# Vibro-acoustic Diagnostics of Rolling Bearings in Vessels

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Rolling bearings for many years have formed part of many mechanisms of various machines. They are also found in vessels. Rolling bearings' failure leads to failures of entire subsystems. For this reason, it is recommended to use objective and non-invasive methods to assess the condition of key bearings having a significant impact on the reliability of operation. Tools of this type include vibro-acoustic diagnostics.

**KEY WORDS**
~ Bearings
~ Diagnostics
~ Vibro-acoustic
~ Statistical measures

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## 1. INTRODUCTION

The attempts to apply methods of vibro-acoustic diagnosis to monitor the components constituting the equipment of ships and other vehicles are generally known (Grządziela, 2007; Grządziela, 2011). One of the components widely used that make part of ships' engines are bearings. They are also applicable due to their reliability in propulsion systems. Rolling bearings are part of a very large number of basic parts of equipment in all vessels. This equipment may include fuel centrifuges (Figure 1), compressors (Figure 2) and different types of pump (Figure 3).

Bearing nodes of propulsion systems and other components are subject to unusual sea loads caused by surging sea and dynamic effects associated with various, often unconventional vessel's assignments.

Damage to one of the bearings on the basis of a chain reaction, could lead to damage to the whole assemblies and subassemblies, which in turn can lead to serious damage of for example drive unit or could affect the safety of the vessel. Early diagnosis of the wear or the damaged individual bearing of for example the engine has a significant impact on the reliability of the entire operation period (Guyer, 1996).

In order to increase safety it would be recommended to refer to objective and reliable methods for monitoring the condition of rolling bearings, especially given the high density of individual components on a small surface and their interaction. One of these methods for determining the condition of the bearings is the method using vibroacoustic method.

Figure 1.
Fuel centrifuge Alfa Laval.

Figure 2.
Two-stage air compressor.

Figure 3.
Outboard water pump.

## 2. THE BEARING AS A VIBRATION AND NOISE GENERATOR

Each even smooth bearing is the source of noise and vibration connected with the movement of loaded rolling elements (Momono and Noda, 1999). Periodically changing load on the rolling elements causes changes in the susceptibility of the contact zones that is the cause of the formation of mechanical vibrations (Łazarz and Peruń, 2008). Other important causes of vibrations are geometric imperfections such as wave and surface roughness, fracture and fatigue of the rolling elements and the raceway surface crumble, as well as operational negligence in the form of impurities or improper lubrication (McFadden and Smith, 1984).

The flexible nature of the contact between the elements of rolling bearings can be modelled in the form of non-linear springs with or without deadening elements (Dietl, 1997; Noda, 1986). The model taking into account the mass of the rolling elements and two springs modelling the contact of the rolling element with the raceway, both outer and inner is shown in Figure 4.

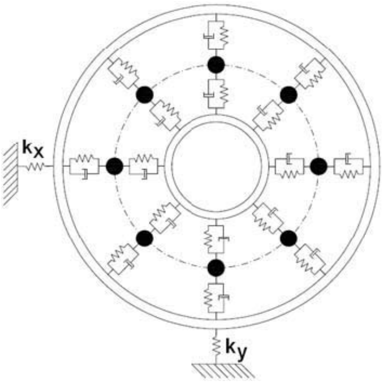


Figure 4.
Model of a dynamic rolling bearing: kx-modulus of elasticity seat in the direction of the x axis, ky-modulus of elasticity seat in the direction of the y axis.

The frequency with which any rolling item passes through the selected internal or external point of the ring of the bearing, depends on the number of rolling elements in the bearing. The frequency of the transition of a single-bead ball bearing through the bearing's circuit is:

$$f_c = \frac{\omega_c}{2\pi} \tag{1}$$

where:
$\omega_c$ - is the angular speed of the cart.

The frequency of the transition of all balls of ball bearing circuit (Eng. BPF - Ball Pass Frequency) determines the pattern:

$$f_{BPF} = zf_c \tag{2}$$

where:
z - the number of rolling elements.

The generated vibrations are poly-harmonic and stem from a change in the stiffness of the contact zone of the rolling element with treadmills and are created by the movement of rolling element bearings. The bearings are then subjected to bending and stretching, which is shown in Figure 5.

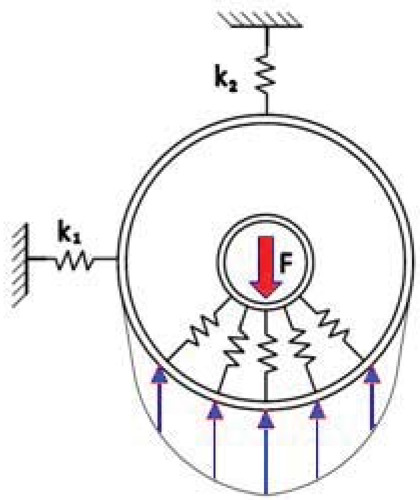


Figure 5.
Rolling bearing axial load.

A heavily loaded rolling bearing can lead to the loss of contact between the rolling elements and raceways. The phenomenon of this type produces strong chaotic vibrations. In addition, the effect of vibration caused by the movement of the roller may increase the uneven distribution of forces aggravating rolling bearing.

It is clear that each rolling bearing is made with different variations (Adamczak et al., 2011; Adamczak et al., 2013). But due to the fact that the bearings are made using the same mechanized devices, you can allow the repeatability of the characteristics of the produced bearings. In addition, striving to reduce production errors and a thorough quality control increase the coefficient of repeatability.

The presented causes of the vibration generated by the bearings make any, even the best made bearing, a source of vibro-acoustic processes of the spectral structure similar to noise. Vibration control positions used by manufacturers generally operate by the general measures, and on this basis make the classification of bearings in terms of fitness.

From the point of view of diagnostics, the level of vibration and noise of the new bearings is rather a kind of distortion, which should be specified in the calibration process while the determination of the parameters of vibro-acoustic processes accompanying all kinds of damage becomes important.

Bearings are inherent with generating audio signals that result from both natural conditions, and may herald the progressive damage if there are signals that the volume exceeds the expected values in the data. Compiling all sorts of sounds generated by the bearing is virtually impossible because of the wide range of frequencies in which the sound signals are contained, and some of them exceed significantly the scope of perception of the human ear in both low and high band. In addition, the difficulty stems from the simultaneous generation of vibration and audio signals by the working bearing.

## 3. GENERATING VIBRATIONS DUE TO THE DAMAGE - PULSE MODEL

Applying impulse force to the elastic system causes its dynamic response dependent on transfer function of the system. The response to the sequence of pulses is, as known, another sequence of pulses. According to equations defining the kinematic dependences determining mutual velocities of bearing's moving parts, the excitation frequency will be different depending on which of the elements have been damaged. To illustrate the phenomenon, we consider flat linear model. Assume that the outer race of bearing is fixed at the same time that the inner race is movable (Figure 6).

Using the proposed linear model, load distribution can be presented as in Figure 7.

It follows that the failure of the outer race will result in almost constant pulse sequence when the fault location of race is in the zone of maximum load. In case of damage of both the rolling element and the inner race, there is a sequence of pulses periodically increasing and decreasing. For bearings loaded only by transverse force, it can be assumed that about half a turn will be devoided of impulse interference.

As follows, the pulse load model can be represented as in Figure 8. The red line on the graph shows the distribution of the load on the bearing.

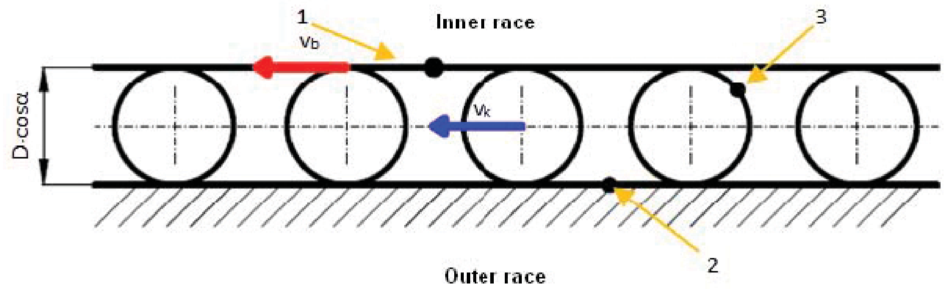


Figure 6.
Model to determine the contact frequency of the damaged component with the other parts of the bearing: $v_b$ – race velocity, $v_k$ – rolling element velocity, • - place of damage: 1 – inner race, 2 - outer race, 3 – rolling element.

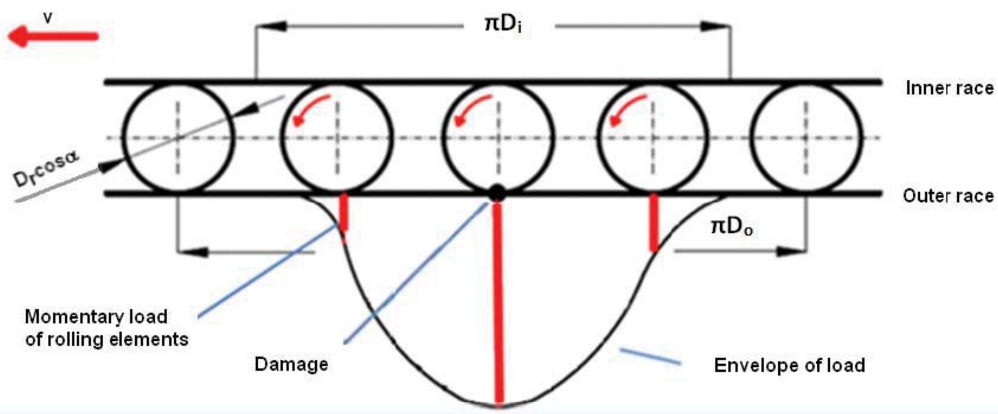


Figure 7.
Flat computational model for determining characteristic frequencies related to the point of damage of each bearing components: v - rolling velocity, $\pi D_i$ - length of rolling way on the inner race, $\pi D_o$ - length of rolling way on the outer race.

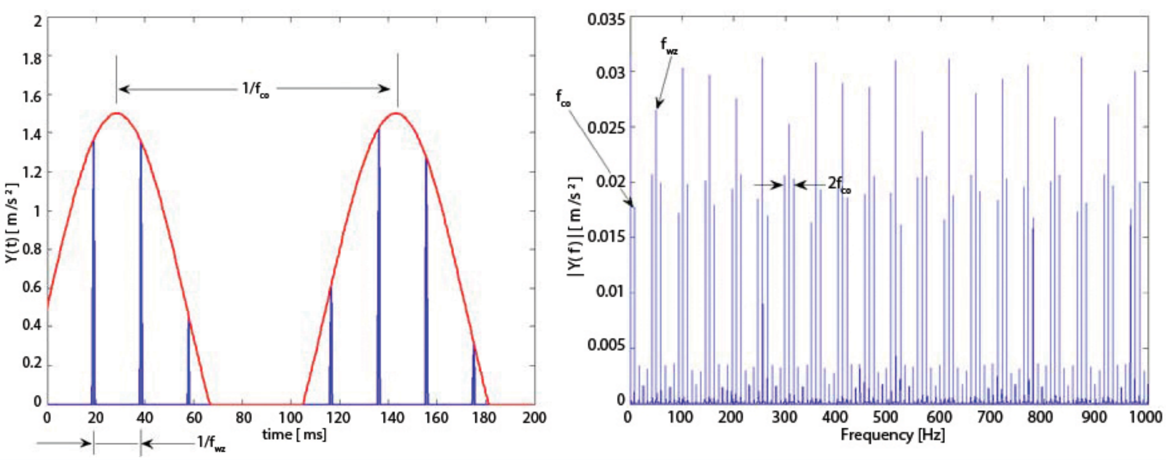


Figure 8.
Typical signals generated by damaged rolling element: $f_{wz}$ - frequency vibrations induced by damage of rolling element $f_{co}$ - frequency resulting from the rotation velocity of the rolling elements cage.

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## 4. CHARACTERISTIC FREQUENCY OF ROLLING BEARINGS

In the course of the operation of bearings, the initial stages of damage to both the treadmill and rolling element, regardless of the type of damage (pitting, cracks, scratches, etc.) generally have a nature of local deformation. This type of consumption shall be accompanied by a specific vibration frequency suitable for the damage to individual items, this frequency is mainly from the rolling element bearings and its contact with a portion of the damaged figure and it stems from the basic kinematic dependence in the bearing (Cempel and Kowalak, 1980). Described dependences according to specific designs have been depicted in 3, 4, 5.

The frequency of the vibrations caused by damage to the inner raceway:

$$f_i = \frac{z \cdot f}{2}\left(1 + \frac{D_r}{D_m} \cos a\right) \tag{3}$$

where:
z - number of rolling elements, f - frequency of rotation of the shaft, Dr - rolling element diameter, Dm- pitch diameter, α - angle of the bearing.

The frequency of the vibrations caused by the damage to the treadmill:

$$f_o = \frac{z \cdot f}{2}\left(1 - \frac{D_r}{D_m} \cos a\right) \tag{4}$$

The frequency of the vibrations caused by the damage to the rolling element:

$$f_{wz} = \frac{D_m \cdot f}{2D_r}\left(1 - \left(\frac{D_r}{D_m} \cos a\right)^2\right) \tag{5}$$

Basing on the above characteristic frequencies is most appropriate in cases where the damage is a point e.g. the pitting or crumble, while for more complex damage there is a need to use more advanced methods of analysis vibration signals (Dziurdź, 2006).

For this purpose one can use e.g. measurements of the amplitude signal as well as dimensionless discriminants, and in more complex cases, for the diagnosis it may be necessary to use methods of analysis of signals in the field of time and frequency. Such methods include short-time Fourier transform and Pseudo Wigner-Ville transform.

## 5. ANALYSIS OF LATERAL VIBRATION ON SAMPLE BEARINGS' ENCLOSURES

Transverse vibration of bearing housing was measured in transverse plane in the zone of maximum load in bearing node with the use of vibration acceleration sensors allowing measurement in the frequency range up to 10 kHz. The signals were recorded with eight-pass data acquisition card VibDAQ+. Sampling frequency of signals was 31,2 kHz. Each time the measurement was about 60 seconds long. The results of the measurements were recorded on the computer's hard drive. During the test, temperature of the tested equipment was controlled. The temperature during tests corresponded to that of the normal operation.

During the test, the forces were affecting the single-row, angular ball bearing resulting from its normal operation. Figure 9 shows the results obtained from the analysis of the recorded signal on bearing after some time and a new one made using simple statistical measure. The measures were created on the basis of recorded vibration signals, which have good diagnostic sensitivity. Figure 10 shows the results of the dimensionless discriminant, often used in the diagnosis.

In the tests (C) the crest factor, (K) the form factor, (L) clearance factor and impulsivity factor were used and in addition, for both bearings the value of the kurtosis has been designated.

On the basis of the results shown, the growth of all designated measurement can be seen. In the case of the effective value of acceleration of vibrations and standard deviation of the increment amounted to approximately 20 %. Changing the average deviation was around 14 %, while the variance was of up to 40 %.

The largest recorded change among the dimensionless discriminants was that of clearance rate value. The change amounted to about 13 %. A little less increase took place in the value of impulsivity. The other coefficients have recorded growth of around 4-6 %.

The biggest difference was in the case of kurtosis. Here, the increment was over seven.

Figure 11 shows the amplitude spectrum of vibration acceleration recorded on the enclosures tested.

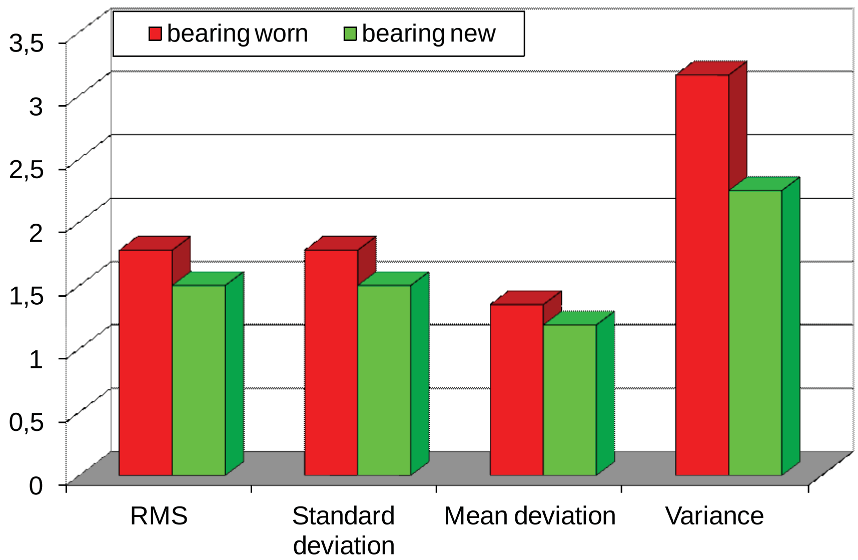


Figure 9.
The value of simple amplitude measures of the designated for the used bearings and the new ones.


Figure 10.
The value of the dimensionless discriminant designated for the used and new bearings.

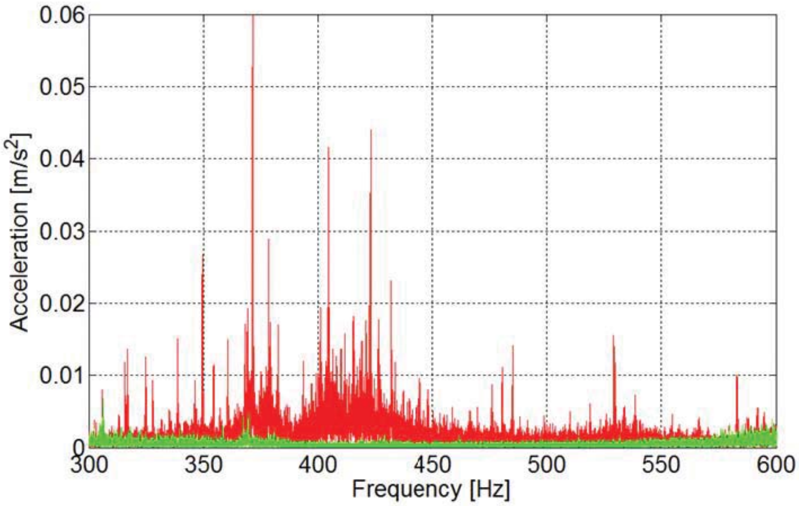


Figure 11.
Amplitude spectrum of vibration acceleration recorded on the tested enclosures.

In the selected range, the greatest diversity of amplitude spectra was observed with the new bearings and the one after some time. In the frequency range 300-600 Hz, vibration acceleration amplitude increase is visible after some time of exploitation.

For diagnostic reasons, it is advisable to conduct studies after varying periods of time. On the basis of the results obtained, it may be possible to determine the frequency intervals showing the greatest amplitude changes that will constitute the basis for making a certain diagnosis of the bearing arrangement.

## 6. CONCLUSION

Vibro-acoustic diagnosis of rolling bearings in vessels faces a number of problems encountered also when diagnosing bearings in automotive vehicles. The main problem is isolating the interesting and important from the point of view of the diagnosis, signals from interference. This refers mostly to acoustic signals, less difficulty occurs when diagnosing using vibration signals. For this reason, in the described research the emphasis was on the use of vibration signals.

On the basis of the studies conducted and of the analysis, the following conclusions are:

- wear and tear of bearings contributed to the increase in the value of measures assigned on the basis of vibration acceleration signal,
- increases in the value indicate a progressive wear allowing, however, for further exploitation,
- the largest difference between the values obtained was for the kurtosis as well as for the variance, in other cases they were less than 20 %,
- in the case of building measures based on signals distorted by the high-energy components generated by efficient or damaged elements, frequency or time-frequency analysis of recorded signal would be appropriate.

The test results show effectiveness of the methods of vibro-acoustic diagnosis.

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