MACHINE CONDITION MONITORING TECHNIQUE USED TO DETECT THE FAILURE OF ROLLING ELEMENT BEARING FOR ISMECA MACHINES IN MANUFACTURING LINE

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ABSTRACT
The performance of the machines pick & place depend on movement of each elements of this machine. Each elements of the machine provide a smooth movement also depend on the rolling-element bearings condition. To ensure that the performance of pick & place machines move smoothly, bearings in this machine need to be monitor/need to be change time to time when this machines is expose to daily operation. Machine condition monitoring technique need to be done every 6 months. Machine condition monitoring techniques for roller element bearings are designed to detect the characteristic fault frequencies. The fault location are inner race, outer race, ball, or cage damage. The four characteristic fault frequencies is necessary that commonly had been neglected by industrial. This research introduces the notion of categorizing bearing faults as either single-point defects or generalized roughness. These classes separate bearing faults according to the fault signatures that are produced rather than by the physical location of the fault. Specifically, single-point defects produce four predictable characteristic fault frequencies while faults categorized as generalized roughness produce unpredictable broadband change due to machine vibration. Experiment results are provided from bearing failed. These results illustrate the vibration and current of bearing failure in situ via shaft current.

Keywords: Pick & place machines; Rolling-element; Bearings; Machine vibration.

1. INTRODUCTION
The first recorded use of rolling elements to overcome sliding friction was by Egyptian construction workers, to move heavy stone slabs, probably before 200 B.C. and possibly by the Assyrians in about 650 B.C. It is believed that some early chariot wheels used crude roller bearing made from round sticks. Around A.D. 1500 Leonardo da Vinci is considered to have invented and partially developed modern ball and roll bearings. A few ball and roller-type bearings were constructed in France in the eighteenth century. The builder of a roller-bearing carriage claimed, in 1710, that his roller bearings permitted one horse to do work otherwise hardly possible for two horses. But it was not until after the invention of the Bessemer steel process in 1856 that a suitable material for rolling-element bearings was economically available. During the remainder of the nineteenth century, ball bearings were rapidly developed in Europe for use in bicycles. The simplest possible bearings are not lubricated plain or sliding bearings-like the wooden cart wheels mounted directly on wooden axles in ancient times. Lower friction and longer life were obtained by adding a lubricant, such as animal or vegetable oil. In modern machinery using sliding bearings, steel shafts are supported by the surfaces of bearings made of a wear-compatible material, such as bronze or TFE. Oil or grease is used in common low-speed applications-lawn mower wheels, garden carts, children’s tricycles-but the lubricant does not completely separate the surface. On the other hand, sliding bearings used with engine crankshafts receive hydrodynamic lubrication during normal operation; that is, the oil film completely separates the surfaces.

Rolling-element bearings are either ball bearings or roller bearings. In general, ball bearings are capable of higher speeds, and roller bearings can carry greater loads. Most rolling-element bearing can be classed in one of three categories: (1) radial for carrying loads that are primarily radial; (2) thrust, or axial-contact for carrying loads that are primarily axial; and (3) angular-contact for carrying combined axial and radial loads.
2. WEAR CAUSED BY VIBRATION.

When a bearing is not running, there is no lubricant film between the rolling elements and the raceways. The absence of lubricant film gives metal to metal contact and the vibrations produce small relative movements of rolling elements and rings. As a result of these movements, small particles break away from the surfaces and this leads to the formation of depressions in the raceways. This damage is known as false brinelling, sometimes also referred to as washboarding. Balls produce spheroid cavities while rollers produce fluting. In many cases, it is possible to discern red rust at the bottom of the depressions. This is caused by oxidation of the detached particles, which have a large area in relation to their volume, as a result of their exposure to air. There is never any visible damage to the rolling elements. The greater the energy of vibration, the more severe the damage. The period of time and the magnitude of the bearing internal clearance also influence developments, but the frequency of the vibrations does not appear to have any significant effect. Roller bearings have proved to be more susceptible to this type of damage than ball bearings. This is considered to be because the balls can roll in every direction. Rollers, on the other hand, only roll in one direction; movement in the remaining directions takes the form of sliding. Cylindrical roller bearings are the most susceptible. The fluting resulting from vibrations sometimes closely resembles the fluting produced by the passage of electric current. However, in the latter case the bottom of the depression is dark in colour, not bright or corroded. The damage caused by electric current is also distinguishable by the fact that the rolling elements are marked as well as the raceways. Bearings with vibration damage are usually found in machines that are not in operation and are situated close to machinery producing vibrations. Examples that can be cited are transformer fans, stand-by generators and ships’ auxiliary machinery. Bearings in machines transported by rail, road or sea may be subject to vibration damage too. Graph in Figure 8 shows the problem roller element bearing.
Fig. 5 Types of bearing have been exposed to long term operation in manufacturing process.

Fig. 6 The outer ring of a self aligning ball bearing damaged by vibration. The bearing has not rotated at all.

Fig. 7 The outer of a spherical roller bearing that has not been adequately lubricated. The raceways have a mirror finish.
2.1 Categorizing Bearing Faults

A single-point defect is defined here as a single, localized defect on an otherwise relatively undamaged bearing surface. A common example is a pit or spall. A single-point defect produces one of the four characteristic fault frequencies depending on which surface of the bearing contains the fault. These predictable frequency components typically appear in the machine vibration and are often reflected into the stator current. In spite of the name, a bearing can possess multiple single-point defects. Generalized roughness is a type of fault where the condition of a bearing surface has degraded considerably over a large area and become rough, irregular, or deformed. This damage may or may not be visible to the unaided eye. Nevertheless, there is no localized defect to be identified as the fault; rather, large areas of the bearing surface(s) have deteriorated. A common example is the overall surface roughness produced by a contamination or loss of lubricant. The effects produced by this type of fault are difficult to predict, and there are no characteristic fault frequencies for the current or vibration associated with this type of fault. Generalized roughness faults are common in industry, while they are often neglected in the research literature. However, when a generalized roughness fault reaches an advanced stage and the bearing is near failure, the fault can typically be detected via the rudimentary techniques commonly employed in industry (e.g., ISO 10816) (MV, 1995). Since many of the newer, more sophisticated condition monitoring techniques focus only on single-point defects, this could explain the discrepancy between the large number of state-of-the-art techniques in the research literature and their lack of use in industry. Ideally, a condition monitoring scheme should be able to identify both types of faults while still in incipient stages of development. The flowchart in Figure 9 illustrates the effects of these two categories of faults and where their fault signatures appear. From this figure, it is evident that both types of faults directly affect the machine vibration, albeit in different ways. These effects are often reflected into the stator current, although there they are typically much more subtle.

2.2 Single-Point Defects

A single-point defect will cause certain characteristic fault frequencies to appear in the machine vibration. The frequencies at which these components occur are predictable and depend on which surface of the bearing contains the fault; therefore, there is one characteristic fault frequency associated with each of the four parts of the bearing (Collacott, 1979). The majority of the bearing-related condition monitoring schemes focus on these four characteristic fault frequencies. These
frequencies are: $F_{IRF}$: inner race fault frequency, $F_{ORF}$: outer race fault frequency, $F_{CF}$: cage fault frequency, and $F_{BF}$: ball fault frequency. A thorough derivation of these frequencies is presented in (Li et al., 2000). The four characteristic fault frequencies are defined in (MV, 1995; Collacott, 1979; Li et al., 2000; Schoen et al., 1995) and illustrated in Figure 10 where the speed of the rotor, $N_B$ is the number of balls, $D_B$ is the ball diameter, and $D_p$ is the ball pitch diameter. The angle $\theta$ is the ball contact angle; this is the angle between the centerline of the bearing and, $F_{RE}$, which indicates the direction of the force that the rolling elements exert on the outer race.

$$F_{CF} = \frac{1}{2} F_R \left(1 - \frac{D_B \cos \theta}{D_p}\right)$$  \hspace{1cm} (1)

$$F_{ORF} = \frac{N_B}{2} F_R \left(1 - \frac{D_B \cos \theta}{D_p}\right)$$  \hspace{1cm} (2)

$$F_{IRF} = \frac{N_B}{2} F_R \left(1 + \frac{D_B \cos \theta}{D_p}\right)$$  \hspace{1cm} (3)

$$F_{BF} = \frac{D_p}{2D_B} F_R \left(1 - \frac{D_B^2 \cos^2 \theta}{D_p^2}\right)$$  \hspace{1cm} (4)

The characteristic fault frequencies are the result of the absolute motion (vibration) of the machine. The stator current is not affected by the absolute motion of the machine, but rather by a relative motion between the stator and rotor (i.e., changes in the air gap). In the instance of a bearing fault, the characteristic fault frequencies are essentially adulterated by the electrical supply frequency and are predicted by Schoen et al., and Stack et al. (1995; 2003). In this equation, is the resulting fault frequency component in the stator current, is the electrical supply frequency, is one of the four characteristic fault frequencies defined by (MV, 1995; Collacott, 1979; Li et al., 2000; Schoen et al., 1995) and is an integer. Experimentation suggests that the presence of a characteristic fault frequency in the machine vibration does not guarantee its presence in the stator current.

$$F_{BNG} = \left|F_F \pm m^* F_v\right|$$  \hspace{1cm} (5)

### 2.3 Generalized Roughness

The purpose of this research is to recognize the importance and illustrate the effects of this second category of bearing faults, generalized (i.e., not localized) roughness. This type of failure is observed in a significant number of cases of failed bearings from various industrial applications. There are a wide variety of causes that can lead to this type of fault. Some of the more common fault sources observed by the authors include contamination of the lubricant, lack or loss of lubricant, shaft currents, and misalignment. While these fault sources may also produce single-point defects, it is common for them to produce unhealthy bearings that do not contain single-point defects (i.e., they contain generalized roughness faults). If one of these bearings is removed from service prior to catastrophic failure (typically because of increased machine vibration), a technician can easily recognize that a problem exists within the bearing because it either spins roughly or with difficulty. However, upon a visual examination (nonmicroscopic), there is no single-point defect and the actual damage to the bearing (e.g., surface roughness, deformed rolling elements, warped raceway, etc.) may or may not be visible to the unaided eye. Since there is no single-point defect, there is nothing to excite any of the characteristic fault frequencies. This research experimentally generates bearing faults that fall under the category of generalized roughness via an externally applied shaft current (Stack et al., 2003). In this method, bearings are placed in a test motor, and a shaft current is injected through the bearing to induce faults in situ. This paper investigates data from ten bearings failed by this method. Among these ten bearings, the fault characteristics include microscopic pitting on all surfaces and microscopic scratches on the rolling elements and cage. None of these ten bearings contain single-point defects. An important point to emphasize from this data is that the specific way in which these bearings fail is unpredictable; therefore, the effect the fault has on the machine vibration and stator current is also unpredictable. As Figure 9 suggests, these effects are broadband changes in the machine vibration and stator current spectra. To illustrate this principle, consider Figure 15. This figure shows the machine vibration and stator current for one bearing. The solid line represents the bearing when it was first installed while the dashed line represents the same bearing once it reached a point near failure. The 60-Hz component is
removed from the stator current before sampling. Figure 15 (top) indicates a significant increase over all frequencies making this fault easily detectable in the machine vibration. However, Figure 15 (bottom) illustrates that the change in stator current is more selective. For this bearing, the only parts of the stator current spectrum affected by the bearing fault are the sidebands (of width 25 Hz) around 60 and 180 Hz. Results for a different bearing are illustrated in Fig. 16 (top) where a similar broadband increase in machine vibration is observed. However, the changes in stator current of Figure 16 (bottom) are in contrast to that of the previous bearing. For Figure 16 (bottom), the only change in stator current is an increase in the noise floor above approximately 200 Hz. In other bearings from these trials, the effects that the faults were observed to have on the stator current included an increase in all components, an increase in the noise floor only, and an increase in all low frequency components (i.e., below 300 Hz). The effects of the generalized roughness faults on the machine vibration in these figures support the claim of broadband changes accompanied by the absence of the characteristic fault frequencies. While the data in these two figures represent the extremes (i.e., a new, healthy bearing and the same bearing near failure), the data acquired at intermediate stages of fault development are consistent with these results. That is, as the fault increases in severity the magnitude of the broadband changes in machine vibration increase accordingly. The figure legends have been updated for Figures 15 and 16. In an attempt to illustrate how the shaft current physically affects the test bearing, consider Figure 11. This is a photograph of the inner race of a bearing that was failed using the shaft current experimental setup taken with a standard digital camera. From this Figure, it is seen that the rolling elements have left a rough track down the center of the inner raceway. The arrows pointing to the top of this track. Above the tip of the arrow is the smooth, polished surface of the inner raceway that has not come into contact with the rolling elements (the darker area). Below the tip of the arrow is a coarse, rough track in the middle of the inner race where the rolling elements have passed and conducted the shaft current. Figure 12 contains a photograph of the boundary between where the rolling elements caused the rough track on the inner race and the untouched portion of the inner race surface. This photograph is a 5 magnification of the area at the tip of the arrow in Figure 11. The left side of Figure 12 is the rough, pitted surface traversed by the rolling elements. The right side is the smooth area untouched by the rolling elements. The vertical lines on the right side are machining marks form the cutting tool that manufactured this bearing. In all photographs taken through the microscope, the black arc and black line are generated by the photography equipment. The black line is for reference and is 400 m in length for all photographs taken at 5 magnifications. This observation further supports the concept of a generalize roughness category for bearing failures. The photograph in Figure 13 was taken at an arbitrary point in the middle of the inner race of a bearing. The top portion of the photograph was taken at 5 magnifications. Notice the general roughness of the surface and the pitting. This roughness was common to all raceways on all bearings failed by this method, albeit in differing degrees of severity for the various surfaces and the various bearings tested. The bottom portion of this photo- graph is a magnification of approximately 10 of the pits from the top photograph. This magnified photograph illustrates the depth of the pits, which were found on all raceways of all bearings failed by this method (again is various degrees of severity). Figure 14 is a photograph of the surface of one of the rolling elements from another failed bearing. The scratches and surface roughness seen here were consistently found on the rolling elements from all bearings failed using this method. This supports the notion of generalized-roughness damage to the rolling elements as well as the raceways.
where the rolling elements have not contacted the raceway.

Fig. 12 Photograph taken at 5x magnification of the boundary between the rough area and undamaged area on the bearing depicted in Figure 11. This area was photographed at the tip of the arrow in Figure 11.

Fig. 13 Photograph of an arbitrary point on the inner race of a bearing failed by the shaft current method. The top photograph was taken at 5x and the bottom photograph is a ~10x magnification of the two pits above. This roughness and pitting was common to all raceways of all bearings failed by this method.

Fig. 14 Photograph of a rolling element failed by the shaft current method. These scratches were common to all rolling elements in all bearings failed by this method.

2.4 Wear Caused by Inadequate Lubrication
If there is not sufficient lubricant, or if the lubricant has lost its lubricating properties, it is not possible for an oil film with sufficient carrying capacity to form. Metal to metal contact occurs between rolling elements and raceways. In its initial phase, the resultant wear has roughly the same effect as lapping. The peaks of the microscopic asperities, that remain after the production processes, are torn off and, at the same time, a certain rolling-out effect is obtained. This gives the surfaces concerned a varying degree of mirror-like finish. At this stage surface distress can also arise.

2.5 Graphs for Vibration and Current of a Bearing failed in situ via Shaft Current
In Figure 15 Solid line is the bearing when healthy and new; dotted line is same bearing near failure. Top: machine vibration indicates a significant increase at all frequencies. Bottom: stator current displays increase in sidebands (~25 Hz at 60 and 180 Hz).

Fig. 15 Vibration and current of a bearing failed in situ via shaft current.
If the lubricant is completely used up, the temperature will rise rapidly. The hardened material then softens and the surfaces take on blue to brown hues. The temperature may even become so high as to cause the bearing to seize.

![Graph showing machine vibration and stator current](image)

Fig. 16 Vibration and current of a different bearing failed in situ via shaft current. Top: machine vibration again indicates a significant increase at all frequencies. Bottom: stator current displays increase in only the noise floor above ~200 Hz. All other peaks remained unchanged.

3. CONCLUSIONS

This paper has introduced the notion of categorizing bearing faults as either single-point defects or generalized roughness. This is important because it divides these faults according to the type of fault signatures they produce rather than the physical location of the fault. The benefit of this categorization is two fold. First, it ensures that the faults categorized as generalized roughness are not overlooked. The majority of bearing condition monitoring schemes in the literature focus on detection of single-point defects. While this is an important class of faults, a comprehensive and robust scheme must be able to detect both generalized roughness and single-point defect bearing faults. Second, grouping faults according to the type of fault signature they produce provides a clearer understanding of how these faults should be detected. This should provide improved insight into how bearing condition monitoring schemes should be designed and applied. Experimental results obtained from this research suggest generalized roughness faults produce unpredictable (and often broadband) changes in the machine vibration and stator current. This is in contrast to the predictable frequency components produced by single-point defects. This research investigates generalized roughness faults produced in situ by an externally applied shaft current. While shaft current is only one way this type of fault can be produced, it is a common source for bearing failures in industry. Microscopic inspection reveals pitting and roughness on all bearing surfaces. This further supports the assertion of a nonlocalized or generalized roughness type of fault.

REFERENCES


