lubrication. This is often only the first analysis, as lubrication tries to overcome other, more subtle, problems. Manufacturers design the bearing arrangement of motors for long life, but often, the bearings do not attain their calculated life expectancy.

Design criteria used for bearing life are based on fatigue of the bearing metal and are usually in terms of L10 life which is the number of hours when, on a statistical basis, 10% of the bearings fail. The average designed bearing life then is five times the L10 life. Commonly used criteria range from an L10 life of one year (average life of five years) for vertical motors and belt drive machines to an L10 life exceeding 100000 h (11.4 years, average life of 57 years) for larger horizontal direct connected motors. The calculated life expectancy of any bearing is based on four assumptions.

1) Good lubrication in proper quantity will always be available to that bearing.
2) The bearing will be mounted without damage.
3) Dimensions of parts related to the bearing will be correct.
4) There are no defects inherent in the bearing.

In addition to poor lubrication, other causes contributing to bearing problems may include

1) Defective bearing seats on shafts and in housings
2) Misalignment
3) Faulty mounting practice
4) Incorrect shaft and housing fits
5) Ineffective sealing
6) Vibration while the bearing is not rotating
7) Passage of electric current through the bearing

Specific problems and solutions for anti-friction bearings will not be detailed here since there are very good papers and publications available for assistance. In the absence of a satisfactory source of information on this subject, [4] contains useful in formation. It is important to properly maintain anti-friction bearings to attain long, trouble-free motor life.

X. SHAFT VOLTAGE

Voltage is generated in the rotor of each induction motor by the magnetic flux passing through nonsymmetrical portions of its path. The nonsymmetries may be very small, and so in small machines have very little effect in generating voltage in the rotor. The effect is more pronounced in larger machines, as it may vary from just a few millivolts in a small machine to over a volt in a large machine when measuring between ends of the motor shaft. In addition, induction motors powered by variable frequency power sources may have appreciably higher shaft voltages, due to the power source transient voltage spikes, than the same motor will have when its power source is a steady sine wave. Also, caution is necessary in installations with variable frequency power sources as the transient voltage spikes may reflect into the power supply and cause higher shaft voltages on other, nonvariable speed machines on the power system.

The shaft voltage will follow a complete circuit, if available, through the motor's bearings and the frame or foundation, allowing current to flow across the bearings. Normally, voltage levels below 0.5 V will not cause harmful currents. When expected or measured shaft voltage is above 0.5 V, provisions are made to open or break the circuit to prevent current flow. The normal method is to insulate the motor bearing at the end opposite to the coupling end where the motor is coupled to the driven equipment. And, of course, other connections to the motor shaft at the end opposite the drive coupling must also be insulated to maintain the open circuit. Special provisions are necessary in special cases to maintain an open circuit, such as insulated drive couplings in large tandem motor arrangements, or when driving in auxiliary oil pump or other device on the outboard end of the motor.

On AFDs, there is still a concern that some medium voltage drives may induce a high frequency common mode voltage and current that may even pass through a conventional insulated bearing since at high frequency the bearing and insulation will act like a capacitor with very low impedance to high frequency voltage. As a result, it may be necessary to add a shaft grounding brush.

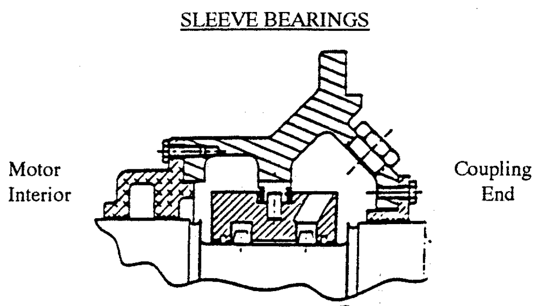


Fig. 19 – Sleeve Bearing

Current through a bearing can also be caused by such things as welding on some part of the machine with the ground attached so that the circuit is required to pass through the bearing, or from static electricity from such manufacturing processes involving leather, paper, cloth, or rubber. Harmful results occur when sufficient current passes from the shaft to the bearing and then to a ground which is continuous to the other bearing. When the current is broken at the contact surfaces between anti-friction bearing rolling elements and raceways, arcing results. This produces very localized high temperature and consequent damage, which is described as fluting and looks like transverse flutes in the bearing raceways. Current in a sleeve bearing results in pits in the surface of the babbitt, and in extreme cases, pits in the shaft journal surface and pulled babbitt.

XI. SLEEVE BEARINGS

Sleeve bearing problems are generally of three types:

1) Hot bearings

2) Wiped or failed bearings

3) Oil leaks.

Sleeve bearings (see Fig. 19), by their very nature, are heat-producing devices. The rotating shaft journal is separated form the stationary bearing bushing only by an oil film. Considering that the oil adjacent to the shaft journal is moving at shaft journal speed, while the oil adjacent to the stationary bearing bushing is stationary, it is apparent that the oil between the two surfaces is being sheared at a very high rate. Shearing of oil requires force, which in a time period equates to power which, being entirely absorbed in the bearing, equates to heat. A three-inch bearing journal, in a 3600 rpm motor, has a surface speed of 2826 ft/mm. The minimum oil film thickness between the rotating journal and stationary bearing will vary from approximately 0.0025 in a cool bearing to 0.0008 in a warm bearing, which is operating near 185°F. The shearing action of the oil thus takes considerable energy. Fig. 20 shows the pressure distribution between the bearing bushing and rotating journal. Note that the actual journal position is not centered in the bearing bushing. This is due to the force required to shear the oil "wedge" which is the oil being fed to the bearing.

The heat generated at the bearing surface is removed through oil being supplied to and flowing through this area, by conduction along the shaft, and by conduction from the bearing bushing to its housing, through the bushing support surfaces. Oil is supplied to the bearing surface by oil rings, which deliver oil from the bearing oil sump, and on larger machines or in high ambient temperature areas by auxiliary oil supplied to the bearing by an external source, and drained from the oil sump back to the external source. The external source may be a motor-pump-cooler unit, or often is pressurized supply, and drain lines, from the driven equipment.

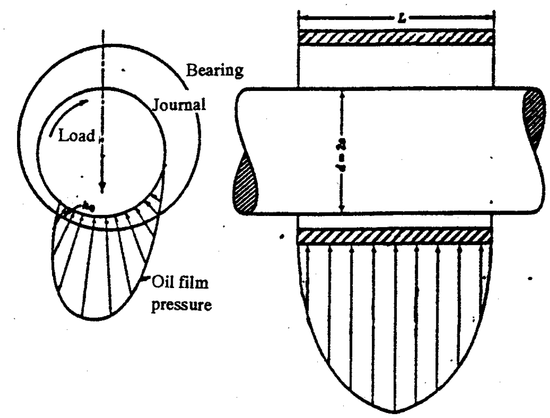


Fig. 20 – Diagram of full bearing showing oil film pressure

Motors are usually designed so that cooling air coming into the motor travels over the bearing housings, cooling them, on the way into the electrical parts of the motor. In this way, many motors have self-cooled bearings. In normal conditions, 3600 rpm motors may have self-cooled bearings up through 3 in. diameter, and 1800 rpm motor bearings may be self-cooled through 4.5 in. diameter. Fig. 21 shows a typical path of cooling air entering a motor. Motor designers extend considerable effort to reduce the heat generated in bearings while maximizing the cooling and the operating oil film stiffness.

High bearing temperature can then have one or more causes. There are several steps which can be taken in an analysis before disassembling an otherwise well-running machine.

The oil rings should be turning a smooth manner, with oil flowing off them in a smooth manner. The rings should not be oscillating rapidly in any direction. Normal rotational speed for oil rings is from one-tenth of the shaft rotational speed at low speed, to 1/20-1/30th of shaft speed for 3600 rpm motors.

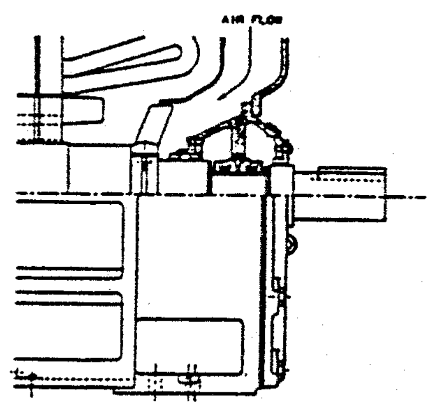


Fig. 21 – Cooling Air Path

Oil should be at its proper level. Foam may appear in the oil level sight glass in the bearing housing for up to 1 h after start-up. During steady operation, there should be only slight foam visible. If the oil looks dirty in the sight glass, there is probably babbitt or other foreign elements in the oil. This requires a disassembly. Feel the outer oil seal to see if it is approximately the same temperature as the bearing housing next to it. If it is significantly hotter, it is probably rubbing the shaft and heating the bearing area. If the motor has a circulating oil supply, confirm that there is oil flow, in the quantity desired, and that the oil supply temperature is reasonable, approximately 35-45°C. Check the air flow into and out of the machine to find if it is normal or restricted, and if the air entering the machine is at a reasonable temperature, usually below 40°C. Check the location of the motor shaft in an axial direction if possible versus the center or extremes of its axial float. Positions of axial shaft float are marked on many motors. Bearing temperature will be higher if a shaft shoulder is running against the bearing bushing.

If all checks so far are okay, including clean oil in the sight glass, the bearing temperature measuring device may be checked to be sure a true temperature is being transmitted to the control or monitor. To check the temperature device, open the auxiliary terminal box on the motor, disconnect the bearing temperature device, and substitute test piece. For a thermocouple, this could be another thermocouple; then hold the measuring end to see if the monitoring instrument indicates the temperature of the hand holding the thermocouple. If the device is an RTD, substitute a resistor for the RTD to check the mounting device. Useful value of resistors to check RTD monitor operations are as follows:

Type of RTD	Resistance (ohms)	Temperature Indicated
10 O at 25°C	11.5	64°C
10 O at 25°C	13.0	103°C
100 O at 0°C	120.0	50.5°C
100 O at 0°C	140.0	101.5°C
120 O at 0°C	160.0	53.0°C
120 O at 0°C	200.0	99.5°C

If the problem has not yet been resolved, the motor needs to be disassembled to examine the bearing bushing and shaft journal. As soon as disassembly has progressed far enough, check the clearance between the inner oil seal and the shaft to find if the inner oil seal has been rubbing the shaft. When the top half of the bearing bushing has been removed, check the bearing bushing alignment with the shaft journal. This can be done by inserting a fine feeler gauge - 0.0015 or 0.002 in. between the shaft journal and bearing bushing in each of the four corners. The feeler gauge should go into the space an equal amount, within, in all four corners.

Examination of the lower half of the bearing bushing should show that the shaft journal was riding equally along the length of the bushing. It could show the shaft riding on one end or on high spots, or perhaps the axis of the shaft journal and bearing bushing were not the same, so that wear spots occur on opposite corners of the bushings. Perhaps the bushing has "pulled" babbitt, babbitt which has softened or flowed, or pitted babbitt, due to electrical currents through the bearings, or the babbitt surface may be destroyed, and the shaft riding on the seals.

For proper operation, a bearing bushing should show contact with the shaft journal axially in a narrow path along the bottom of the bushing from one end to the other. Abrasive screen can be used to lightly remove high spots in the babbitt to attain a good contact pattern. Bearings are carefully designed, for their, application, to exacting dimensions. Usually, removal of less than 0.0015 in thickness of babbitt will result in a satisfactory contact pattern if dressing is needed. Some bearing bushings supported near the ends may require more babbitt to be removed from one end to attain a good pattern. See Fig. 16 for typical clearance between the shaft diameter and bearing bushing bore.

Oil ring speed is important to provide sufficient oil to the bearing surface. Oil rings are driven only by friction of the oil film between the ring and shaft, so any burrs or roughness on the ring or in the ring slot of the bushing must be removed. The bearing arrangement can then be reassembled with the above in mind. Since the shaft will rise and be supported by the oil film during operation, normal practice is to adjust noncontacting shaft seals with one-third of the clearance on the bottom and two-thirds on the top, one-half on each side. Fig. 15 illustrates normal shaft seal diametrical clearance. After assembly, free rotation of the rotor by hand will ensure no rubs, and free rotation of oil rings while turning the rotor will ensure their proper oil delivery.

Oil leak problems in sleeve bearing arrangements are sometimes very subtle and difficult to resolve. Among the easier to solve problems are leaks in piping, leaks at entrance to the capsule, such as an oil level glass, and metal-to-metal joints not properly prepared with sealant such as RTV or Permatex. Joints that may leak include, for instance, between the upper and lower half of the split bearing capsule and the capsule faces where the seals are attached. Sometimes, the tapped holes for capscrews securing the shaft seals go through the wall into the oil cavity, below the oil level, so care is required during assembly.

The oil level, including any foam on top of the oil, must be well below the lowest point of the shaft where it comes through the shaft seal. If an oil which is prone to foaming, such as refrigeration oil, is used, oil may seep out through the shaft seals. When using other types of oil, contact motor manufacturer. High grade mineral turbine oils are less prone to foam and are recommended for motors.

In labyrinth-type sealing arrangements, a drain at the bottom of the inner half of the labyrinths of the first labyrinth seal on each side of the bearing bushing will drain the condensed oil vapor, which has been 'caught" by the seal, back into the oil sump, rather than allow the condensed oil to build up and seep out of the bearing along the shaft.

Varied arrangements are used to minimize the frothing of oil in the bearing cavity, such as seal rings on the bearing bushing, covers over oil slingers, etc., with the goal of keeping to a minimum the amount of oil vapor generated in the bearing cavity. Part of preventing leakage of oil vapor either to the outside or into the motor is to keep the generation of vapor available low; the other part is to keep the pressure in the bearing cavity low. An internal pressure or vacuum below 0.2 in of water column in the bearing cavity will normally prevent leakage of oil vapor.

Motors are cooled by air flow which is normally drawn into the motor over the bearing housings. See Figs. 21 and 22. This air cools the bearings before entering the motor rotor and stator. The velocity of cooling air past the bearing housing can be as high as 3000 ft/mm, depending on the size and speed of the motor. This air flow creates a vacuum in the vicinity of the inner shaft seals, and if these seals are not effective or properly assembled, will draw a vacuum in the bearing cavity, and thus draw oil vapor into the motor. There are various shaft sealing methods, among which is the arrangement of Fig. 21. This labyrinth arrangement, used on medium sized motors, consists of two individual labyrinths. The space between the labyrinths is vented to outside the motor, and allows vacuum inside the motor to draw air from the vent through the inner labyrinth, which reduces or eliminates the vacuum at the labyrinth adjacent to the bearing, so that the pressure/vacuum in the bearing cavity remains at a safe, low level.

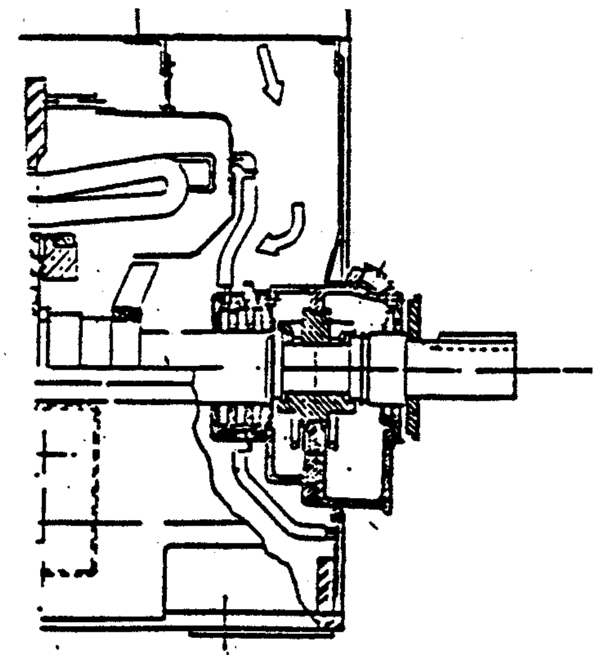


Fig. 22 – Bearing Sealing Arrangement

Fig. 22 illustrates the bearing sealing arrangement on a large high speed machine. This labyrinth has an additional feature in that pressured air flows into the first chamber, between the first and second labyrinth. Most or all of this air is drawn into the motor, through the motor-side labyrinth. The second chamber is vented to atmosphere, to neutralize the pressure, so that air is not forced into or oil vapors drawn through the labyrinth seals adjacent to the bearings. Sizing of shaft seals and other bearing features is carefully calculated and designed, so that careful reassembly as originally assembled, with the above considerations in mind, will usually eliminate oil leakage problems and lead to successful bearing operation.

X. CONCLUSION

Successful motor operation depends on many things, but most importantly, the application and environment must be known and its effect on motor performance understood. This paper attempted to highlight the most common causes of motor troubles, which account for the majority of problems. The key to successful troubleshooting is to identify and analyze all the possible causes, and then eliminate each one either by testing or calculations until the problem is properly identified. This method helps the troubleshooter avoid jumping to conclusions and making modifications to components that are not at fault. Just because a component does not perform properly does not necessarily mean that it is at fault. Other environmental factors may be causing the failure, and the failures will continue until the environmental factor is corrected.

REFERENCES

[1] R. R. Burke, "Maintenance program spots, corrects machine vibration," *Elec. World*, Jun 27, 1966.
[2] R. W. Smeaton, Ed., *Motor Application and Maintenance Handbook*, R.R. Burke, contributing author. New York: McGraw-Hill, 1969/1987.
[3] W. R. Finley, "Noise in induction motors-Causes and treatments," *IEEE Trans. md.* AppL, vol.27, no.6, 1991.
[4] Bearing Installation and Maintenance Guide, SKF USA, Inc., February 1992
[5] W.R. Finley, M.M. Hodowanec, W.G. Holter, "An Analytical Approach to Solving Motor Vibration Problems," *IEEE PCIC Conf. , Sept. 1999*