INVESTIGATION OF TRANSFER IMPEDANCES OF MOUNTED ROLLING BEARINGS

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ABSTRACT

Common methods of accessing the degree of damage in rolling bearings are based on empirical methods and on measurements of the signal generated by an existing damage.

To know the spare time of a rolling bearing before the damage actually occurs, a physical model should consider parameters like surface roughness, velocity and others. However, there exist some requirements: determining the correct transfer impedance between source and transducer and assuring that other sources of noise are eliminated.

This work concentrates on the determination of the transfer impedance of mounted rolling bearings.

INTRODUCTION

One of the most frequent causes of malfunctions or breakages in rotating machines are fatigue faults on the surfaces of rolling bearings. Field researches [1] indicate that 90% of the total amount of different ball bearings fault is related to either an inner or outer race flaw, whilst a rolling element flaw or, rarely, a cage flaw is the cause of the remaining malfunctions. Some empirical methods to evaluate the remaining life based on vibration analysis of damaged rolling bearings have been described in the literature [2, 3].

To go towards a deeper understanding of the behaviour of rolling bearings, one should try to model the contact between the rolling elements and the races in which they roll [4]. A physical model used to predict the vibration generated by the contact between the rolling elements and its races should take into account parameters such as roughness of the surfaces, velocity, load on the bearing, the contact area and others. It is also desirable that this model is capable to deal with common defects of the surfaces in order to predict the extent of these damages and, if possible, the remaining life cycle of the bearing. Additionally, the prediction of the vibration produced by the bearing requires the knowledge of the transfer impedances from the point of excitation to the point of measurement.

The transfer impedance is the ratio between the spectrum of the driving force in the point of excitation and the spectrum of velocity in the point where the measurements are taken (normally on the surface of the machine).

An electrodynamic shaker could be used to excite the structure, however there are two major drawbacks. At first, the frequency range of excitation is limited due to its mechanical properties. Moreover, it would be necessary to dismount parts of the machine, including the bearings, which alters the transfer impedance.

This paper describes a method of measuring the transfer impedance exactly - in magnitude and phase - using a special piezoelectric exciter that substitutes one of the rolling elements.

Special care has to be taken in its construction and calibration in order to obtain the exact driving force. This transducer has the advantages of extending the frequency band of excitation (up to 200 kHz or even more) and allowing the measurements to be undertaken in a mounted bearing.

With the transfer impedances and the measured acceleration (or velocity) on the surface of the machine, the causal vibration force inside the bearing can be calculated.

PHYSICAL MODEL

The physical model of the contact between the rolling element and it's races should take into account, among other things, the roughness profile of the contact surfaces and the area of contact. The vibration produced by the movement of the rolling element over the race's surface will also depend on the kind of contact between the surfaces.

Considering a ball rolling over a race (Figure 1), one can see that the roughness profile affects the movement in such a way that the rolling element is constantly being submitted to impacts. The generation of vibration is related to these impacts. More than that, the roughness profile of the surface will determine the movement of the ball. Figure 1 also shows a scheme of the elastic contact between a ball and a race. The contact forces between the surfaces, as well as the contact impedances and displacements are also shown.

The variety of surface profiles is enormous and different obstacles such as dips and steps have to be modelled. Also the kind of movement of the rolling element and the type of excitation that is submitted, is related to the size of the obstacles compared with its own size. In an undamaged bearing, for example, the roughnesses of the surfaces are small compared to the size of the rolling element. However, a surface damage, such as a pitting, can have a size comparable to the diameter of the rolling element, thus representing a different obstacle.

The investigation of the vibration excitation related to each kind of unevenness will permit the generation of vibration profiles for various roughnesses and types of obstacles. Also, the roughness of the surfaces and the type and amount of obstacles can be increased, so that the deterioration stages of the bearing can be simulated. Later on, with the help of the transfer impedances and these excitation signals, the expected vibration on the surface of the machine can be predicted and compared to the actual vibration signal measured.

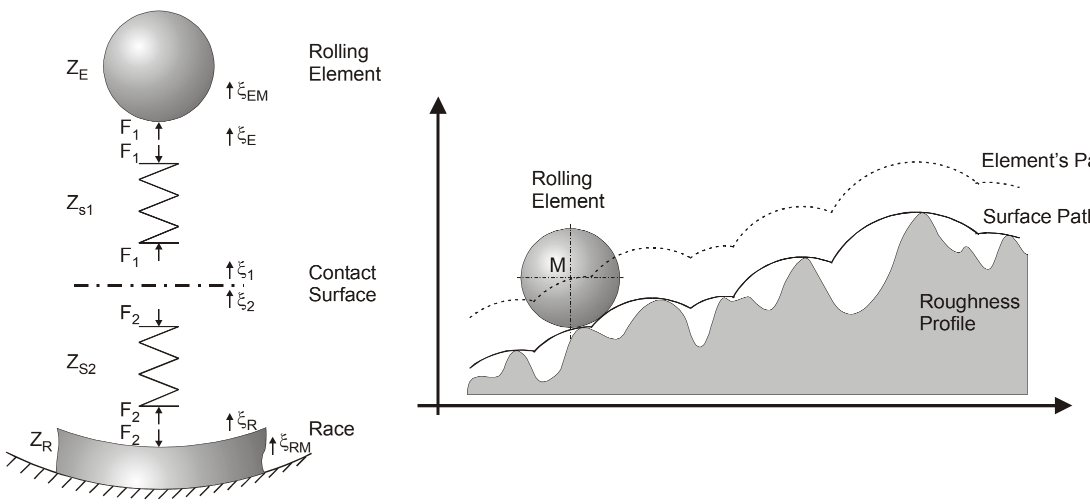

Fig. 1.- Physical model of the contact between rolling elements and races

It should be also taken into consideration that the movement of the ball and the excitation generated varies with the load applied to the bearing. For higher loads, the area of contact between the surfaces is bigger, increasing the amount of impacts suffered by the ball. On the other hand, a higher load restricts its movement.

The velocity also has influence in the excitation signal generated, as different behaviours of the rolling element are expected when it overcomes an obstacle.

Different kinds of rolling elements have also to be included in the investigations, as the area of contact, their dynamics and other parameters are changed.

THEORETICAL ASPECTS

The signal produced by the contact of the rolling surface and the tracks (F_1) can be measured with the sensors (S_i) on the surface of the machine. The transfer impedances, denoted by Z_{1i} in Figure 2, describe the behaviour of the system between the excitation point and the sensors.

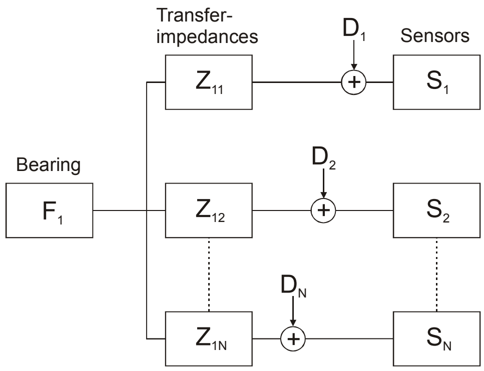

Fig. 2.- Vibration transmission from the bearing to the sensors

For each position of the piezo element, i.e. for each different point of excitation, and for each different position of the sensors, there exist a unique transfer impedance that has to be evaluated. However, for each combination of the positions of excitation/measurement the signal is disturbed by unwanted noise (D_i) coming from other sources.

The measured force is given by:

$$F = \frac{1}{N}\sum_{i=1}^{N} S_i Z_{1i} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{F_1}{Z_{1i}} + D_i\right) Z_{1i} = \frac{1}{N}\sum_{i=1}^{N} F_1 + Z_{1i} D_i = F_1 + \frac{1}{N}\sum_{i=1}^{N} Z_{1i} D_i \qquad \text{(Eq. 1)}$$

The use of various sensors and the averaging of the signal enhances the signal-to-noise ratio while preserving the useful information related to the bearing under investigation. This relationship is shown in Equation 1. When using and averaging N signals of structure-born sound, the level of wanted signal will increase with $6\ dB \cdot ld(N)$. Due to the fact that the noise signals D_i are not correlated, their level will increase merely $3\ dB \cdot ld(N)$. The result is a gain of $3\ dB$ signal-to-noise ratio per linear superposition of two signals with the same level. Another advantage of parallel data acquisition with several accelerometers is to check if the logged data belongs to the tested bearing and not predominately consists of noise signals. Furthermore, it is possible to select frequency bands with a high signal-to-noise ratio for diagnostic purposes.

The transfer impedances should also be evaluated for different radial loads in order to determine different operational conditions.

TEST FACILITY

The test facility consists of a commercial cylindrical roller bearing (inner diameter 55 mm, outer diameter 100 mm) mounted between two other supporting bearings. A special housing was constructed to allow a cable inlet for the transducer’s power supply and the application of radial load. A computer with an AD/DA-card generates the exciting signal (sine sweep) to the piezo actuator and captures the response from the accelerometers. The experimental set-up is shown in Figure 3.

A low-pass filter smoothes the quantisation steps produced by the I/O-card thus preventing the system to produce dynamic intermodulation distortion and aliasing products. Due to the requirement of driving the actuator with high voltage, a power amplifier connected to a transformer is used. Inside the machine the piezo actuator excites the bearing. The signal modified by the transfer impedance can be acquired with accelerometers on the machine's surface and has to be amplified before the analog-to-digital conversion for a better resolution. In order to avoid undesirable aliasing effects, a second low pass filter is used before digitising. In addition, other parameters like temperature of the bearing and the actual applied load are logged. The experimental set-up (on the left side of the dotted line) has to be calibrated and its influence has to be compensated with a reference measurement in order to eliminate the divergences caused by the measurement devices.

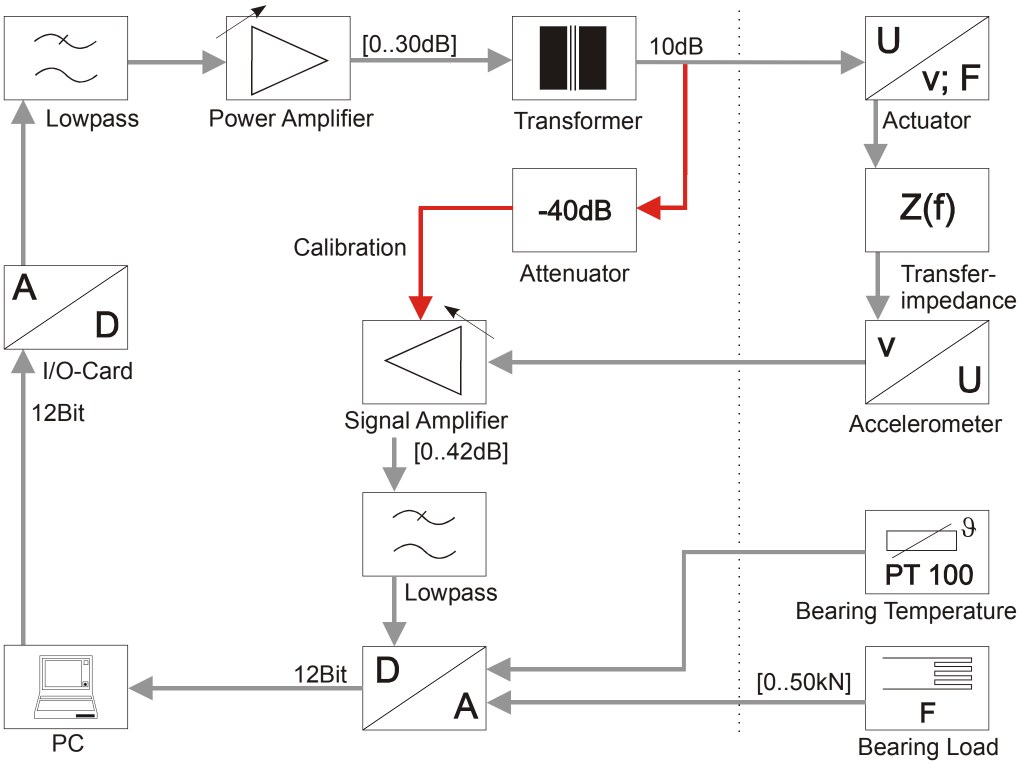

Fig. 3.- Experimental set-up of the mounted bearing

THE PIEZO TRANSDUCER

The measurement of the exact transfer impedance requires that the bearing has to be mounted in the machine. This requirement makes it impossible to measure the exciting signal directly and, for this reason, the piezo transducer has to be correctly calibrated.

The excitation element that will be mounted directly in the bearing is made from one of the bearing's rolling elements. The small cylinder (12 mm diameter and 16 mm length) is cut longitudinally into three pieces and the middle part is replaced with two piezo elements glued to a copper blade, as shown in Figure 4. This inverse-parallel configuration has the advantage over using one monolithic piezo that the isolating of one of the steel caps against the electric ground is dispensable.

The piezo ceramics are positioned perpendicular to the radial direction inside the bearing to make sure the force produced is in the radial direction. Various positions of the transducer along the bearing's perimeter, different sensor positions and several radial loads will be used for the measurements.

Special care has to be taken in the construction of this actuator. The contacts should be welded to the steel caps before gluing the piezo ceramics, because the heat can affect its polarisation. For the same reason, care should be taken while grinding the piezo ceramic to the size of the cylinder.

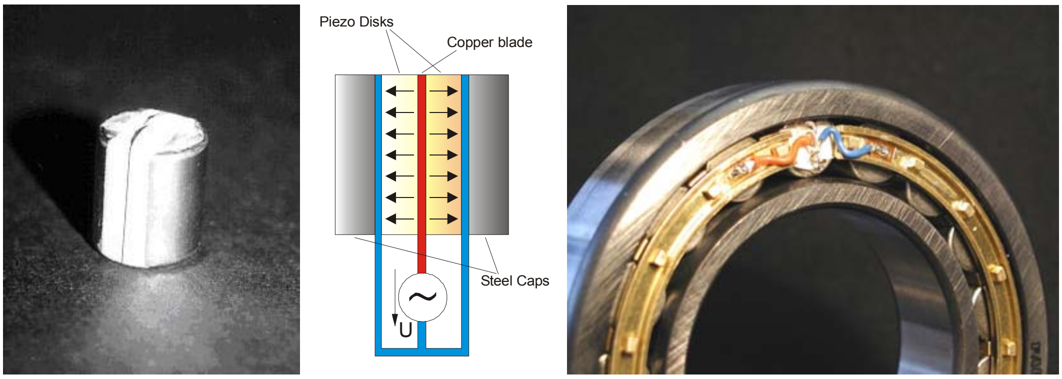

Fig. 4.- Bearing cylinder and the mounting of the piezo elements.

The force (F) generated by the transducer in the bearing can be obtained indirectly by measuring the velocity $v|_{F=0}$, the voltage $U|_{F=0}$ and the electric impedance $Z_e|_{F=0}$ within a calibration procedure before mounting the transducer. $F=0$ in Equation 3 means that the transducer is loaded with no radial force.

Describing the piezoelectric transducer as reciprocal quadripole with the following matrix (Eq. 2) relationship Equation 3 can be derived. In order to achieve a high accuracy, the velocity $v|_{F=0}$ is measured with a high precision laser vibrometer.

$$\begin{pmatrix} F \\ v \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} U \\ I \end{pmatrix} \qquad \text{(Eq. 2)}$$

When using the transducer as exciter in the mounted bearing with different radial loads, only the voltage $U|_F$ and the electric impedance $Z_e|_F$ have to be measured to calculate the exciting force with Equation 3.

$$F = U\Big|_F \left.\frac{U}{v}\right|_{F=0} \left\{ \left.\frac{1}{Z_e}\right|_{F=0} - \left.\frac{1}{Z_e}\right|_F \right\} \qquad \text{(Eq. 3)}$$

RESULTS

Figure 5 shows the frequency response for two accelerometers positioned on the surface of the machine above the bearing. A load of 10 kN was applied and the actuator sends an excitation sweep from 0 to 70 kHz. The signal is averaged 128 times.

Now, with the help of the signal from the calibrated actuator, the transfer impedances can be determined and later used to calculate back the exciting force inside the bearing.

This preliminary result shows that the actuator and the experimental set-up are working properly and that future measurements are possible with this methodology. It is to be considered now the calibration of the sensors in order to calculate the exciting force and the transfer impedances.

Future works include a complete evaluation of the transfer impedances for different positions of sensors and different radial loads applied to the bearings. Also, the integration of these results within the physical model has to be realised.

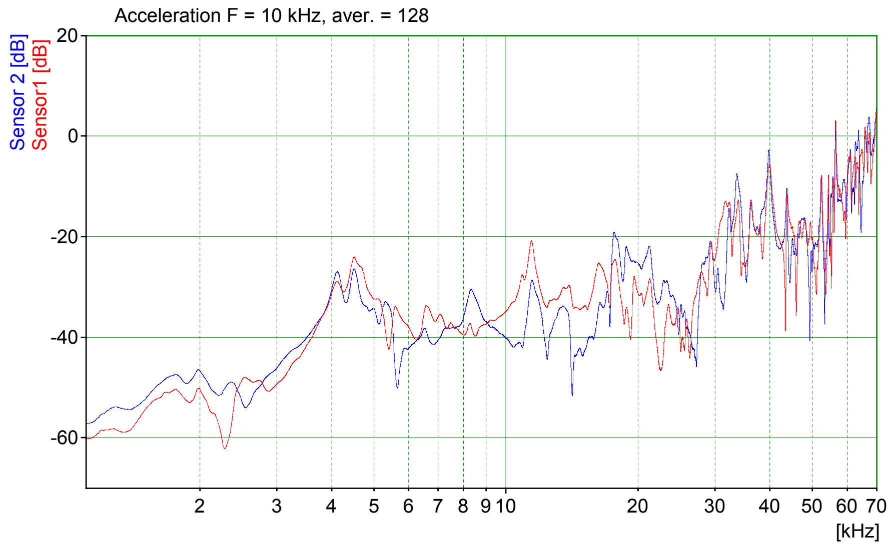

Fig. 5.- Measurement results

CONCLUSIONS

The calibration and use of a piezo transducer to obtain the transfer impedance of a mounted rolling bearing was described. The transfer impedance, together with a suitable model for the contact between the rolling elements and its races - to be developed in the future - makes possible the prognosis of the actual condition of the bearing.

This physical model should predict the vibration generated by the contact between surfaces in mint conditions, as well as abrade surfaces. Different degrees and types of wear have to be simulated so that a database of excitation signals can be generated. With the help of the transfer impedances measured in the machine, one will be able to generate vibration patterns to be compared with the actual signal of a running machine. In this way, the actual condition of the bearings can be evaluated and, as a consequence of this, the remaining life cycle of the bearing.

Future work also has to be done in order to measure different loads and different positions of the sensors.

Nevertheless, the procedure to calibrate and obtain the transfer impedances seems to be valid and preliminary results shows its feasibility. Different types of bearings, with different rolling elements can be tested with this methodology, provided that suitable actuators are built.

This approach has the advantage that the transfer impedances are obtained with mounted bearings using one rolling element (modified with built in piezo transducer as described above) as exciting force. In this way the exact transfer impedance can be measured without negative influence of the measurement set-up.

One should expect different transfer impedances for different machines, bearings and loads applied. However, the use of this technique in all these cases is possible.

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