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Non-Linearity of Stiffness Ball-Bearing to Support the Preventive Maintenance Rotating Machinery

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Abstract

Rolling element bearings are one of the machine components that transmit excitation and play an important role in the effective operation of rotary machines. This element is one of the main non-linear sources of machine rotation which significantly influences machine stiffeningThe main source of non-linearity comes from internal radius clearance, unbalanced forces, Hertzian contact, stiffness, damping, number of rolling elements, bearing preload, and so on. Routine maintenance tasks such as lubrication, cleaning and inspection can help prevent premature bearing failure and extend machine life. By performing routine preventive maintenance, businesses minimize downtime and increase productivity, ultimately resulting in cost savings and improved performance. This research has provided a practical understanding of the phenomenon, with wear there will be a response to various defects that must be considered, such as unbalance, mis-alignment, wear and others.Theoretical analysis and experimental results show that the large dynamic force on the roller due to unbalanced forces on both sides of the roller and deviation of the axial distance of the bearing are the main causes of abnormal wear. In the following article we discuss common causes of bearing failure, best lubrication practices, how to check and clean bearings, when to replace them, and much more.

Keywords: *Predictive Maintenance, Preventive Maitenance, wear, Hertziant contact, Ball bearing*

1. Introduction

A machine is composed of several elements that move/rotate (rotation) or are stationary. In its function, the rotational elements are generally supported by ball bearing elements and rolling bearings as seen in Fig. 1. These bearing elements are the most critical points in the machine structure, so that the performance of the machine is also influenced by the performance of the bearings. Defects in bearings can be a source of

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vibration excitation whose vibration response has certain characteristics. Fig. 1 and Fig. 2 shows the arrangement of the rotation elements of a cone bearing and the defects that occur in the trajectory of the rolling element (outer race).

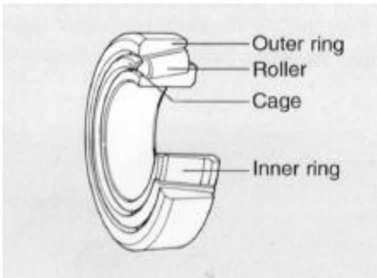

Fig. 1 Cone bearing (source NTN CAT. No.3017/E).

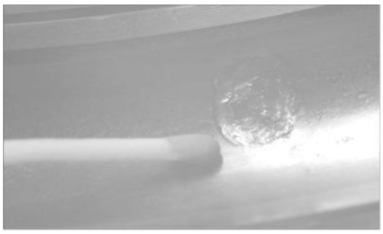

Fig. 2 Photo indicating a defect in the bearing (14)

Although bearings are not the main cause of vibration problems in machinery, because they are elements that are sensitive to the excitation forces that occurs, this element can transmit vibration responses from other elements such as shafts, rotors, etc. In this way, bearings can provide information about the condition of the machinery, both rotating and non-rotating elements. Therefore, detecting bearing damage during machining operations by measuring its vibration response is one method that is increasingly being used

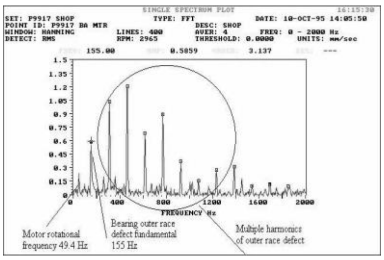

Fig. 3 Vibration response spectrum due to defects in the bearing groove [4]

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The use of CBM (Condition Based Maintenance) technology on rotating machines by utilizing vibration signals through monitoring vibration levels (trend monitoring), in many industries has become a requirement in the field of maintenance. The advantages obtained by using vibration techniques are data sampling carried out under operating conditions, the ability to detect vibration levels and defect locations, as well as failure analysis. This supports maintenance techniques, especially to prevent greater loss/damage.

The use of ordinary/conventional (visual) inspection techniques will experience problems if the damage that occurs cannot be detected normally (hidden damage). This obstacle can be overcome by using vibration technology. Carrying out vibration measurements and analysis on rotating machinery on a regular basis makes it possible to detect and determine the location of damage that may occur, such as mass unbalance and bearing wear or defects. This is possible because the damage that occurs will give rise to new vibration excitations which will be transmitted into bearing reaction forces. By using a vibration sensor, the response of the bearing reaction force can be sampled and then analyzed. Analysis of this response will lead to the vibration characteristics of defects in bearings and machining systems. Indicated defects can be bearing defects (BPFO, BPFI, spall, etc.), or defects in other elements (misalignment, unbalance conditions, gear damage, etc.).

The magnitude (level) of vibration response in machinery can be caused by bearing elements due to the following factors [1]:

a. As a structural element that determines the stiffness of machinery.
b. As a vibration generator due to the load distribution on the bearing which varies cyclically/repeatedly (Figure 4).
c. As a vibration generator due to geometric defects caused by imperfect fabrication processes, installation processes or wear and defects during use.

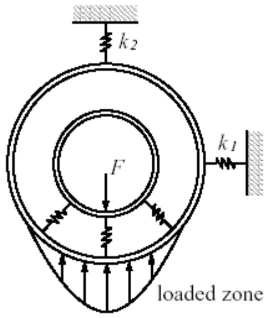

Fig. 4 Sketch of load distribution in rolling bearings [2]

Bearing systems have been the subject of much research, including in dynamics laboratories. Among them, Irwanto [11] carried out a theoretical study and analysis of the vibration response of the shaft system supported by rolling bearings, Iskandar [12] carried out an experimental study and theoretical analysis of the vibration

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response of the rotor shaft system due to unbalanced masses and defects in the bearings. Tjahjowidodo [10] conducted a theoretical study and analysis of nonlinear vibration responses in the rotor shaft system using the Volterra functional circuit. In this regard, theoretical and experimental studies on bearings with increased wear (gap/clearance, cd) as a bearing defect (Fig. 5) are being carried out.

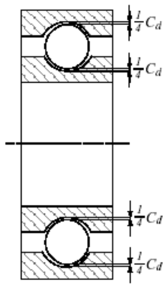

Fig. 5 Wear (Clearance/gap, Cd) in ball bearings [2].

Several related studies that have been carried out Internationally include Harris [1], determining bearing stiffness by applying Hertz theory, then White [3] formulating the stiffness of ball and rolling bearings and studying its effect on the vibrations that occur. Lim [6], formulated bearing stiffness by reviewing aspects of bearing geometry and kinematics. Aktürk [5], studied radial and axial vibrations in a rotor shaft system supported by a pair of ball bearings by varying the preload and number of balls. Jang and Jeong [7], studied a non-linear model to analyze ball bearing vibrations due to waviness defects in rotor shaft systems supported by 2 or more ball bearings as supports.

The results of preliminary research and literature review show that excitation forces in the form of impulses can occur due to interactions between the rotational elements of the bearing and defects in the bearing groove. This type of excitation in the form of impulses causes the vibration response measured in the bearing housing to resemble the shape of the FRF (Frequency Response Function) curve of the rotor shaft system. However, this study does not explain the influence of roller/ball bearing wear and its effect on stiffness.

At the end of this introduction the author tries to convey the aim of this research. This research is intended to determine the maintenance time for preventive and predictive maintenance. Apart from that, maintenance can reveal the signature of rotational engine damage.

2. THE PROBLEM

CBM by utilizing vibration technology has reached an intensive development stage in order to support predictive maintenance. This maintenance technology is very effective, because detecting damage to rotational elements can be done while the machine is still operating and accurate results can be obtained. In this way, the hidden nature of conventional maintenance techniques can be eliminated and ultimately catastrophic conditions can be avoided.

This maintenance technology is carried out by periodically measuring the vibration response that occurs in the bearing housing. The presence of defects in both rotational elements and non-rotational elements, when the machine is operating, will produce a force/variation in force X(ω) which will be transmitted to the bearing housing. By knowing the dynamic characteristics H(ω) of the bearing housing, the vibration response Y(ω) of the support can be analyzed, and can be written in the following equation:

$$Y(\omega) = H(\omega).X(\omega) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

The dynamic characteristics of the bearing housing H(ω) and the response obtained from the measurement results Y(ω) can be used to analyze the input signal X(ω) which occurs due to the rotation of the rotor system. This can be illustrated by the increase in energy around the defect as shown in Fig. 6. It is observed that the different shape of the defect in the bearing rolling element path will provide a different energy stress wave. The bearing reaction force signal around the defect in the form of an impulse has a wide frequency content, so it will provide its own response characteristics.

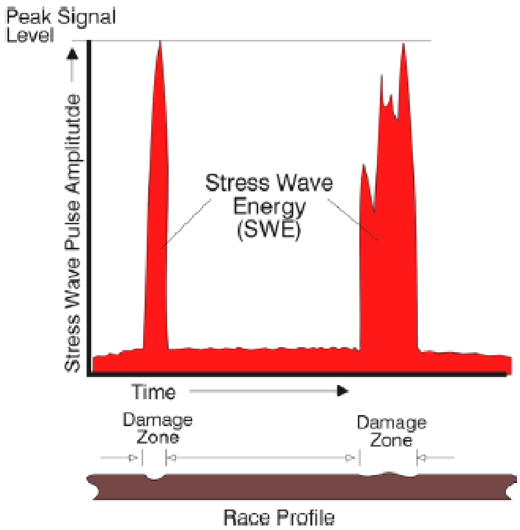

Fig. 6 Stress Wave Energy around a defect [11].

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The results of sampling vibration response data on supports using a signal analyser and accelerometer sensor can be presented in frequency (ω) and time (t) domain formats. In this way, vibration characteristic analysis can be carried out which provides information regarding the presence of defects in both bearing elements (BPFO, BPFI, cage, spall, etc.) and non-bearing elements (misalignment, unbalance conditions, gear damage, etc.).

Research by modeling defects in ball bearings and their supporting structures has been developed in the dynamics laboratory, especially to represent the presence of unbalanced masses, defects in bearings and accelerated tests. Defects in bearings that have been studied are spall in the bearing rolling element track (inside and outside) and cage (Fig. 7), as well as the presence of natural wear that occurs in the bearing. The analytical method has been developed to study non-linearity using the Volterra series method, as well as simulations using Matlab software. So far, the existence of non-linearity phenomena in bearings has been identified and therefore the dynamics laboratory has focused on comprehensively studying the influence of bearing wear on the characteristics of the vibration signal.

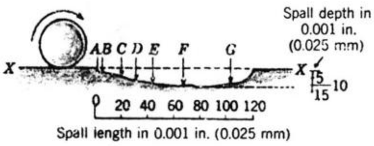

Fig. 7 Spall defect profile in outer race rolling bearing [1]

The proposed research is a continuation of research that has been carried out previously, namely regarding the dynamics and kinematics of ball and rolling bearings by paying attention to wear defects that may occur in an effort to explain nonlinearity phenomena. The research plan is intended to explain the emergence of harmonics and frequency response shifts in measurement signals which can support the development of predictive maintenance techniques. In this regard, a test set-up was designed to represent wear defects. In this case, roller bearings and cone bearings were chosen as test bearings because of the possibility of representing wear defect conditions (gap/clearance). The roller bearings used are roller bearings with a removable outer race. These conditions make it possible to carry out machining processes to simulate wear. The experimental study was directed at determining the influence of each parameter such as wear, load and rotation, on the vibration response. Based on the data that will be obtained, it is hoped that mathematical modeling and simulations can be created.

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In initial research, it was possible to observe the effect of wear on the bearing by modeling it as a single degree of freedom (SDOF) system as shown in Fig. 8.

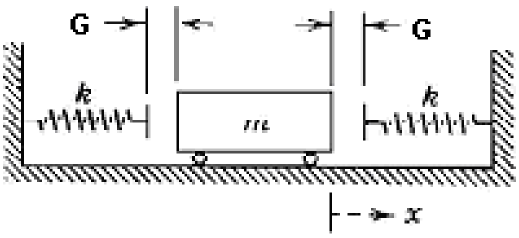

Fig. 8 One-dof modelling in the presence of G wear

Increased wear G, will occur in line with increased wear on the bearing. From the model simulation in the presence of wear, it is observed that there is a shift in the vibration response and the emergence of harmonics, as shown in Fig. 9. Mathematical modeling of the shift in the vibration response and its harmonics in the presence of increased wear and other local defects in the bearing will be very helpful for CBM.

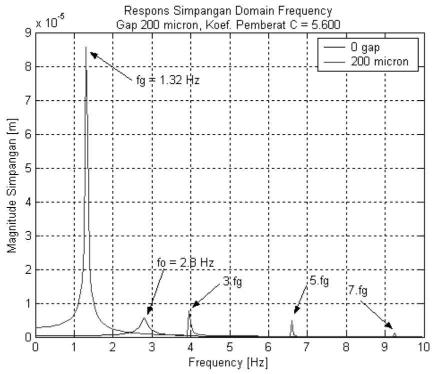

Fig. 9 Shift in vibration response and harmonics due to wear of 200 microns

3. SOLUTION PLAN

The analysis in this research is directed at obtaining a comparison between the vibration response in the presence of wear and the reference vibration response (without wear). The difference in vibration response is due to changes in the force generated in the bearing housing. By comparing the theoretical frequency ratio with the experimental frequency ratio, an analysis of wear defects in bearings with increased wear can be

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developed. In general, the proposed research methodology in relation to answering the problem of bearing nonlinearity can be expressed in a diagram as shown in Fig. 10 and 11.

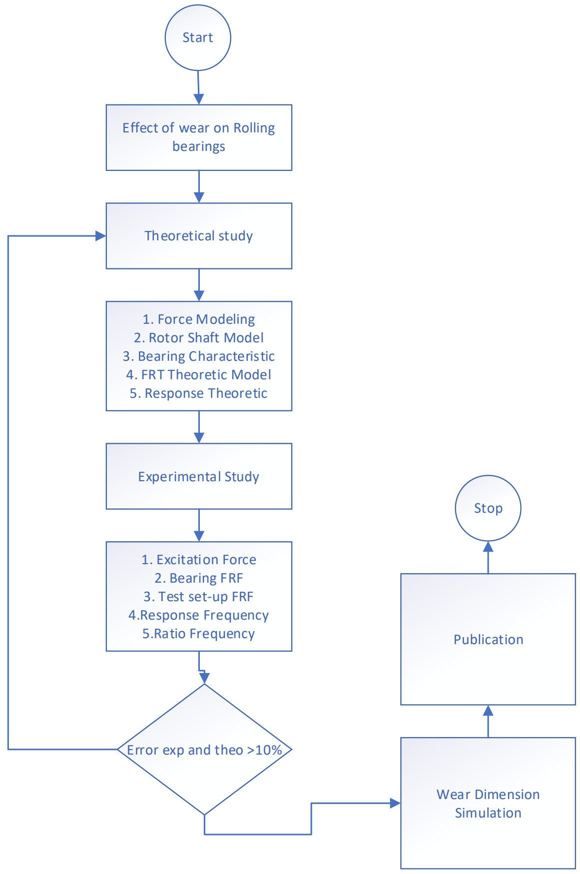

Fig. 10 Developed theoretical and experimental study flow diagram

3.1 Hertzian contact between rolling elements.

The contact problem between bearing elements in this study is proposed to be solved by assuming contact occurs on an elastic surface, so that Hertzien contact theory can be used to determine nonlinearity stiffness in bearings. The relationship between the radial force acting and the radial deflection (δr) that occurs can be formulated as [1]

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$$\delta_r = \frac{1.976x10^{-6}\ F_r^{\ 2/3}}{Z^{2/3}\ D^{1/3}\ \cos^{5/3}\alpha} \quad \text{(2)}$$

By knowing the working radial load (Fr), number (Z), diameter (D) and contact angle (α) of the bearing element, the radial deflection (δr) can be determined. The radial force acting on the bearing can be written in the following equation [1]:

$$F_r = Z.K_n.(\delta_r - \tfrac{1}{2} P_d)^n.J_r(\varepsilon) \quad \text{(3)}$$

Meanwhile, the stiffness that occurs in bearings can be formulated as follows [1]:

$$K = 6{,}916x10^{-4}\ Z\ D^{1/2}\ \cos^{5/2}\alpha\ \delta_r^{\ 1/2} \quad \text{(4)}$$

Looks at the eq. (4), the bearing stiffness is non-linear as a function of the deflection of the bearing rolling element in its trajectory. By using load distribution integral Jr (ε) [1], initial research can determine the nonlinearity of cone bearing stiffness with wear of 4 μm as shown in Fig. 11.

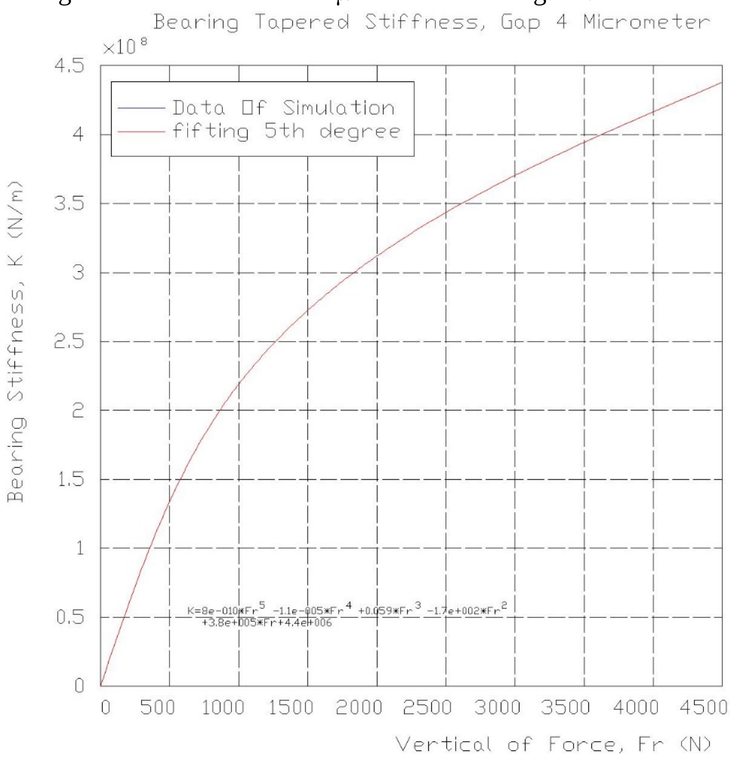

Fig. 11 Tapered bearing stiffness curve, wear 4 μm.

3.2 Geometry of rolling elements of bearings and their trajectories.

The rolling elements of bearings and their tracks are components resulting from the fabrication process so it is very likely that they will have surface defects, such as waviness, roughness, etc. Poor use, installation or lubrication processes also play a role in the occurrence of wear defects. This condition may also cause centralized (local) defects such as spall. At this stage of discussing surface defects, the analysis focuses on mathematical modeling of the presence of wear defects which influence the vibration response, [1, 2].

In this research, dynamic studies, kinematic studies and a combination of kinematic and dynamic studies will be carried out. Kinamatic studies are carried out by paying attention to the mass movement of the rolling elements in the presence of shaft rotation, rolling elements and bearing geometry.

3.3 Clearance gap in rolling bearings

The increased wear that occurs will change the stiffness properties of the bearing. This condition is thought to be the main parameter that causes changes in the bearing system response. A computational study of determining bearing stiffness at various wear levels is proposed to observe how the changes occur mathematically. FEM supporting studies will be carried out to support computational studies of the bearing element system.

4. Conclusion

1) Machines that have a low failure rate and reliability must clearly undergo preventive maintenance operations within a short period of time.
2) The application of the preventive maintenance model to the machine under study proves that the preventive maintenance process functions to reduce the failure rate because the rate returns to zero after carrying out each preventive maintenance process.
3) The results showed that preventive maintenance operations led to an increase in the average time period of machine operation between failures due to the average time between machine failures.
4) The results of machine reliability estimates before carrying out maintenance operations gradually decrease over time at different speeds and give a general indication that these machines cannot be relied on to work for long periods of time without failure.
5) This research has produced a signature of wear on the bearing so that the characteristics of the vibration are known, and can be used as information about machine stoppin

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A Brief Author Biography

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***2nd Author Name* –** He was born May 3 1964, in Bandung Indonesia. In 1986 he had the opportunity to study in France and in 1989 -2009, he returned to Bandung Indonesia he had the opportunity to take a job in Gas Turbine engine repair station as Part timer as tooling and repair Engineer (1989-1994), and in the same place be a Full timer (1994-2009) as a Specialist Engineer / Propulsion Engineer and in the same time until now as he is being a lecture at Aeronautic Program study aeronautic majoring Gas Turbine Engine. In 2012, He graduated as Master of Mechanical Engineering specialist on energy conversion from Gadjah Mada University Jogjakarta Indonesia. He continued his research activities in the field of heat transfer, thermodynamic and Gas Turbine engine technology.