Design of Machines and Structures, Vol. 2, No. 1 (2012), pp. 53–62.
https://doi.org/10.32972/dms.2012.005

ON COMPUTATIONS OF VIBRATIONS AND FREQUENCIES OF ROLLING BEARINGS

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This paper summarises the sources and the reasons of developed vibrations in rolling bearings. Equations are given to compute the developed vibrations according to the professional literature. The behaviour of rolling bearings is analysed detailed in different frequency range

1. Introduction

Rolling bearing as a mechanical element or machine element has been used in the Ancient Rome. It has a very different shape than it has nowadays, but the principle of the operation was the same. It had wooden rolling elements and it was used in the wheels of coaches. After the fall of the Roman Empire, many magnificent scientific results were forgotten, like bearings in wheels of coaches. [1]

Leonardo da Vinci the grate scientist of the Middle Ages dealed with shaft mountings, that is to say bearings. Unfortunately as with many other ideas of his own, he just made sketches about the bearing, there is no known prototype of them.

In our days the bearing is one of the most often used machine element in machines and equipments. Bearings after the patent of Philip Vaughan (1794) have been made significant expression to the engineers in the meaning of their different operation circumstances and rolling problems. Judging their condition and defining the rest of their lifetime have caused a huge headache for the engineers.

2. Beginning steps

The first large scale examination to estimate the state of heavy machines and judge their running conditions was made by T. C. Rathbone. Scientific vibration diagnostic of our days was built upon their work. The scientific level of the modern vibration diagnostic was generated by the development of computing equipments and the claims of the industry.

Rathbone was the chief engineer of Turbine and Machinery Division, for the Fidelity and Casualty Company of New York. He started to deal with the measurement and the documentation of the machine vibration at the beginning of the 1930's. He first publicated his results in 1939 with the title of „Vibration Tolerance" in the periodica Power Plant Engineering. This paper was about the diagnostic of the vibration level rising in case of rough operation deriving from unbalancing machines. [2] His results were summarised in a chart (*Figure 1.* Rathbone chart).

The Rathbone chart classifies machines into seven divisions:

- 1. Sensory perception level,
- 2. Very smooth,
- 3. Good,

– 4. Fair,
– 5. Slightly rough
– 6. Rough – needs correction,
– 7: Very rough – correct immediately.

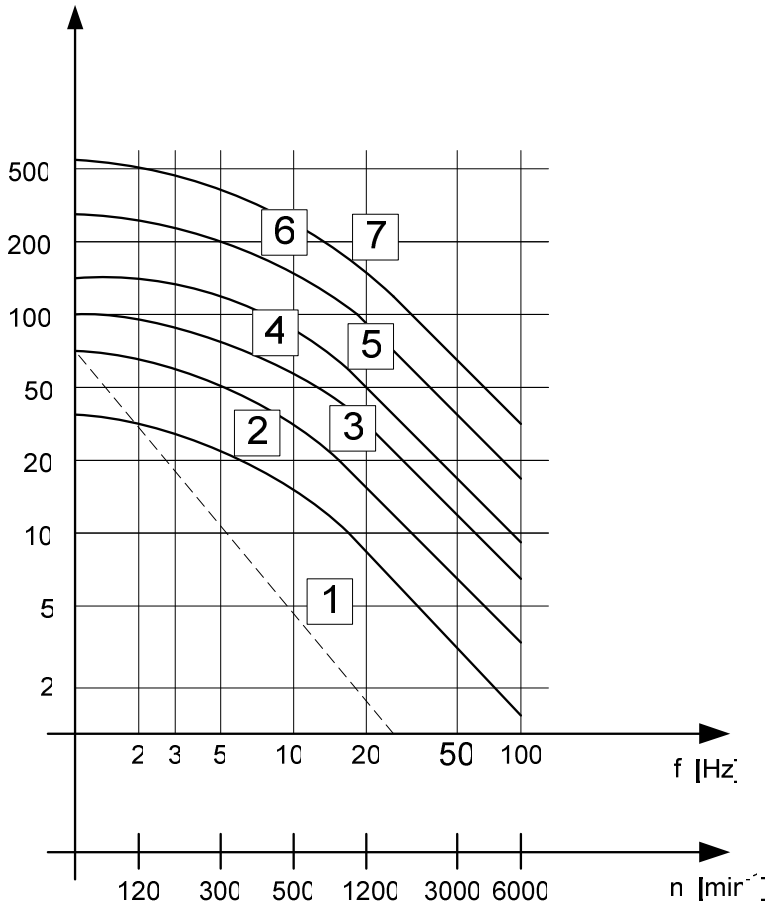


Figure 1. Rathbone chart [3]

Of course his results are not up to date and not proper for our days regulations, but his work was very significant milestone in this filed of science.

The determination of the acceptable vibration level in case of rolling bearings is still in use was based on this chart and the measuring results of the engineers working for ENTEK IRD. In Europe the chart for rolling bearings was signed as the original Rathbone diagram for many years (*Figure 2*.).

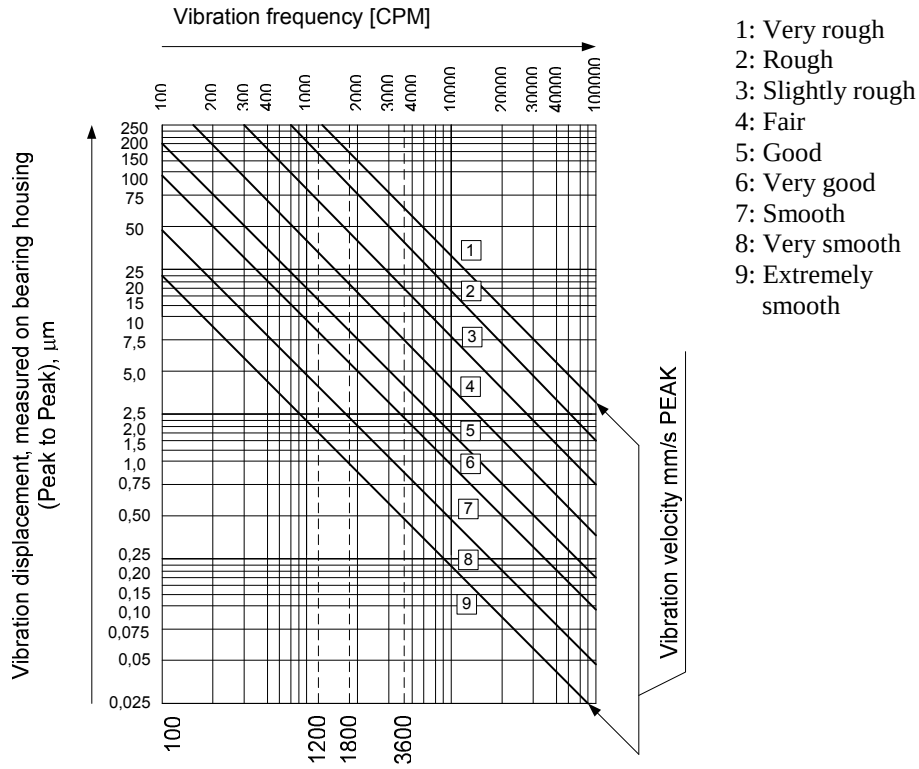


Figure 2. Chart summarising the results of ENTEK IRD [8]

3. The behaviour of rolling bearing is different frequency range

The vibrational behaviour of rolling bearings can be divided into several ranges according to the frequency. This can be seen in *Figure 3*. [4]

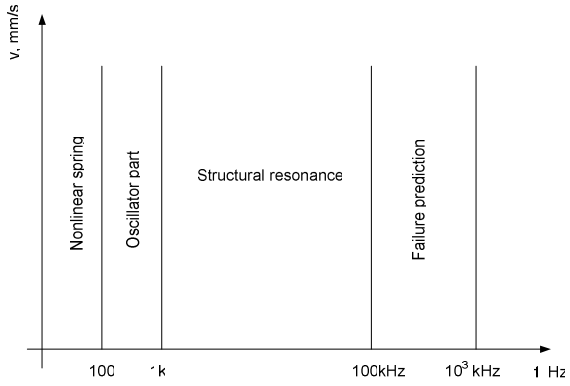


Figure 3. The vibrational feature of rolling bearing according to the frequency ranges [4]

3.1. Non-linear spring

The rolling bearing under 100Hz can be modelled by a nonlinear spring. This model consists of 3 masses. A spring element and an absorber element mean the connection between the masses. Mechanical model can be seen in *Figure 4.*

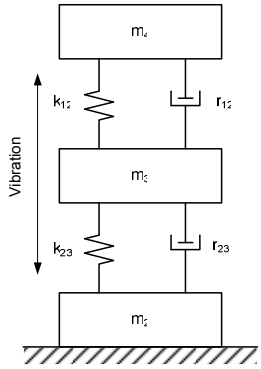


Figure 4. Mechanical model of rolling bearing

With the signs of *Figure 3.:*

- m_4: outer ring
- m_3: rolling elements
- m_2: inner ring
- k: rigidity of spring element
- r: the coefficient of absorber element

The connecting surfaces in the rolling bearing are extremely small. In a sense of mechanics the connection is a point (in ball bearing), or a line (in roller bearings). Bearing can be examined according to the Hertz theory. With the help of this theory the deformation can be determined in the connection point or line and around. Of course this theory uses simplification, but this is not means such a big difference as we should generate if we examine the model as a pure rigid body [4], [5].

The Hertz-theory uses a couple of conditions; examinations can be solved according to them.

Conditions:

- The size of the connecting surfaces is much smaller than the size of the connecting elements.
- The load is perpendicular to the common tangent plane of the connecting elements.
- The material of the connecting elements is homogeneous and isotropic.
- Friction between elements is eliminated.

3.2. Vibration emitter, planetary gear analogy, developed frequencies

On the horizontal axle of *Figure 3*. the next behavior stage can be seen. In this stage that has an interval from approximately 100 Hz to 1kHz, the vibration emitter behavior of

rolling bearing is the determinative. This kind of behavior is the consequence of the structure the rolling bearings have. To understand the influence, let us see how the bearings are working.

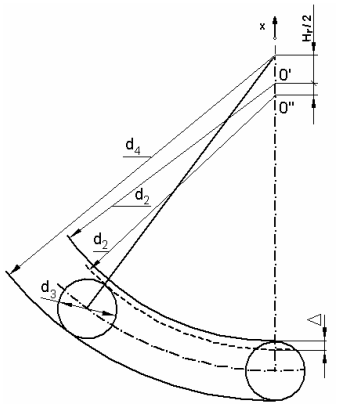


Figure 5. Seat evolved on one or two rolling body caused by the internal clearance of rolling bearings

It is known that bearings are built in with internal clearance. This means that the clearance between the inner ring and the outer ring is bigger than the featuring size of the rolling body. In cases like this moments can occur during the operation of the rolling bearings, when two rolling bodies prop the inner ring and there are moments as well, when only one rolling body provides the shoulder of the inner ring (*Figure 5*.). This phenomena results the Δ size movement of the inner ring in radial direction, so a kinematic excitation. Therefore polygon-frequency arises. Calculation of the polygon-frequency can be solved according to equation (1).

$$f_p = \frac{n_k}{60} [\,Hz\,] \tag{1}$$

n_k is the revolution of the cage in min^{-1} unit.

When the internal clearance of the rolling bearing eliminated, then the kinematic excitation would be disappeared and the rolling bearing would be a pure rigid body. In circumstances like this rolling bearings could not be operated.

Of course the polygon-frequency is not the only frequency that features rolling bearings. In cases of bearings that are ensuring kinematic pure rolling other rolling frequencies can be divided into two groups, depending on whether the inner or the outer ring is rolling. [6]

In case of rolling inner ring:

- The frequency of the inner ring:

$$f_2 = \frac{n_b}{120}\left(1 + \frac{\cos\alpha}{\frac{d_k}{d_2}}\right) \cdot z_g . \tag{2}$$

– Cage-frequency:

$$f_k = \frac{n_b}{120}\left(1 - \frac{\cos\alpha}{\frac{d_k}{d_3}}\right). \tag{3}$$

– The frequency of the rolling element:

$$f_3 = \frac{n_b}{120}\left(\frac{d_m}{d_g} - \frac{\cos^2\alpha}{\frac{d_k}{d_3}}\right). \tag{4}$$

In case of rolling outer ring:

– The frequency of the outer ring:

$$f_4 = \frac{n_k}{120}\left(1 + \frac{\cos\alpha}{\frac{d_k}{d_3}}\right) \cdot z_g. \tag{5}$$

– Cage-frequency:

$$f_k = \frac{n_k}{120}\left(1 - \frac{\cos\alpha}{\frac{d_k}{d_3}}\right). \tag{6}$$

– The frequency of the rolling element:

$$f_3 = \frac{n_k}{120}\left(\frac{d_m}{d_3} - \frac{\cos^2\alpha}{\frac{d_k}{d_3}}\right). \tag{7}$$

Quantities in (2)–(7) equations:

n_b : rev of the inner ring,

d_k : (featuring) diameter of the cage,

z_g : number of the rolling elements,

d_m : middle diameter of the rolling bearing,

d_g : diameter of the rolling element,

α: angle of action (in case of deep groove ball bearings $\alpha = 0°$),

Indexes 2, 3, 4 means inner ring, rolling element, outer ring.

Solving the computations rev of each elements of the rolling bearing is needed. Rolling bearing is able to be substituted by a OI planetary gear. Through this planetary gear analogy Kutzbach-construction can be applied for determining the revs (*Figure 6.*).

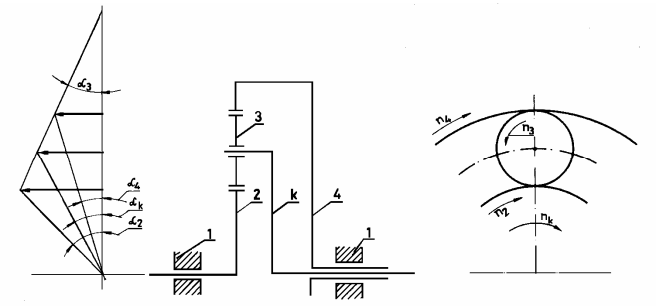


Figure 6. Rolling bearing substituted by planetary gear for defining revs

Besides the above mentioned frequencies others are also appears during the operation of rolling bearings originated from imbalance and the failures of the geometry.

3.3. Frequencies deriving from imbalance

In case of each element that has rolling movement vibration deriving from imbalance occurs. Sometimes this vibration is higher, sometimes it is lower. Even in case of the most perfect manufacturing a few imbalance is still rest in elements.

Evolving frequencies:

- Shaft frequency generated by forces:

$$f_t = \frac{n_2}{60}. \tag{8}$$

- Cage frequency generated by forces:

$$f_k = \frac{n_k}{60}. \tag{9}$$

- Housing frequency generated by forces:

$$f_4 = \frac{n_4}{60}. \tag{10}$$

- Roller frequency generated by forces:

This frequency usually can be eliminated. Rollers generally compensate the effects they have. If it cannot be eliminated computations can be solved according to the equations (11), (12).

From main movements:

$$f_{g1} = \frac{n_3}{60}. \tag{11}$$

From collateral movements:

$$f_{g2} = \frac{n_s}{60}. \tag{12}$$

Collateral movements evolving in those bearings that are not able to ensure kinematic pure rolling. Bearings like this are e.g.: angular contact ball bearing or deep groove ball bearings that are also loaded by axial force

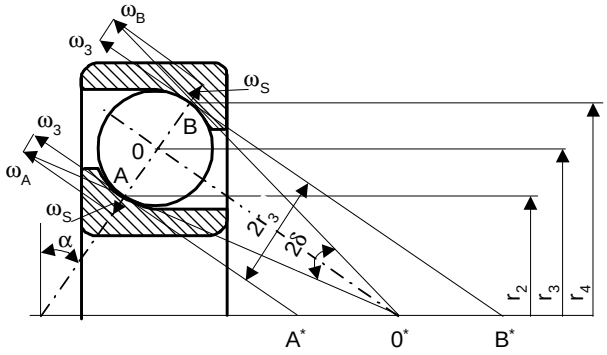


Figure 7. Sketch of an angular contact ball bearing

n_s can be counted according to *Figure 7*. by the next equation:

$$\omega_s = \omega_3 \frac{r_3}{r_k} \sin\alpha. \tag{13}$$

3.4. Frequencies deriving from the failures of the geometry

The running surfaces of real rolling bearings and the surfaces of the rolling elements are not pure true to type surfaces. According to this not perfect elements while rolling down on each other generate different sizes of irregularity.

The failure of running surfaces is usually waviness. This can be originated from the production and the circumstances of the assembly. The generated frequencies can be counted according to the following equations:

– Effect of the geometry failure in case of inner rings:

$$f_2 = i_2 \frac{n_{k2}}{60}. \tag{14}$$

– Effect of the geometry failure in case of outer rings:

$$f_4 = i_4 \frac{n_{k4}}{60}. \tag{15}$$

i_2 and i_4 in equation (14) and (15) are the number of the failures appearing on the given elements, in case of waviness i_2 and i_4 are the number of the waves. n_{k2} and n_{k4} are the rev of the cage related to the inner ring and outer ring.

Failures appearing on the surface of the rolling elements are polygon failure mainly. Counting the frequency generated by the polygon failure should be done according to equation (16):

$$f_3 = i_3 \frac{n_3}{30}. \tag{16}$$

Rev n_3 is the rev of the rolling body own shaft.

3.5. Eigenfrequencies (resonance frequencies)

In case of equipment consist of rotating machine elements eigenfrequencies of these elements should be kept in front of the designer's eyes. Permanent operation of an equipment like this on the rev that results an excitation proper for one of the elements' eigenfrequency is forbidden. Calculating eigenfrequencies on paper is to be solved only in case of those elements that has a very simple geometry. With the development of the computer technology finite element softwares are able to determine the eigenfrequencies even in case of difficult geometry as well. Eigenfrequency depends on the material and the size of the geometry. In case of rolling bearings eigenfrequencies of the inner and the outer ring are important. Frequency images of eigenfrequencies can be seen in *Figure 8.* Determining the eigenshapes was carried out by a FEM program.

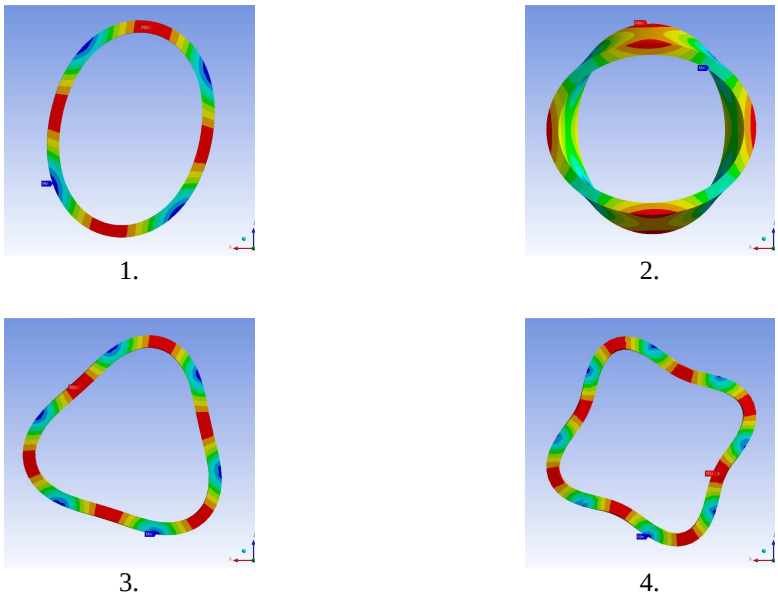


Figure 8. Resonance shapes of Eigen frequencies in case of rolling bearing rings (first 4)

3.6. Damage prognosis

In case of damages other frequencies appear over the above mentioned ones. These frequencies can be originated not only from the damage of the rolling bearing but it also

can be caused by a false assembly, or an improper construction of the connecting elements (housing, shaft). Let us see a very simple example. Rolling bearing is positioned in a bore through an interference fit. Unfortunately the bore was made wavy. Because of the interference fit the outer ring of the rolling bearing adopts the wavy shape, so the running surface of the rolling elements also gets wavy.

The literature helps the engineers realising the failures of rolling bearings independent of the reason of the failure by different spectrum pictures determined by several measures and analysis.

On the field of vibration diagnostic there are a lot of measuring methods developed for determining the state of bearings. *Figure 9.* shows their application according to the frequency values.

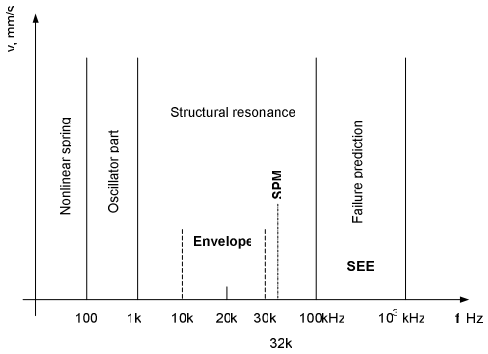


Figure 9. Suggested measuring methods in different frequency intervals [4]

4. Conclusion

The paper introduced how wide the range of frequencies a rolling bearing can perform is. It should be noticed that the above introduced calculations are only typical for normal operation. Frequencies generated by different failures were only mentioned. Analysing the spectrum of a bearing all above mentioned frequencies should be taken into account so the failures generated frequencies to be identified, and on this basis arrangements can be made.

Acknowledgement

"This research was carried out as part of the TAMOP-4.2.1.B-10/2/KONV-2010-0001 project with support by the European Union, co-financed by the European Social Fund."

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