TIMKEN POWER SYSTEMS

Comprehensive Drivetrain Solutions for Industry

DIAGNOSTIC AND MAINTENANCE CONSIDERATIONS FOR THE INDUSTRIAL DRIVETRAIN

ABOUT TIMKEN POWER SYSTEMS (TPS)

Consisting of the founding members of the American Gear Manufacturers Association, and the American Bearing Manufacturers Association (Philadelphia Gear and Timken, respectively), and a coast-to-coast network of leading regional gear, bearing and electrical service brands (The Schulz Group, Wazee Electric, Smith Services, H&N Electric, Standard Machine, H&N Wind Services and Timken Industrial Bearing Repair), TPS is dedicated to providing the most technologically advanced, value-added solutions in the market today.

TPS products and services are found in use worldwide: from underground and surface mining, to offshore drilling platforms, to wind turbine nacelles, to gas, coal, hydro and nuclear power generation, to infrastructure markets like steel, cement and water management – and on through to the most mission critical applications of the American military. The depth and breadth of this combined experience uniquely positions the Timken Power Systems group to serve its customers by reducing downtime and extending the lifecycle of their power transmission equipment.

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I. INTRODUCTION

Sometimes it's difficult to take a holistic view of things. When discussing industrial drivetrains it can be no less daunting a task as one might apply to personal finance decisions, developing a capital project, or even navigating the complexities of the human body. Perhaps it is this last example that best puts the following discussion into proper context.

Just as the body has many organs that function both independently and in concert with others, the industrial drivetrain is similarly composed of many parts that have individual design functions, but are nevertheless dependent on a multitude of other components to ensure they run at peak efficiency.

In this way, one might think of electronic controls as the brain, the motor as the heart, the foundation and bearings supporting the drivetrain as the skeletal system, the couplings as the joints, the gearboxes as the muscles, lubrication as the blood, and the driven equipment as the "life" as it were, that brings forth whatever output is required.

The goal of this paper, then, is to raise awareness about some of the key factors that can influence the health of an industrial drivetrain, and to make clear that, in many cases, the affected component may merely be symptomatic of an underlying cause of substandard performance, or even catastrophic failure. Taking a broader, more holistic approach in considering influences on the entire drivetrain may result in optimal equipment performance and less downtime.

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II. THE IMPACT OF ENVIRONMENTAL CONDITIONS

Even the most well designed equipment can fail if not properly maintained, but effective routine maintenance includes more than just changing the oil, greasing the motor or replacing filters, it involves an in-depth understanding of how the environment can affect the long-term well-being of the equipment.

There are many environmental factors that can significantly influence service life and this discussion will address several of the more influential factors. As defined by Webster's Dictionary, environment is "the total of circumstances surrounding an organism or group of organisms, especially the combination of external or extrinsic physical conditions that affect and influence the growth and development of organisms."

This is exactly why a holistic approach to the maintenance and operation of industrial equipment is vital to long term success. Physical conditions that can impact equipment include temperature, temperature variation, humidity and condensation, and atmospheric contamination. These environmental factors, if properly managed, can increase the life and performance of the overall drivetrain.

Temperature Variations

Temperature variations can have disastrous effects on drivetrain life and wellness and have impacts on lubricant viscosities as they relates to temperatures in the surrounding environment.

When lubricants and cooling oils are chosen for particular drivetrain applications, viscosity at normal and "cold iron"conditions should be considered. At normal operating temperature, a viscosity must be selected that will maintain an adequate oil film in the case of gear teeth and bearing loads, or grease consistency adequate to ensure the proper operating condition of the motor.

In the case of a gearbox that is "cold iron," for example, oil viscosity must be low enough so that when the unit is operated, the splash lubrication or force-fed lubrication system is capable of distributing oil to where it is needed and in the proper amount. If the oil is too thick (due to excessive cold), there may be no splash, or the pump in the force-fed lubrication system might stall, thus failing to supply oil to critical surfaces.

The same situation applies to electric motors. Before a motor is started, its windings are at the temperature of the surrounding air (ambient temperature). Upon start-up the temperature inside the motor begins to rise. NEMA has standardized on an ambient temperature of 40° C, or 104° F for all motor classes in terms of rating the insulation class. But in all cases, the combination of ambient temperature and the temperature increase during operation is what establishes the maximum temperature for the windings of a given motor. This varies from one class of motor to another. What does not vary, however, is the negative impacts of operating at higher temperatures than allowable.

Environmental Effects on Lubrication

Though discussed in more detail in section IV, there are several options to consider when choosing oil for a specific application and temperature differential that should be mentioned here. Some lubricants have a flatter temperature index, that is, as temperature increases, viscosity decreases at a lesser rate than other comparable lubricants. For example, if synthetic oils in gearbox applications are compared to mineral oils, the synthetics have a flatter temperature index, and at a low temperature will be less viscous as compared to a similar viscosity mineral oil.

Some geographies experience severe temperature swings from summer to winter. There are applications in the Western United States that deal with 125° F temperatures in the summer and –40° F temperatures in the winter. Unless different viscosity oils and greases are used with the changing seasons, the lubricants in the severe heat of the summer can be reduced to a kerosene-like consistency, and to a virtual "solid" in the cold of winter. In both cases, the extreme temperatures can put rotating parts and equipment in jeopardy. In most instances production cannot shut down for inclement weather, so must be managed through use of such devices as oil heaters in winter, and air to oil or water/glycol to oil coolers in summer.

Humidity and Condensation

Uncontrolled humidity can ruin equipment within a very short time period. Virgin metal surfaces such as gear tooth surfaces and bearing rollers and races in rolling element bearings, if not protected by an oil film or a suitable preservative will experience rust corrosion almost immediately. Humidity, when combined with a significant temperature change, can condense the moisture from the air and cause a "raining effect" within the motor or gearbox housing, exposing the motor windings, gear teeth or bearing surfaces to corrosion in the form of rust.

This temperature change can often be attributed to the temperature differential between night and day, or the temperature change from the relatively hot operating state of the equipment to the ambient temperature following equipment shutdown. And all of this is in addition to the elements of wind-driven rain or snow, leaking roof structures, or flooding conditions that have on the rise in recent years.

Atmospheric Contamination

Varying operational conditions require a release or introduction of air to properly equalize the internal pressure within the rotating equipment to that of the surrounding atmosphere. As a result, most gearboxes are designed to include breathers, whose sole purpose is to regulate and ensure proper airflow, and in some cases, filter out harmful atmospheric contaminants that enter the gearbox and could be harmful to its moving parts. Similarly, motors are often designed with breather tubes, air flow labyrinths, "weep holes" or desiccant devices.

By seeping into openings created in damaged shaft seals, or improperly maintained breathers, for example, atmospheric contamination can wreak havoc with industrial drivetrain equipment. Particulate contaminants like fly ash in power plants and coal dust in open pit and deep mines are typical of those contaminants that introduce abrasive particles into the lubrication system. The circulation of oil by a pump or grease that exposed to the air can actually become the transportation medium that delivers the contamination to the most vulnerable locations within the equipment, gradually wearing away at components and putting the machine at risk of breakdown.

Like humans, (again that holistic analogy!), enclosed rotating equipment needs to breathe on a regular basis to attain their full lifespan. Breathers permit internal casing pressure to equalize with atmospheric pressure when the machine's operating temperature causes the air inside the casing to expand. If the expanding air volume cannot equalize with the ambient atmospheric pressure, the heightened internal pressure can cause shaft seals to leak. To avoid this condition, the breather – regardless of type or style – allows for continuous pressure equalization to mitigate the intrusion of atmospheric contaminants.

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Breathers can vary from the simple, like the one shown in figure 1a. Devices such as this do the job of equalizing pressure inside the casing with the surrounding atmosphere. This is achieved by use of passing air through a vent hole. However, moisture that might be in the atmosphere due to humidity or other conditions is permitted to enter or exit without interference. Once the moisture gets inside it may condense and form rust on internal elements, including the housing surface itself.

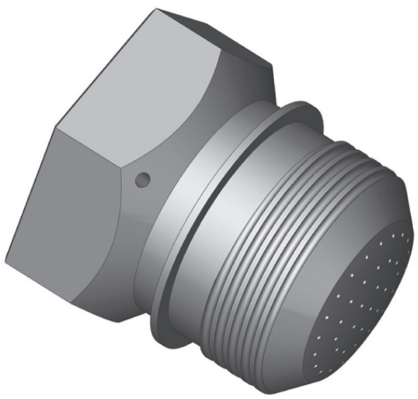

Figure 1a: Simple Air Breather

An upgrade from the commodity type breather is an oil bath breather (figure 1b). This breather also contains a hygroscopic filter. Oil bath breathers force the entering air from the surrounding atmosphere through a small volume of oil located at the bottom of a gooseneck, then through a specially designed hygroscopic filter. The oil (due to its viscous nature) removes impurities suspended in the atmosphere by sticking to the suspended particles and keeping them in the oil bath. The air then continues its path through the breather and passes through a hygroscopic filter designed to retain the moisture from the air, and thereby preventing it from entering the machine's housing.

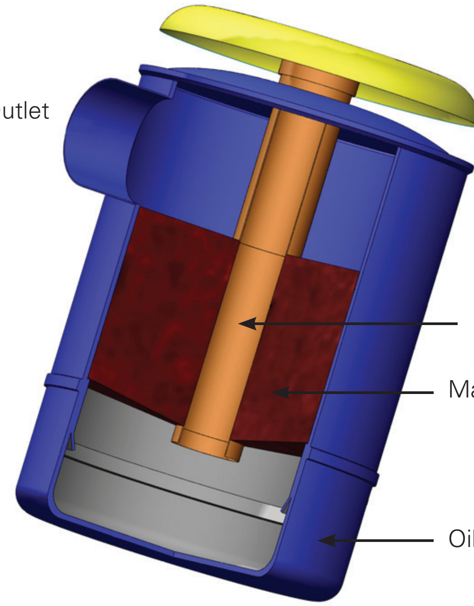

Figure 1b: Oil Bath Breather

Types and Uses of Seals

There are several complications that can arise from a constant flow of air through the equipment since the space between a rotating shaft and the equipment's housing is an area where atmospheric contamination ingress is possible. A variety of sealing strategies can be employed to alleviate this issue and typically have two main considerations: 1.) how to keep lubricant in; and 2.) how to keep airborne contamination of dust, moisture, etc., out.

A single lip type seal (lip facing inward) is designed to contain the oil that runs along the shaft as it rotates (see figure 2). It is constructed from a flexible material like rubber (i.e. Buna N, Viton) or Teflon. Service life is highly dependent on constantly supplying the proper amount of oil as it runs along the shaft while rotating. Without the proper lubrication and cooling, the life span of this type of seal could be measured in days, or even hours. Note that these seals will not prevent leakage if submerged under a head of oil.

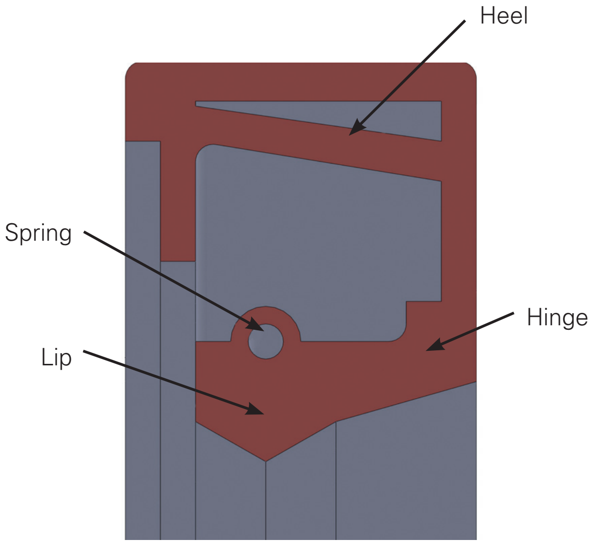

Figure 2: Single Lip Seal

Dual lip seals work on a similar principle but offer a significant additional feature. The outer lip faces outward to keep out atmospheric contamination, and the inner seal faces inward to contain the lubricant. The secret to keeping this seal configuration properly functioning is to ensure that the space between seals contains an adequate amount of grease.

Labyrinth type seals are typically employed for higher speed applications and are used to seal hydrodynamic type bearing side flow leakage that runs along the shaft outside diameter from exiting the housing (see figure 3).

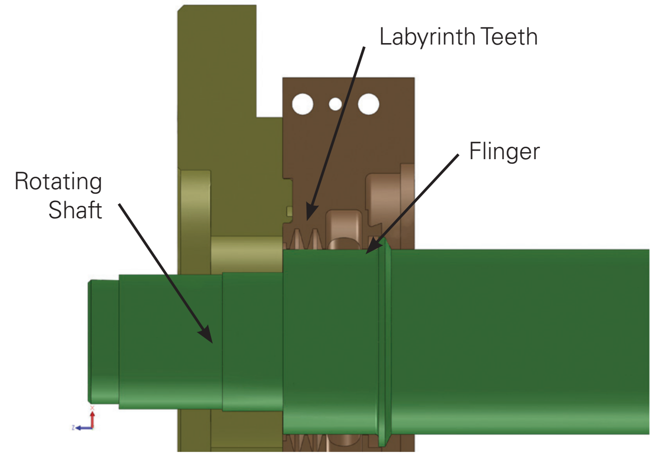

Figure 3: Labyrinth Seal

These seals use a series of knife edge "scrapers" to remove lubricant from the shaft and direct it to a drain hole at the bottom of the labyrinth cavity. Much like lip seals, this design is only effective in prohibiting oil running along the rotating shaft from leaking beyond the last labyrinth cavity. The effectiveness of the labyrinth type seal depends primarily on two conditions: 1) seal to shaft clearance; and 2) the speed of the shaft. An effective seal to shaft clearance is typically two times the bearing clearance. For higher speed applications where the shaft speed is moving at a fast rate, centrifugal force tends to throw the oil running along the shaft radially away from the shaft. The labyrinth cavities are designed such that they effectively trap the flung oil and channel it back to labyrinth drain ports. As with single lip type seals, leakage due to a positive oil head, or oil directly impinging at the shaft to seal interface will not be prevented.

Another type of labyrinth seal which uses the same isolating technique to keep out external atmospheric contaminants and maintain a proper oil seal employs a series of labyrinth spaces. These spaces change the direction of escape or entrance routes and create pressure differentials and turbulence to restrict flow and control leakage. These seals rely on gravity, the weight of the fluid and centrifugal force to maintain an effective seal (see figure 4).

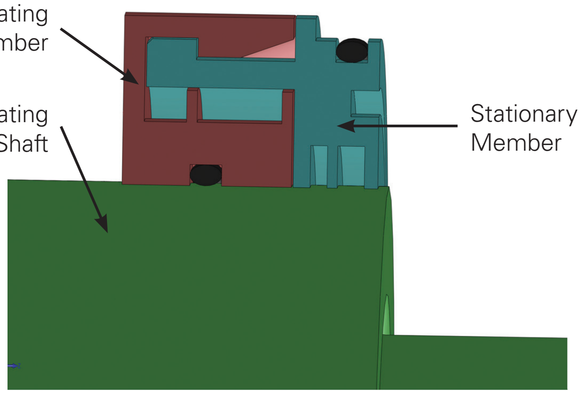

Figure 4: Labyrinth Space Seal

For applications in environments with heavily contaminated atmospheres such as coal dust in a coal mine, taconite dust in the iron fields or fly ash in a power plant, a taconite type seal design is often employed (see figure 5).

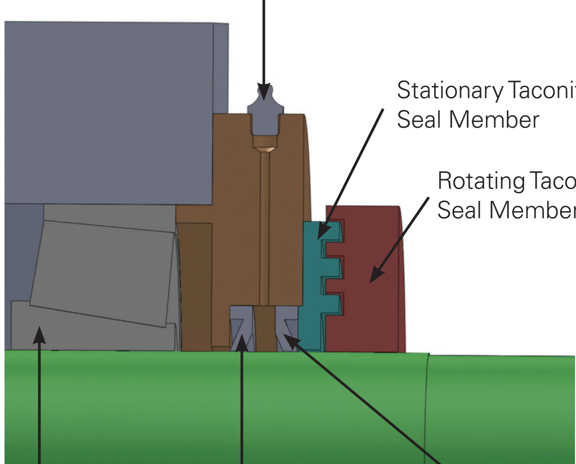

Figure 5: Taconite Type Seal

The taconite design is readily used in conjunction with other sealing methods, and consists of a member that rotates with the shaft that has a series of raised concentric lands. These lands spin relative to a static member that has similar raised lands that are located in the relieved concentric grooves of the rotating member. The grease that is pumped into the lip seal cavity must lift the outer lip seal and be pumped into the circumferential spaces between static and rotating taconite seal members. As long as grease is maintained between lip seals and between the taconite seal members, this sealing method is extremely reliable.

The last type of seal we will discuss here is a face type seal, often used to prevent seal leakage where certain conditions exist that preclude adequate sealing by other less expensive designs, such as when there is a positive head of oil on the seal, where operating temperatures are high, or when excessive misalignment between the rotating shaft and housing bores exist.

Most face seals consist of a rotating and static member interface that operates on an oil film. Typically one member is held to the corresponding member by an external force (i.e. spring force or magnetic force (see figure 6). This face type seal relies on magnetic force to maintain the oil sealing function.

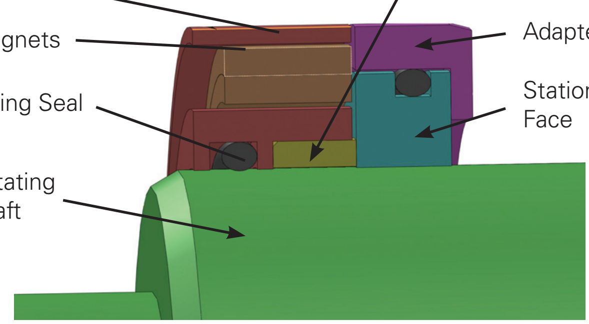

Figure 6: Face Type Seal

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With an abundant number of seal choices, it would seem that any type of external contaminant ingress could be prevented. Unfortunately, failures of motors, gearboxes and bearings can often be traced back to faulty seals that were not properly monitored and maintained. The damage from heat as a result of improper gearbox lubrication, the absence of appropriate grease between seal barriers in motors, or failures to properly monitor and maintain the seals as part of a comprehensive routine maintenance can lead to costly failures.

Now that we have completed our discussion on some of the major environmental influencers that affect the industrial drivetrain, including temperature, humidity and condensation, atmospheric contamination, and the use of breathers and sealing technologies to mitigate these affects, we will now move on to a discussion of the science of sound and acoustics as it relates to these machines.

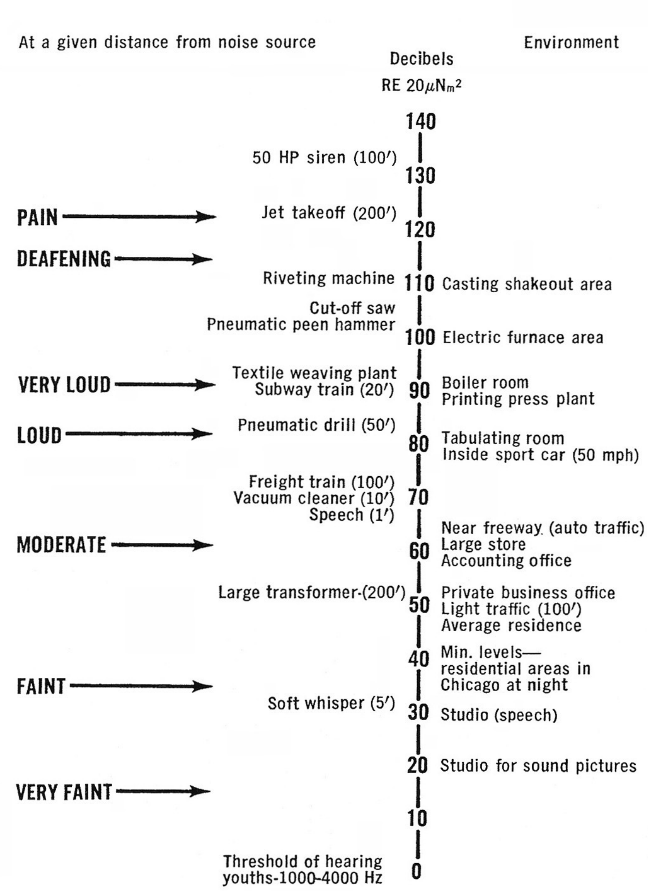
III. ACOUSTIC PROPERTIES OF INDUSTRIAL MACHINERY

Just about everything a person does involves motion. This motion produces "sound." Electromechanical industrial drivetrains designed to increase human capabilities, are necessarily noisier than people. The word noise implies a loud, harsh or undesired sound. Scientifically speaking, "sound is a disturbance that propagates through an elastic material at a speed characteristic of the medium." A clearer way to think of it is incremental changes in air pressure (vibration of air molecules, in other words).

The audible frequency range of sound is often taken as between 20Hz (Hz = Hertz, as in cycle per second) and 20,000Hz (20KHz). However, the human ear has trouble hearing much below 200Hz or above 10KHz. Although our hearing frequency range is limited, we can distinguish both very low and very high levels of pressure fluctuation.

The loudest sound pressure possible is ±1.0 atmosphere (±14.7 psi or ±1 bar), which is something that may occur at the center of an explosion, for example. The threshold of hearing, at about 1,000Hz, is normally around ±0.0000000002 bars (.002 µ bars = .0002 µ atmospheres = 20 µ Newton/meters sq. = .0002 dynes/cm sq. 3 x 10-9 psi). This gives the ear a dynamic sensitivity of about 10-9 power. Because of this high sensitivity, a decibel (dB) scale has to be used, which is familiar to those is working in industrial fields. Figure 7 gives a table of common sound levels and some simple ratios in terms of decibels (dB).

TYPICAL A-WEIGHTED SOUND LEVELS



Typical A-weighted sound levels measured with a sound-level meter.

INCREASE IN LEVELS (DECIBELS—20 Log $\frac{P}{P_o}$)	PRESSURE LEVEL (P) INCREASE
1 dB	1.12 times
3 dB	1.41 "
6 dB	2.00 "
10 dB	3.16 "
12 dB	4.00 "
20 dB	10.00 "
40 dB	100.00 "

Figure 7: Typical A-Weighted Sound Levels

How Operating Environment Influences Sound

Anyone who has held a conversation in a completely empty room and compared it with a similar conversation in a room filled with heavy cushioned furniture, carpet and draperies, understand how sound varies from one location to another. ANSI Standard S12.31-1990 (R-2001) gives four definitions for environments in determining the sound power (energy) of sound sources. These four environments are described as a free field, free field above a reflecting plane, a diffused field, and a semi-reverberant field. To describe what is meant by these fields it is necessary to introduce the concept of sound power level.

The sound power of a source is the total sound energy radiated by the source per unit of time. The level of sound power (Lw), like sound pressure, is expressed in terms of decibels. However, it is extremely important to recognize the difference between sound power level (Lw) and sound pressure level (Lp). Sound power is the energy at the source. The sound pressure is the fluctuation of air pressure at the point of measurement. The sound power of a source is independent of the environment. Whereas, the sound pressure measured near a source is highly dependent on environment. The paradox is that we must measure sound pressure to calculate sound power (sound power cannot be measured directly).

A "free field" environment around a sound source can be thought of as being like a fan running on top of a tall flag pole in the middle of 1,000 flat acres of open land. In a free field, all the sound is radiated away from the source and the pressure waves lose their strength as they dissipate into the surrounding air.

The further away from the source, the lower the measured sound pressure level. The opposite of a free field is a reverberation chamber (diffused field), with a source placed in the center of the empty room with hard skewed walls, floor, and ceiling. Almost all of the sound from the source will be reflected around the room and back at the source so that the sound pressure level measurements at any point in the room are about the same.

Obviously, industrial equipment environments are neither free field or diffused field, but rather some form of semi-reverberant field. In a semi-reverberant field depending on room size, reflecting objects, absorption and other acoustical conditions, the reduction in dB from 5 feet away to 10 feet away from the source could be less than 1 dB or as great as 6 dB. The point being that a dB sound pressure measurement is highly influenced by its acoustical environment.

Another extremely important consideration when evaluating generated sound pressure level of machinery is that sound can be "structure borne" for considerable distances without significant attenuation. Structural steel beams may provide a path for structure borne sound (vibrations) to travel significant distances, and then radiate "airborne" sound pressure levels at nearly the same level as at the source. Furthermore, structure borne sounds may excite natural resonances of other equipment and structures, and thus create a sound pressure level louder than the source under investigation. If the sound levels of a gas turbine driven-gear-compressor system, for example, are being measured to determine the "gear noise," one could ask the following questions:

1. What is the major noise source; turbine, gear unit, compressor, piping or structure?
2. How much of the noise is traveling through the support structures and radiating at some point other than its source?
3. Is the gear unit mesh frequency exciting a natural resonance in the sheet metal cover of the turbine, or the piping, etc.?
4. Is a blade pass frequency exciting a natural resonance of the bull gear web or the gear housing?
5. What are the sound levels at different loads or speeds?

This list could be continued at great length, but one can see that there are many different influences when trying to determine the sound level of a gear unit in the middle of a power transmission system. The exact same gear unit may generate completely different sound levels in two different systems, and motor can be similarly affected. So, if an "accurate" sound power level can be established for a source, it is the only method for rating the source independent of environment. If dB "A" sound pressure level is used as a criterion, it must be remembered that the environment and mounting will influence the results of "A".

Tolerances and Specification of Sound Levels

There are many different types of specifications for limiting sound levels. However, it may be best to classify two general areas of concern:

1. The level that is normal or satisfactory for the type of equipment or application.
2. The level that is acceptable or safe for people who must hear without damage in the area of the operating equipment.

Both of these areas of concern are difficult for accurate evaluation because of the lack of information on sound power levels of all sources, characteristics of all environments, and because human sensitivity to noise varies.

Therefore, general or normal guidelines have been established as acceptance criteria. Satisfactory equipment sound level specifications are normally stated in terms of acceptable octave band levels for eight principal bands.

It must be recognized that a specification level has to be pointed toward a specific environment whether it be a test stand or a field measurement. We normally want to use the test stand, at the point of manufacture, as the acceptable environment. It is reasoned that the semi-reverberant field of a test stand is similar to many installation environments and therefore, within limits, the sound pressure levels will be similar.

Trying to comply with specifications that are pointed toward hearing conservation (OSHA, state and local ordinances) presents a different situation. To meet OSHA requirements, (see figure 8) one must know the position of the people exposed to the generated sound and the duration of the exposures. Presently, if an operator stands near a machine generating 98 dB "A" at five feet for only two hours out of every day, the area meets the environmental requirements of OSHA. However, the same installation would not meet OSHA requirements if the operator had to stay in the area of 98 dB "A" for three hours or more each day.

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O.S.H.A. AND WALSH-HEALEY PUBLIC CONTRACTS ACT

Rules and Regulations 1910.95 Occupational Noise Exposure

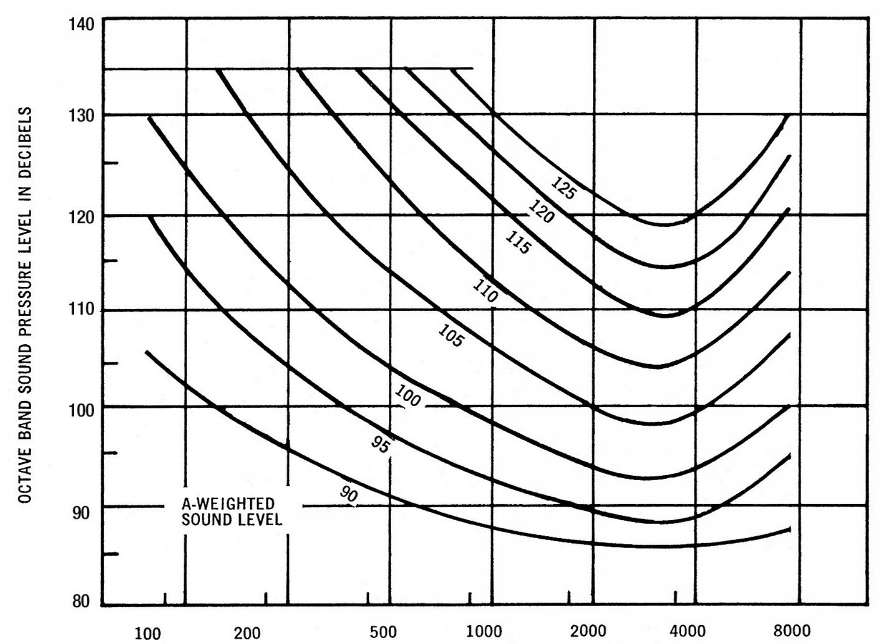
(a) Protection against the effects of noise exposure shall be provided when the sound levels exceed those shown in Table 1 of this section when measured on the A scale of a standard sound level meter at slow response. When noise levels are determined by octave band analysis, the equivalent A -weighted sound level may be determined as follows: (see graph)

(b) When employees are subjected to sound exceeding those listed in Table 1 of this sections, feasible administrative or engineering controls shall be utilized. If such controls fail to reduce sound levels within the levels of the table, person protective equipment shall be provided and used to reduce sound levels within the levels of the table.

(c) If the variations in noise level involve maxima at intervals of 1 second or less, it is to be considered continuous.

(d) In all cases where the sound levels exceed the values shown herein, a continuing, effective hearing conservation program shall be administered.

Exposure to impulsive or impact noise should not exceed 140 dB peak sound pressure level.



Equivalent sound level contours. Octave band sound pressure levels may be converted to the equivalent A-weighted sound level by plotting them on this graph and noting the A-weighted sound level corresponding to the point of highest penetration into the sound level contours. This equivalent A-weighted sound level, which may differ from the actual A-weighted sound level of the noise, is used to determine exposure limits from Table 1.

Table I
Permissible Noise Exposures[1]

Duration per day, hours	Sound level dBA, slow response
8	90
6	92
4	95
3	97
2	100
1½	102
1	105
½	110
¼ or less	115

[1] When the daily noise exposure is composed of two or more periods of noise exposure of different levels, their combined effect should be considered, rather than the individual effect of each. If the sum of the following fractions: C1/T1 + C2/T2…Cn/Tn exceeds unity, then the mixed exposure should be considered to exceed the limit value. Cn indicates the total time of exposure at a specified noise level, and Tn indicates the total time of exposure permitted at that level.

Figure 8: O.S.H.A and Walsh-Healey Public Contracts Act

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It must be emphasized that a manufacturer cannot supply equipment to meet an OSHA dB "A" rating if the position of the operator or exposure time is unknown. It therefore becomes more realistic for the user to specify permissible sound levels in terms of octave band measurements at a specified distance, or overall dB "A" level at a specific location and environment.

Another highly important consideration is that most environments contain more than one noise source. Therefore, we must sum their amplitude, as stated earlier. This means when supplying individual components in a system, each must be significantly below 90 dB "A" if the whole system is to be below 90 dB "A" at a specific position.

Noise not only may impair hearing – it has been known to increase blood pressure, heart rate, gastrointestinal tract responses and cause bad psychological effects. The loudness of a sound depends on its frequency, and there are different scales used to determine relative loudness. Noise does not have to be loud to be annoying. The sound of a dripping faucet, chalk squeaking on a blackboard, or a high pitch siren are good examples. Impact noises about 45 dB "A" will generally awaken people asleep at night, no matter how innocent it may look on a sound level meter. Generally, broadband "steady-state" noises (hum) are less annoying than an intermittent noise (beats), pure tone (whine) or impulsive noise (impact). Harmful steady-state noise may be overlooked, whereas quiet beats may be subject to scrutiny. Therefore, even if a unit within an industrial drivetrain meets a specified sound level it can be annoying and become a subject of complaint.

Methods of Lowering Generated Sound Levels

Upon reviewing the expected sound level, or hearing a "noisy" unit, the first question may be "how could the generated levels be improved or lowered?" There are three general approaches to lowering generated sound levels:

1. Enclose or isolate the source so that the operators are shielded from the noise
2. Absorb sound that may be normally reflected
3. Eliminate or lower the sound energy produced at the source by improved quality or design

Generally speaking, absorbing or isolation of sound from sources is the most economical means of lowering sound levels. Because some generated sounds are machine characteristics, no amount of redesign or improved quality will eliminate these sounds. However, when possible from an operation standpoint, the most desirable method of lowering sound levels is by design or quality improvements. Improved sound or vibration levels achieved from "smoother" operation will also tend toward lower dynamic loads and improve the durability life of the prime mover, gear reducers or increasers, bearings and couplings.

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Causal Examples of Problematic Sound Levels

Instruments that provide the operator with not only the amplitude of the vibration or noise, but, also the predominant frequencies can be a tremendous aid in determining problem cause. These causes normally present themselves as follows:

1. Imbalance: Presents itself at a frequency equal to once per shaft revolution and it will increase in amplitude as speed is increased.
2. Misalignments: Will present themselves also at once or sometimes twice and three times per shaft revolution. However, the amplitude will remain fairly constant with speed changes.
3. Friction: This is difficult to pinpoint by vibration and noise frequency of occurrence, which may be very high when continuous sliding occurs. It may also be random, high-amplitude, shock-type pulses, as in hydrodynamic bearing rubbing. It may be irregular and often violent.
4. Looseness: This may cause unbalance, misalignment and friction rubbing at moderate and high speeds. At low speeds, it may display itself as an irregular rattle. Often it shows up at twice shaft rotational speed.
5. Casing Distortion: This is often an indirect cause of vibration and noise, which also leads to unbalance, misalignment, or friction. It will tend to change in amplitude with load or operating temperatures, when speed is held constant.
6. Critical Speeds: These occur through any given speed range and are points at which a rotating system vibrates torsionally or laterally at a particular frequency. Rotors characteristically show violent increase in amplitude at particular critical speeds but are fairly stable above and below these speeds. A critical speed may change frequency with load and temperature.
7. Resonances: these also display themselves as frequencies at which system members vibrate. The distinction from critical speeds is that resonances occur in other than rotating members, and can affect alignment. Resonances occur at fixed frequencies and change in amplitude with load and temperature.
8. Gear Tooth Profile Wear: This will show up at tooth mesh frequency (i.e., rotating speed times number of teeth) and multiples of this mesh frequency.
9. Bearing Instability: Improperly designed rolling element bearings will cause high-frequency vibration at several times rotational speed, also friction vibration will occur. Lightly loaded hydrodynamic bearings will tend to whirl at .43 to .47 times the rotational speed. This so-called "half-frequency whirl" will "on-set" rotor instability with speed or temperature changes and may continue until the rotor is completely stopped.
10. System Pulses: These may occur in many types of systems, such as the vane-pass frequency of a pump or compressor (rotational speed times the number of vanes), and the beating of reciprocating engines which cause frequencies at one-half and one-quarter rotational speed at various amplitudes.
11. Windage: From couplings and other rotating parts (generally broadband noise), but can be at a bolt pass frequency or fan blade pass frequency.

Note: Some of all of these types of vibration and noise frequencies can be generated in rotating equipment. Major frequencies can interact and cause frequency modulation and phase shifts. Any combination, sum, difference and multiple (harmonics) of the prime frequencies can occur if the forcing magnitude and system degrees of freedom are such that they will cause and allow the generated vibration to become predominant. Generally, only the prime frequencies will present themselves as problem modes, but, sometimes very elusive frequencies do appear, and can require exhaustive analysis to determine the root cause.

Figure 9 - Common Sources of Airborne and/or Structure-borne Sounds

In this section of the paper we have tried to give a useful overview on a very complex subject. In summary, when sound levels are being discussed, we must be mindful of the following considerations:

1. What specification(s) are applicable and what required levels must be achieved?
2. Does the standard or normal unit of the type being considered meet the requirements?
3. What improvement and costs are involved when a design change or improved quality is specified?
4. What costs are involved if enclosures, isolations, or absorbing materials are used?

IV. LUBRICATION METHODS AND SYSTEMS

Ultimately, the goal of owners and operators of rotating equipment is to achieve a return on their investment by maximizing output and minimizing downtime. Continued reliability and successful operation can be largely dependent upon the constant supply of proper lubricant delivered in the correct quantity to support all modes of operation.

The purpose of a lubrication system – whether it be a simple grease fitting, or a complex fore-fed system is to provide an protective film at the contacting surfaces of all working components to reduce friction and wear. In addition, the lubricant can help remove and dissipate heat. Other lubrication functions include the transfer and/or removal of wear particles, as well as the filtration of rust and corrosion and any other undesirable contaminants in certain applications. So it follows that failure to lubricate rotating equipment as proscribed can lead to premature failure.

Understanding Lubrication

Lubrication can be defined as the control of friction and wear between adjacent surfaces by the development of a lubricant film between them, called an elastohydrodynamic (EHD) film. EHD film thickness between gear tooth surfaces, for example, is quite small, usually less than 1.25 micrometer (0.00005inch). However, it is still quite significant since if the adjacent surfaces are not fully separated, the EHD film leaves local areas of contact between the surfaces, making them vulnerable to surface fatigue.

Viscosity is a characteristic of fluids to resist flowing freely. It is one of the most important characteristics of a lubrication fluid. The viscosity of lubricating oils changes appreciably with temperature, and is generally stated at two temperatures, 40°C (100°F) and 100°C (210°F). Viscosity is usually expressed in terms of the time required for a standard quantity of a fluid at a given temperature to flow through a standard opening.

The fatigue life of contacting components such as gear teeth and bearing rollers is determined by a complex combination of speed, load, lubricant temperature, clearance and alignment. The lubricant's role in this interaction is determined primarily by speed, viscosity, and temperature. The effect of these factors on the fatigue life of elements can be dramatically altered at higher temperatures with lower viscosity, and thinner resultant oil films. The selection of the correct lubricant for any application requires a careful study of expected operational and environmental conditions.

Types of Lubricant

Several factors must be considered before choosing a lubricant – the unit's operating speed and load, temperature range and lubricant availability, to name a few. The science of tribology (the study of friction, wear, lubrication, and of interacting surfaces in relative motion) is vast and well beyond the scope of this paper. What follows then, are some general descriptions of the types of lubricants commonly seen in an industrial setting.

Greases (typically used in industrial motors NLGI Grades 2 and 3) should have good base oil viscosity as mentioned above, be able to resist high-temperature oxidation, and have low oil bleed, anti-wear, and low-temperature torque characteristics.

High-load oils, called Extreme Pressure (EP) lubricants, contain selected additives that increase the load-carrying capacity of gearing by forming a film on the metal that provides component separation under higher load conditions. Extreme pressure lubricants are ideal for use when severe operating conditions are anticipated. Oftentimes, these lubricants will contain more than one chemical additive for load capacity enhancement over a wide temperature range, such as phosphorous and sulfur.

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Petroleum-based lubricants (typical of gearboxes and other industrial equipment) are complex mixtures derived from the refining of crude oil. Petroleum products have been found to excel as lubricants in most applications. Mineral oils are usually compounded with different chemical additives to improve specific properties – properties such as increased lubricant life, resistance to rust and oxidation, and even increased load-carrying capacity.

Synthetic lubricants consist of base fluids manufactured by chemical synthesis or molecular restructuring to meet specific physical and chemical qualities desired for certain operating parameters, such as high-temperature thermal and oxidation stability; low-viscosity variation over a broad temperature range; low-temperature capability; and/or long service life. Care must be taken when synthetic lubricants are substituted for previously utilized lubricants. Compatibility with other components like rubber lip seals, rubber O-ring seals and housing paint must be established. Many synthetic lubricants contain an ester chemical linkage, which allows the lubricant to perform well at both high and low temperature ranges.

Synthesized hydrocarbon lubricants contain some of the advantages of chemical synthesis (esters), but have a similar structure to mineral oils, making them compatible with mineral oils while not being detrimental to seals and paints (esters have low compatibility with some polymeric materials such as those used in seals and paints, for example). In some cases these are good alternatives to "full" synthetic products due to increased performance over mineral oils at a reduced cost.

In general, the lowest viscosity oil capable of forming an adequate oil film at all operating conditions should be chosen. However, in practice, the lubricant chosen is often a compromise between the requirements of the various lubricated components – such as gears and bearings – and the particular application requirements such as large ambient temperature differentials.

Splash and Force-Fed Lubrication Systems

There are a variety of lubrication systems in use, but the most commonly seen are splash lubrication systems, and force-fed lubrication systems. The intent of both types of systems are the same, to distribute oil to each component for lubrication and cooling of that component, while minimizing heat generation by oil churning. To operate a given unit at maximum efficiency, auxiliary cooling schemes are sometimes employed. Adding cooling fins to increase the surface area of the casing, for example, can increase the heat transfer from the motor or gearbox housing to the ambient air.

Splash Lubrication (Reservoir System) systems require the equipment to be filled to a predetermined lubrication oil level. Rotating gear elements within a gearbox, for example, must dip into the oil and "sling" it into troughs, pockets or directly to bearings and gear meshes requiring lubrication and cooling oil. Feed troughs are employed to capture oil that is "slung" onto the upper gearbox housing wall by a dipping gear element. This oil drips into the trough, which, in turn, distributes that oil to the bearings. Such systems are better suited for gearboxes containing rolling element bearings than those with journal bearings, which require far more oil.

Splash lubrication systems are far simpler and less expensive than force-fed systems, but are limited. When shaft speeds increase and the heat generated becomes excessive, or when lubricant must be targeted to precise areas within a given machine (such as gear and bearing interfaces), splash systems may no longer be adequate. Sometimes auxiliary cooling can be used in combination with splash lubrication to increase thermal ratings by forcing air past the radiating surfaces of the housing, or by use of a water jacket that is isolated from the lubrication oil sump.

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Force-Fed Lubrication Systems can be closed or open loop. In a typical force-fed lubrication system, a shaft-driven oil pump or a motor-driven oil pump draws oil from the machine's sump through a suction pipe. The oil is directed from the pressure side of the oil pump through a filter to cleanse the oil, and through a cooler employed to cool the oil. A pressure relief valve is typically located before this filter to protect the system from too high an operating pressure. If the filter becomes clogged, the relief valve will permit the unfiltered oil to bypass the filter. Another relief valve is often located at the inlet to limit the oil feed pressure if the system contains both a shaft-driven and a motor-driven pump, and both are running at the same time.

In the example of a gearbox, a shaft-driven oil pump is a pump that is driven by one of the rotating gear shafts. Some lubrication systems will include both a motor-driven and a shaft-driven oil pump. The motor-driven pump can be activated at startup to supply full oil flow prior to the shaft's rotation, and until the attached lube oil pump is running at a speed sufficient to supply adequate oil flow. This can also serve or as a backup in case of failure of the main shaft-driven oil pump.

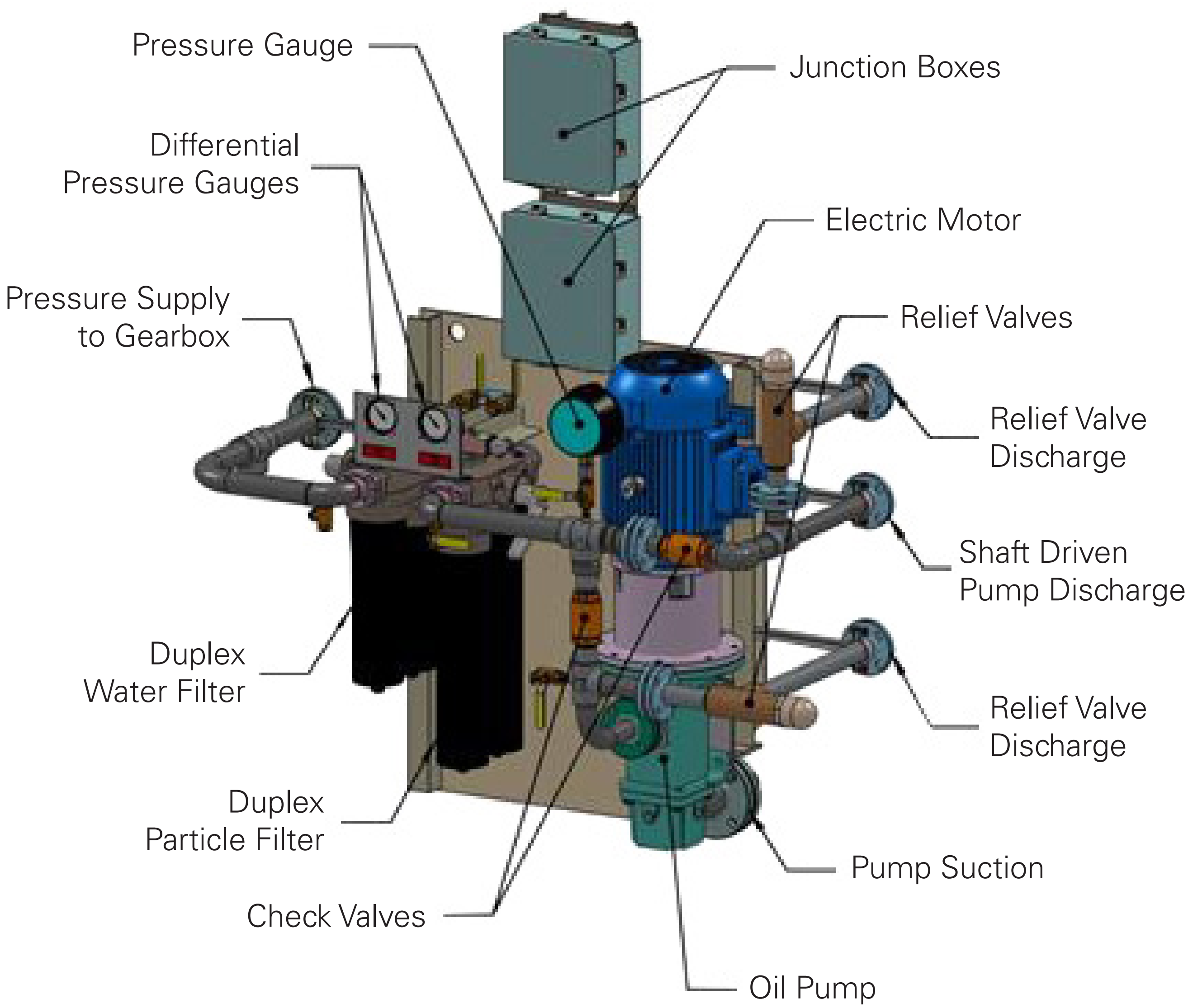

Figure 10: Example of Force-Fed Lubrication System

Lubrication System Components

Check valves are located so that the main pump does not pump through the auxiliary system and that the auxiliary pump does not pump into the pressure side of the main oil pump. A bypass is provided at the cooler, serving as both a pressure relief valve and/or a thermostatically controlled valve set so that the pressure drop across the cooler is limited during times when the oil is cold; additionally, temperature and pressure sensors are located at various critical points throughout the system.

Oil pumps deliver a given quantity of oil over a wide range of oil temperatures and viscosities and should be capable of priming itself and overcoming pressure drops in the line between the oil reservoir and the suction port of the pump. The most common method of lubricant delivery is the positive displacement pumps that deliver a given quantity of fluid with each pump rotor revolution, directly proportional to its operating speed. These pumps can be mounted to the unit and driven by one of the gearbox shafts, or independently mounted with an electric motor or other prime mover driving. When the pump is shaft-driven, oil flow will vary directly with shaft speed. In a gear pump, as the gears rotate, fluid is trapped between the gear teeth and the case, and is carried around the pump casing to the pump discharge oil port.

Filtration systems are designed to remove contamination due to a variety of causes such as: internal component wear that generates particles washed into the oil stream; or foreign particles finding their way into the system during assembly, maintenance and everyday operation. In addition to the filtration of fluids, the lubrication filters often incorporate a bypass for clogged element conditions, a magnetic device to trap ferrous particles, and/or a visual or electronic cleanliness indicator. Filter media must also be compatible with the lubricant, meet viscosity requirements without excessive pressure drop, and remove harmful particulates. In most cases the filter should be located on the pressure side of the pump so warmer, less viscous oil is being filtered. Filter elements can be cleanable and reusable or disposable. Cleanable filter elements are usually made of wire mesh, with cleaning commonly accomplished using an ultrasonic liquid bath or air pressure.

Coolers in force-fed lubrication systems must be capable of achieving the required oil temperature drop when exposed to the maximum ambient air temperature anticipated for the application. However, a generous temperature margin should be applied during design to account for cooler deterioration.

The two types of coolers used are liquid-to-liquid and liquid-to-air coolers. In oil-to-water (liquid-to-liquid) coolers, hot oil gives up heat to cooler water, resulting in cooler oil and hotter water. Where water is unavailable, radiators are used to blow cooling air over oil tubes. However, air-to-oil (liquid-to-air) coolers require larger envelopes than water-to-oil coolers; in addition, hot days will limit the amount of cooling a radiator can achieve.

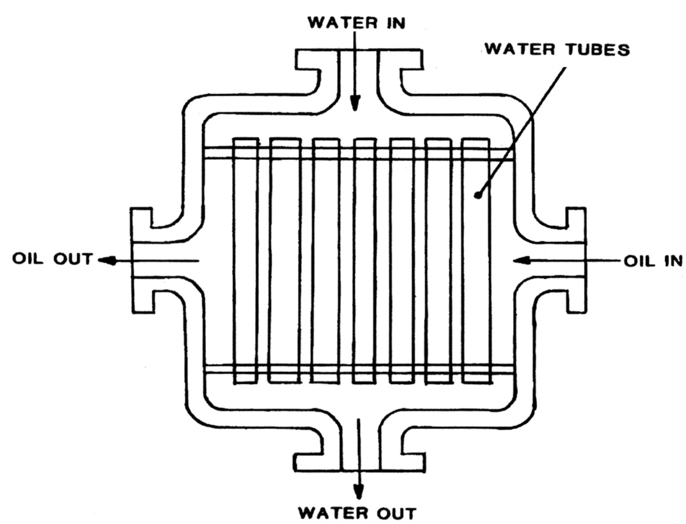

Figure 11: Typical Oil-water Cooler Configuration

Oil reservoirs may be integral with the machine or separately mounted and connected by piping. The level of oil in the reservoir will vary from a maximum when the unit is shut down and oil has drained from lines and components, to the minimum permitted during operation. Therefor the reservoir tank must have sufficient volume to accommodate the drain backflow and still retain some air space at the top. To ensure complete draining for cleaning and oil changes, the unit should be fitted with a drain connection located at or near the bottom of the sump. However, the oil pump suction line should be located slightly above the reservoir bottom to prevent sediment from being pulled into the suction line. Oil return lines should be piped into the reservoir near the maximum operating level away from the area around the pump suction connection so that the incoming oil must travel the maximum distance to the pump suction. By maximizing this dwell time, the oil has more time to lose any entrained air before it is again circulated through pumps, filters and coolers.

Breathers (described in detail in Section II) are used to vent pressure that may be built-up in the unit, which may result from air entering the lubrication system through seals or the natural heating and cooling of the unit. When a cold gearbox starts up, for example, the heat generated during operation will cause air pressure to build within the gearbox housing.

Lubrication system piping is intended to distribute lubrication oil in accordance with system design requirements and should be as simple and direct as practical. Piping connections can cause problems at assembly and startup, so it is good practice to have only one external oil feed connection, with all other oil passages placed inside the system casing – this means that any slight leakages in the piping connections will be internal and harmless. This also means there will be less chance of damage during installation. In all, the piping arrangement must be carefully designed to minimize pressure drops and leakage sources.

Lubrication Monitoring

In providing reliable service, the lubrication system must incorporate sufficient sensors to allow continuous and complete monitoring of the lubrication system's operating condition.

Resistance temperature detectors (RTDs) allow continuous monitoring of temperatures at key locations, such as oil supply and drain temperatures, as well as sump temperature. RTDs should be duplex type to obtain redundant readings for accuracy or to supply a backup.

Temperature switches are typically used as a trigger to alarm or shutdown the prime mover when excessive temperatures are experienced, and can be used as a permissive for cold temperature start-up. These switches are typically located in the main oil reservoir and lube oil supply lines.

Pressure switches are used as a mechanism to trigger the operation of auxiliary back up pumps, as well as to initiate a signal for system shutdown when pressure is lost at the main oil inlet to the gearbox or other rotating piece of equipment.

Flow switches are used as a trigger to signal loss of flow below the minimum oil demand requirements of the system.

Water detectors alert users to the presence of water in the oil, which is one of the most harmful contaminants. Not only does it reduce viscosity, water can react chemically with EP additives under certain conditions with the potential to encourage ionization or even form corrosive acids.

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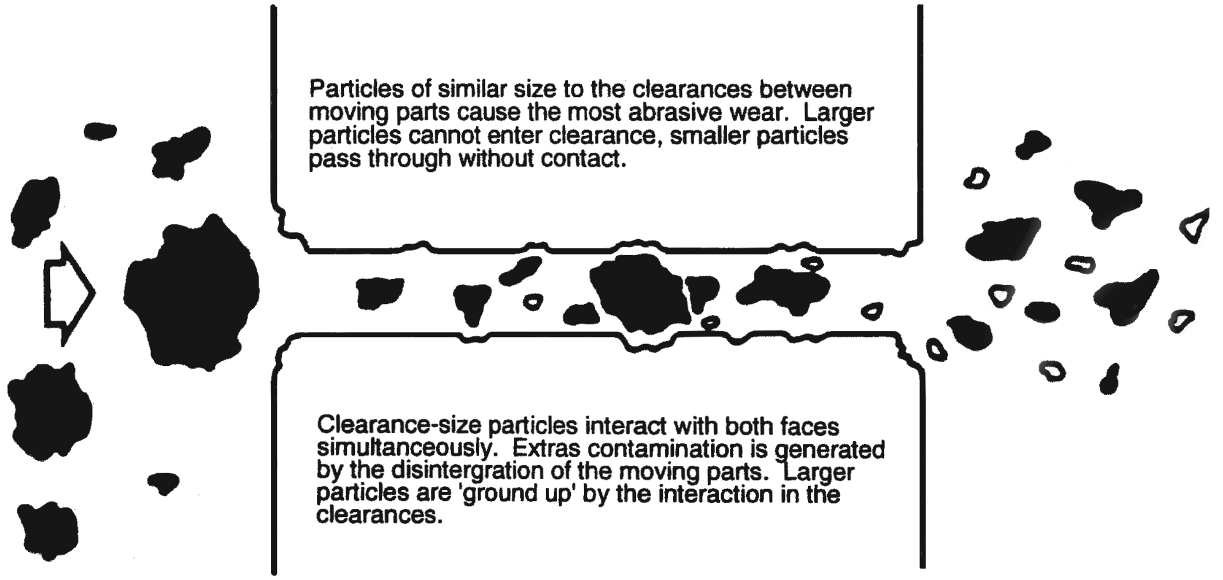


Figure 12: Abrasive Wear of Contaminate Particles

Lubrication System Maintenance

Given the integral role that the lubrication system plays in the overall life of industrial drivetrains, they must be continually maintained to assure peak performance. A systemic method of inspection, condition verification, and documentation to avoid unexpected failures is critical. The following are areas of concern for maintaining a properly functioning lubrication system.

1) **Cleanliness** – Obviously, dust, dirt, grit and wear particles in the lubricant supply must be kept to a minimum and filters and strainers should be serviced regularly to avoid circulating contaminants within the system.

2) **Lubricant condition** – The service life of a lubricant is negatively affected by a number of factors, including high temperatures, water and/or emulsions, solid contaminants, and operating environment. Oil samples should be drawn from the oil sump at scheduled intervals and analyzed by the lubricant supplier or a reputable maintenance provider.

3) **Sensor/switch settings** – An annual check on all switches and sensors should be performed to verify operation as per the system schematic's specified settings. System vibration and environmental conditions can alter settings, ultimately affecting critical timing and initiation of sensor functions.

4) **Auxiliary pump function** – Pumps and other motorized accessories should be checked at scheduled intervals to verify operability, proper oil delivery, pressures, and motor power draw. Relief valve settings should be checked to ensure that the required oil delivery is supplied to the gear drive at the proper pressure.

5) **Flow and pressure check** – Flows and pressure drops at the cooler, filters, and inlet to the rotating equipment should be routinely monitored and recorded to identify any adverse trends that might be developing.

6) **Cooler condition** – An annual check of cooler condition is important to maintain cooler efficiency. Water-cooled heat exchanger coolant ports should be checked for any fouling or blockage. All sacrificial anodes should be replaced. Air-oil cooler core fins should be checked and cleaned of any dirt build up that would affect heat transfer efficiency.

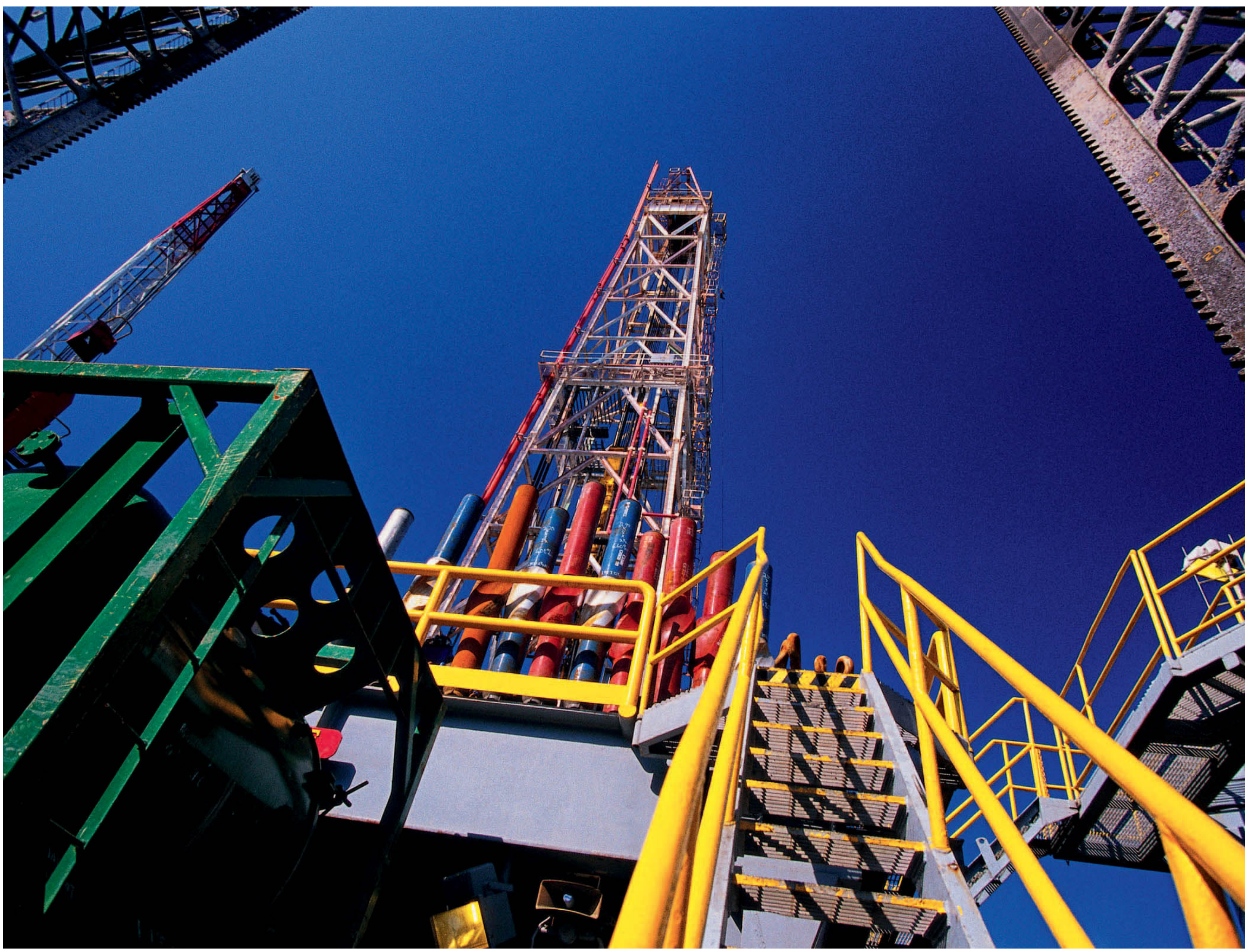
7) **Breathers** – Oil breathers should be checked frequently, as any blockage in the breather could potentially lead to leakage elsewhere in the drivetrain in order to relieve pressure.

8) **Visual component check** – The entire lubrication system should be checked daily for all indicator gauge readings, pipe connections, vibration, bolted connections, oil leaks or seepage, loose accessories and wiring connections.

9) **Sound levels** – The operating sound level of the pumps should be routinely noted. Any increase in sound level could indicate the presence of air in the lube system, blockage at the pump intake, air leaks in the pump shaft seal, worn or loose parts in the pump, filter blockage or high oil viscosity from the pumped fluid being too cold.

10) **Grease points** – Some motors and pumps are equipped with greased bearings, which must be lubricated at manufacturer recommended intervals.

Clearly, the lubrication system plays a vital role in the ultimate successful operation of an industrial drivetrain. Continuing such success is largely dependent upon the uninterrupted supply of the proper quantity, quality and condition of lubricants from grease, to mineral oil, to synthetics. Developing a systematic method of inspection, condition verification, and documentation – as well as partnering with a lubrication and/or manufacturing expert that can provide further insights into lubrication system operation – is essential to avoid any unexpected lubrication system shutdowns and any possible subsequent equipment damage.



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V. PREVENTIVE MAINTENANCE

When equipment fails, often a plant manager's biggest concern is how to get the equipment running again. However, equally important to getting it back online is discovering 1) why the equipment failed, and 2) how such a failure can be prevented in the future. But plant managers and reliability engineers don't always have the in-house resources to identify the root cause of such problems, ultimately leading to their recurrence. Preventive maintenance is defined as the regular performance of equipment maintenance practices in order to avoid future equipment problems. An important first step in any preventive maintenance program is learning to identify the contributing factors of equipment failure. Once the cause of failure is determined, one can take steps to avoid the problem in the future. The purpose of this section is to highlight some diagnostic tools to, ultimately, help stakeholders understand the fundamentals of effective preventive maintenance programs.

Lubrication/Oil Analysis

Always important when there is potential metal-to-metal contact, effective lubrication is extremely critical to all rotating equipment. Proper lubrication will help prevent both gear and bearing failures resulting from insufficient or interrupted lubrication. By contrast, many motor and bearing failures are due to over application of lubricant (see figure 13).

Figure 13: Failure Caused by Over Greasing of Motor

Maintaining proper lubrication necessitates following proper lubrication practices. These include selection of the appropriate lubricant, keeping oil clean and free of foreign materials, and maintaining a sufficient supply of lubricant. Because selecting a lubricant is based on so many independent factors – driven equipment type, load type, speed, operating temperatures, input power, and reduction ratio in the case of gearboxes – choosing a lubricant should be left to a specialist. This is especially true considering the amount of specialized lubricants and additives now available.

Lubrication shortcomings that result in metal-to-metal contact cause failure modes like scoring and galling that may not result in immediate failure, or lubricant film breakdown resulting in such high temperatures that immediate and catastrophic damage occurs. Abrasive wear may also occur as the result of foreign materials present in the lubricant, or corrosion could occur in the case of water contamination.

Still, maintenance professionals are not helpless and have several important tools at their disposal for diagnosing lubrication problems. One of these tools, oil analysis, plays a crucial role in not only preventing such problems, but in assessing the overall health of rotating equipment.

By analyzing particulate content and concentration in the oil, engineers are able to monitor the condition of the equipment. Further analysis of the oil yields vital information concerning the condition of the lubricant used in the equipment (see figures 14 and 15).

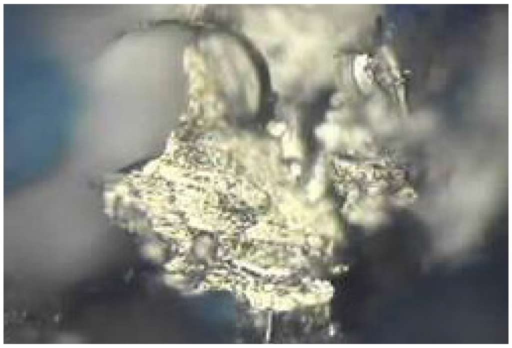

Figure 14: White Metal Particle Misaligned with Magnetic Field

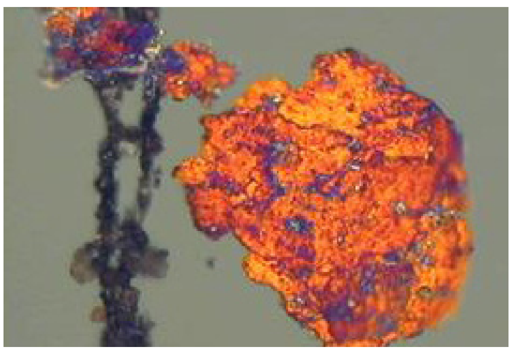

Figure 15: Sample of Magnified Oil Analysis Indicating Roller Bearing Contact Failure

Analysis of the lubricant could alert engineers to possible problems within the lubrication system itself, for example, which is not a small consideration. Equipment that has exhibited frequent mechanical problems, or that would cause an outage were it to fail, should be checked regularly, and include a visual inspection of the lube skid, piping, filtration system, etc., to ensure there are no leaks or pressure losses.

In a sort of "tail wagging the dog" example, lubrication problems can sometimes be detected by examining the equipment wholly independent of the lube analysis program. Gear tooth pitting, for example, is characterized by a large number of very small pits, distributed evenly over the working surface of a gear. The appearance of such pitting is often an indication of gear overload, but it may also be indicative of lubrication problems caused either by some corrosive medium within a lubricant, or by improper lubricant additives not suited to the application.

Vibration Analysis

Vibration – the motion of a body about a reference point caused by an undesirable mechanical force – is a key indicator in the diagnosis of machine faults. Each machine fault generates a specific vibration profile, and a single vibration measurement provides information concerning multiple components. The frequency of the vibration is determined by the machine geometry and operating speed.

By analyzing shaft vibration, engineers are able to determine whether the cause of the machine fault is imbalance, misalignment, general looseness or wear, bearing defects, gear defects, or some other unforeseen problem. Therefore, it is critical not just to capture the data, but to have a qualified vibration analyst determine what the collected data is actually saying.

Imbalance is the force created by a rotating body when its center of mass is offset from its center of rotation. High radial peaks at 1x shaft RPM, low axial vibration at 1x shaft RPM, low harmonics of shaft RPM, and 1x RPM sinusoidal pattern in the time waveform characterize imbalance (see figure 16). Imbalance can cause other faults to appear as well. Once a structure is vibrating, any number of ancillary components can become loosened. Hardware and piping are good examples of items that are loosened due to excessive vibration.

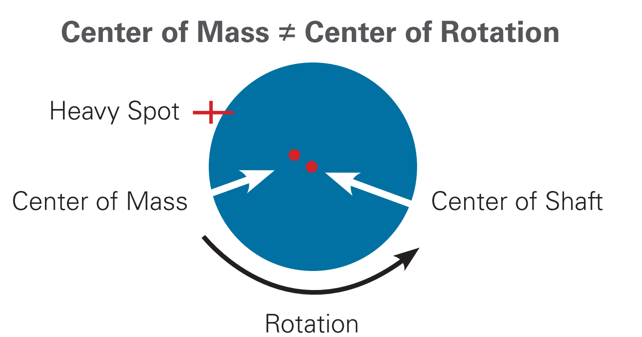

Figure 16: Imbalance Causing Appearance of Gear Faults

Misalignment is the deviation from a common centerline during operation. Misalignment can occur as offset (shafts are meeting square, but not on a common centerline), angular (shafts are meeting at an angle from one another), or both. For example, damage caused by misalignment is visible as a fracture originating at one end of a gear tooth, or the failure of a motor to be able to rotate the gear shaft at all. Misalignment can be the result of loose bearings that result in shaft deflection and part of any preventive maintenance program would include the inspection of such bearings to ensure they are running with the proper clearance and are in satisfactory condition. Foundation checks should also be done to ensure no member of the drivetrain has a "soft foot" that is presenting itself in a vibration pattern, but is gradually taking its toll on the rotating equipment.

Wear is another fault determinable by vibration analysis, and can cover a broader range of gear damage, from scoring and galling, to abrasive wear, to plastic yielding, which presents as a severe "flow" of surface material resulting in lip ledges at the end of gear teeth. Motor bearings are also particularly subject to wear and can cause premature failure if not addressed expeditiously.

Good vibration collection and analysis practices give engineers sufficient data to analyze the health of the critical elements within an industrial drivetrain, as well as provide them with the data they need to determine the cause of failures after-the-fact. Additionally, it can be used to track the health of equipment and aid in scheduling maintenance events to help avoid unscheduled process shutdowns.

Thermal Imaging

The advancement of various predictive maintenance diagnostic tools has gotten simpler and cheaper over time. Though there is no substitute for the specialized interpretation of diagnostic data, as referenced above in terms of oil and vibration analysis, it is still fair to say that the availability of affordable hand-held digital tools provides a great early warning system to maintenance and reliability engineers the world over.

Thermal imaging tools are a good example, and are a useful addition to the preventive maintenance tool kit. These devices allow operators (in-house or outside experts) to get a surface scan of a machine's temperature, and pictorially represent variations from the norm that could indicate trouble (see figures 17 and 18), as well as provide "before and after" verification of machine performance.

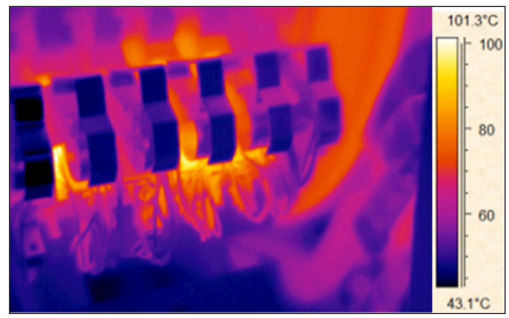

Figure 17: Unequal Current Distribution from Unequal Spring Force to Motor Brushes

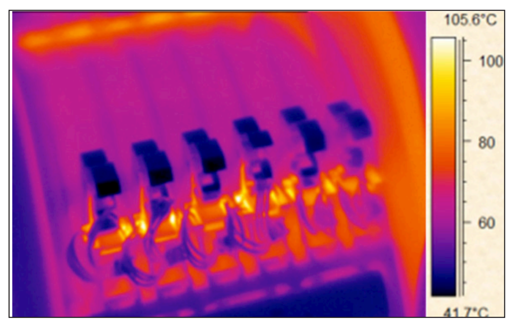

Figure 18: Uniform Current Distribution with New Springs After Motor Overhaul

Though not as sophisticated as some of the data collection instruments already mentioned, in a general way they can be used to assess everything from bearing temperatures inside gearboxes, to determining the health of brush springs in DC motors. Thermal imaging tools are designed to (literally) highlight if adequate cooling is taking place within the machine, and with frequent and scheduled use, they can be used to trend data over time to give meaningful information about what's going on inside a particular gearbox, coupling, pillow block bearing or electric motor, etc.

Finding a problem before it becomes a problem is always the challenge for preventive maintenance programs and plays a key role in identifying where potential problems are, and, at the same time, allowing maintenance teams to better sequence the order in which their equipment is repaired or replaced. This is true whether the work is done on-site or in a shop, and is equally true whether the work is being performed by in-house staff or outside specialists.

Remote Equipment Monitoring

Environmental factors often place equipment under strains that it was not designed for, as we discussed in detail in Section II. But it's not only corrosion from a humid environment, or wildly varying temperature swings that can cause maintenance challenges. Many of the most difficult challenges have to do with the equipment's lack of accessibility, as much as the atmospheric or production environments in which it may find itself.

Difficult to access equipment often results in poor to non-existent preventive maintenance. Let's consider but one example: cooling tower motors and gearboxes, which are often located 50 or more feet above the ground, and inside tight physical spaces. These environments are clearly more susceptible to failure due to corrosion and contamination that eventually can destroy bearings, gears and motor windings. Compounding the problem, safety concerns often do not allow for inspection of the units while they are running.

Remote equipment monitoring is perhaps one of the best ways to assess equipment condition by pre-warning of impending problems and allowing the operator the opportunity to fix a small problem before it turns into a big one. The installation of remote monitoring equipment, vibration probes, temperature probes, lube oil or grease level indicators, water detectors, etc., offer the ability to read the measured parameters at a remote and safe location. Unfortunately, a lot of the industrial rotating machinery comes with little in the way of sophisticated remote monitoring technology, and it needs to be installed after the plant goes online in many cases.

Let's continue with our cooling tower example. Unless pre-specified, these drivetrains come with little to no monitoring equipment: no vibration pickups, no temperature probes, no pressure sensors, yet they are among the most difficult units on which to perform inspections and preventive maintenance. There is not a "one size fits all" answer here. Risk of failure must be measured against the cost associated with the instrumentation of a given system, and some can be too costly to make sense as investments for the long term. However, there are many cost effective actions that can be taken, both before and after system installation that can provide an additional measure of reliability.

Establishing a Preventive Maintenance Program

While identifying the cause of equipment failure can sometimes be as simple as looking closely at the damage, discovering the root cause of such a problem is often considerably more difficult. The bottom line is that most plants do not have the sophisticated equipment needed to identify shaft vibration anomalies or analyze oil samples for foreign materials. Without these resources it is difficult to establish a preventive maintenance program in-house.

Because of this, many companies decide to outsource to a third party. Though we at Timken Power Systems are not taking a position on whether to do that or not, we can offer some things to consider when selecting a preventive maintenance and repair service provider. Repair and overhaul services are a necessity, as ultimately all equipment will need maintenance at one point or another. So in addition to on-site or remotely monitored diagnostics, it's important to have thought through these solutions so that maintenance downtime does not negatively affect production.

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Key service areas that can be in place ahead of time should cover breakdowns, scheduled maintenance, parts reconditioning, service upgrades, reverse engineering, alignment and balancing. Providers should be thoroughly skilled in performing root cause analysis. For repairs, full disassembly and cleaning, inspection and measurement, engineering evaluation, up-rate recommendations, performance of repairs and full-speed tests should all be accomplished.

The ability to troubleshoot is part of a comprehensive preventive maintenance program. Such troubleshooting duties include engineering assistance in identification, and swift resolution of operational problems. Other important services (mentioned earlier) include vibration and oil analysis. These two monitoring techniques are paramount in identifying equipment anomalies before they become a problem.

Any good preventive maintenance contract should include a strong warranty on the equipment serviced. Whether it's a motor that has been rewound, a bearing that has been modified to meet time constraints, or a gearbox that needs to be up-rated to handle new production demands, it is the warranty that often demonstrates the provider's level of confidence and experience.

Preventive Maintenance Checklist:

Equipment Repair

- Breakdowns
- Scheduled Maintenance
- Parts Reconditioning
- Service Upgrades
- Reverse Engineering
- Alignment and Balancing
- On or Off-Site Services

Oil Analysis

- In-Service Condition Monitoring of Lubricant and Operating Equipment
- Wear Particle Analysis
- Monitor Mechanical Condition of Wearing Parts
- Monitor Lubricant Viscosity
- Measure Concentration of Contaminants in Oils and Greases

Vibration Analysis

- On-Site Diagnostic Assistance
- Phone Support
- Web-based Support and/or Analysis
- Preventive Maintenance Program Support
- Turnkey PM Services
- System Design and Calculations

Troubleshooting

- Obtain Engineering Assistance to Identify and Swiftly Resolve Operational Problems Including:
  - Temperature (Thermal Imaging)
  - Wear
  - Sound
  - Vibration
  - Instrument Alarms
  - System Failure

Failure Analysis

- Determine Root Cause of Rotating Equipment Failure
- Evaluate Entire System
- Identify Root Cause and Permanent Corrective Action Including:
  - Review of Operational Loads
  - Component Design
  - Maintenance Practices
  - Failed Component Evaluation

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Preventive Maintenance Summary

While identifying the cause of equipment failure is only the first step in establishing an overall preventive maintenance program, it is an important step. The information gathered will ultimately serve as the foundation for planning future preventive maintenance – a particular necessity when working with mission critical equipment. Such information will also help service technicians to avoid making the same mistakes after initial equipment repairs. Once this information is determined, working with a service provider to establish a complete preventive maintenance program is important in maintaining equipment for future use, as well as lowering equipment lifecycle costs.

It's important to note that preventive maintenance measures are taken not only to ensure equipment is kept running; these efforts are also made to keep equipment running at peak output levels. This often means up-rating the motor or gearbox for optimum output based on its application. By performing a detailed review of the drivetrain and its application, engineers can determine the equipment's up-rate potential. Though this often requires outside resources, it is a virtual non-starter in the absence of preventive maintenance data to "guide the way."

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VI. FINAL COMMENTS

Though industrial drivetrains vary greatly from one application or market segment to another, there are some common overarching principles that often can be applied across this wide spectrum of equipment. Though this subject is more exhaustive in its purview than the space we can dedicate to it in this paper, we have endeavored to sensitize end-users and plant decision makers to some key factors that can have dramatic influences on how power transmission equipment operates in the real world.

Viewing the drivetrain as an integrated system – as opposed to a sort of bill of material of independent parts – can enhance plant operations, production runtimes, and extend the mean time between failures. Further, this concept can be used to enhance existing preventive and/or predictive maintenance programs and a process can be developed to track and document historical changes to some components and discern what, if any, effects these changes will have on the entire drivetrain over time.

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TIMKEN POWER SYSTEMS FACILITY DIRECTORY

Philadelphia Gear

Headquarters & Tech Center
901 East 8th Avenue, Suite 100
King of Prussia, PA 19406
Phone: 610-265-3000
www.philagear.com

Northeast Regional Service Center
100 Anchor Mill Road
New Castle, DE 19720
Phone: 302-633-4600
www.philagear.com

Southeast Regional Service Center
1242 24th Avenue
Hueytown, AL 35023
Phone: 205-424-0442
www.philagear.com

Midwest Regional Service Center
Timken Power Systems
8529 West 192nd Street
Mokena, IL 60448
Phone: 708-720-9400
www.philagear.com

Gulf Coast Regional Service Center
10830 Train Court
Houston, TX 77041
Phone: 713-224-4900
www.philagear.com

Gulf Coast OEM Manufacturing
Timken Power Systems
5610 Brystone Drive
Houston, TX 77041
Phone: 713-224-4900
www.philagear.com

Western Regional Service Center
12935 Imperial Highway
Santa Fe Springs, CA 90670
Phone: 310-605-2600
www.philagear.com

H&N Electric

Motor & Gear Repair
4224 East B Street
Pasco, WA 99301
Phone: 509-547-1691
www.hnelectric.com

H&N Wind Services

Generator & Gear Repair
4224 East B Street
Pasco, WA 99301
Phone: 509-547-1691
www.hnwindservices.com

Schulz Group

Maine Industrial Repair Services
60 Darin Drive
Augusta, ME 04330
Phone: 207-623-7500
www.maineindustrial.com

Schulz Electric
30 Gando Drive
New Haven, CT 06513
Phone: 203-562-5811
www.schulzelectric.com

Stultz Motor & Controls
190 Riverside St., Unit 4A
Portland, ME 04103
Phone: 207-699-2501
www.stultzelectric.com

Smith Services

Motor & Gear Repair
801 Turnpike Road
Princeton, WV 24739
Phone: 304-431-2446
www.smithservices.com

Standard Machine

Gear & Bearing Repair
868-60th Street East
Saskatoon, SK S7K 8G8
Phone: 306-931-3343
www.standardmachine.ca

Timken Industrial Bearing Services

Carolina Service Center
7LSP Road
Union, SC 29379
Phone: 864-424-1600
www.timkenpowersystems.com

Indiana Service Center
3419 North Home Street
Mishawaka, IN 46545
Phone: 574-288-7188
www.timkenpowersystems.com

Timken Gears & Services India, Ltd.

Raipur Service Center
GE Road Near Kumari Toll Plaza
Durg, Chattisgarh - 490042
Phone: +91 (80) 67218000
Web: www.timken.com

Wazee Electric

Motor & Gear Repair
4850 Moline Street
Denver, CO 80239
Phone: 303-623-8658
www.wazeeco.com

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