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VERTICAL VERSUS HORIZONTAL ROTORS DYNAMICS AND DIAGNOSTICS

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Abstract. *The development of modern rotating machines the need for effective methods of diagnostics has arisen. As the size of the machinery constantly reduces, it is crucial to develop effective methods for evaluation of technical conditions not only for the entire rotating system, but for each damaged element, such as antifriction and journal bearings, couplings, gears, etc. The optimization of rotating system goes through theoretical modelling based on FEM, bond graph theory, prototyping and experimental vibration testing in laboratories and machines in situ. Nodal defects should be discovered in early stage of their development. This article describes the diagnostic studies of rolling bearing faults in horizontal and vertical rotor systems that were performed at the specially designed research bench. The research bench is composed of a rotor with a disc with the changeable excitation mass fixed on it, rotor driven by asynchronous AC motor controlled by frequency inverter. Rotor, mounted in supports, using single row deep groove ball bearings 6004, class C3. During the research first and second non-defected, rolling bearings were replaced with rolling bearing with inner and outer ring race defects. Experiments conducted by changing the rotor axis of rotation from vertical to horizontal. Experiments were performed with permissible imbalance (according to ISO 1940-1) with maximum allowable imbalance and with more than 2 times higher than permissible, assessing the level of allowable imbalance magnitude according to standard G6.3 class for rotary systems with flywheel impeller. Measurements of mechanical vibration acceleration measured with a 4 acceleration transducers, mounted on the supports. This article focused on statistical analysis of the measured transducers data. New statistical parameter, "Ratio of bearing defect visibility (RBDV)" designed. This parameter helps in quantifiably assessing the influence of differently oriented rotor dynamics to bearings failures diagnostics.*

1 INTRODUCTION

Rotating machinery with horizontal rotor axis is more widespread in the industry. For this reason, most of the scientific researches focus on the monitoring of the horizontal rotation axis machinery condition and fault diagnostics methods development through mechanical vibration measurements. There is less numbers on vibration monitoring and fault diagnostics available in research materials, as vertical rotation axis machines are used relatively less frequently in industry. Comparing mechanisms with horizontal rotating axis to machinery with vertical axis of rotation, the greatest difference in design is in their radial and axial bearing supports. Some scientists carried out rotor system researches with deep groove ball bearing diagnostics. The studies focused on a new way of vibration data statistical spectrum and cascade processing methods [1, 2]. Many papers studied different defects of deep groove ball bearings using analytical models and FEM [3, 4]. Valuable data is given on the fault development of rolling element bearings and their diagnostics [5, 6]. Flexible vertical rotor modeling and failure diagnostics with experimental testing in situ presented in [7]. This data suggests more efficient ways in providing condition monitoring and prediction of unexpected failures in rotor systems with deep groove ball bearings. Articles [8, 9] focus on problems related to radial gap failure diagnostics of rolling bearings. Chaotic kinematics of rotors with roller bearings, including nonlinearities as radial gaps, increase vibration levels in high order harmonics. This makes the defect diagnostics of bearings difficult in the early stage of development [10, 11, 12]. The scientific works, which are intended to analyze rotor systems with vertical axis of rotation are dedicated to analyze dynamics of these systems and anisotropy of rotor supports, but not intended to researches development of rolling bearings diagnostics

The task of this paper is to evaluate the quantitative differences in horizontal and vertical rotation axis rotors dynamics influence to their defected bearings diagnostics.

2 THE EXPERIMENTAL SETUP

The experimental test stand, shown in Fig. 1, has been set up in order to investigate failure diagnostic differences testing a damaged 6004/C3 P6 single row deep groove ball and new bearings in horizontal and vertical axis rotors. The AC motor controlled by frequency inverter drives a rotor. Rotational speed during measurement has been changed from 100 to 3050 r/min. The rotor bearing supports 1 and 2 were mounted in a=50 mm, a + b = 550 mm distances from flywheel disc. The rotation axis of the rotor kit has been switched from horizontal to vertical position. At first, the brand new 1st and 2nd ball bearings was tested and then, it has been replaced with the defected bearing. Separate tests were provided: the first one with artificial defect on the inner ring race and second - with artificial defect on the outer ring race, as shown in Fig.3. In order to evaluate the vibration severity of the rotor, variable imbalance was used. Measurements were carried out with imbalance of 27 g mm, (maximum permissible imbalance, according to ISO 1940-1, is 125 g mm) then imbalance were changed to 125 g mm and last measurements were performed with imbalance of 300 g mm. The balancing mass was attached to the rotor flywheel disc at radius r_u. The absolute vibration velocity of bearing supports has been measured with four accelerometers 1xa, 1ya and 2xa, 2ya mounted in two perpendicular directions at each bearing support. Experimental data has been processed using multi-channel vibration signal analyzer "OROS".

As shown in table 1, the damaged bearings with defects of inner and outer rings races, kinematic vibration frequencies simulated. Constant rotational speed of inner ring n_i = 3050 r/min and outer ring was fixed: ball diameter d_r = 6,35 mm, number of balls 9.

Constant rotation speed of inner ring, n_i=3050 r/min=50,83 Hz and outer ring n_e=0 r/min	Typical vibration frequencies, Hz
Rotational frequency of rolling element cage, f_c	20,2
Vibration caused by radial fault of the rolling element, with consideration to its impacts only against the inner or only against the outer ring, f_{r1} [Hz]	119
The passage of rolling elements over defect in the rotating inner ring, f_{ip}	276
The passage of rolling elements over defect in the stationary outer ring, f_{ep}	182
Vibration caused by radial fault of the rolling element, with consideration to its impacts against the inner and outer rings, f_{rp} [Hz]	238

Table 1. Kinematic vibration frequencies with stationary outer ring for the bearing SKF 6004–2Z/C3 P6

The ring races defects of the bearing's inner and outer rings formed artificially as shown in Fig. 2. The stationary mode measurements considered at a constant rotational speed of 3050 r/min with residual imbalance of 300 g mm with a permissible imbalance of 27 g mm and maximum permissible imbalance of 125 g mm.

The permissible imbalance chosen in order for the rotating system to generate valuable inertia force to act on the testing bearings. Maximum permissible imbalance for such rotors is 125 g mm, calculated according to ISO 1940-1 rotor's imbalance grade G 6.3:

$$U_{per} = 9549 \cdot G \cdot \frac{m}{n} = 125\, g \cdot mm \tag{1}$$

Where: *G6.3* – balance quality grade 6,3 *mm/s*; *m=6,35* kg – mass of the rotor; *n=3050* r/min – constant rotational speed.

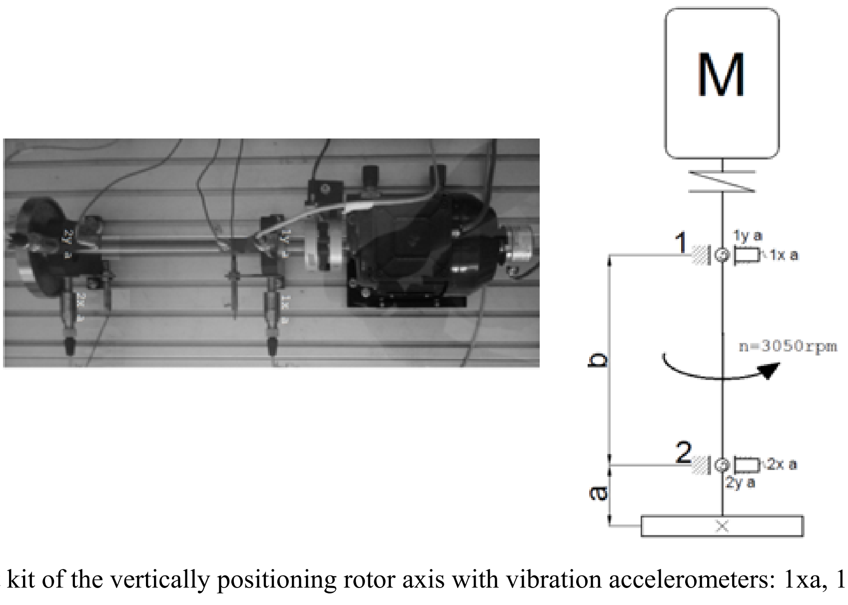
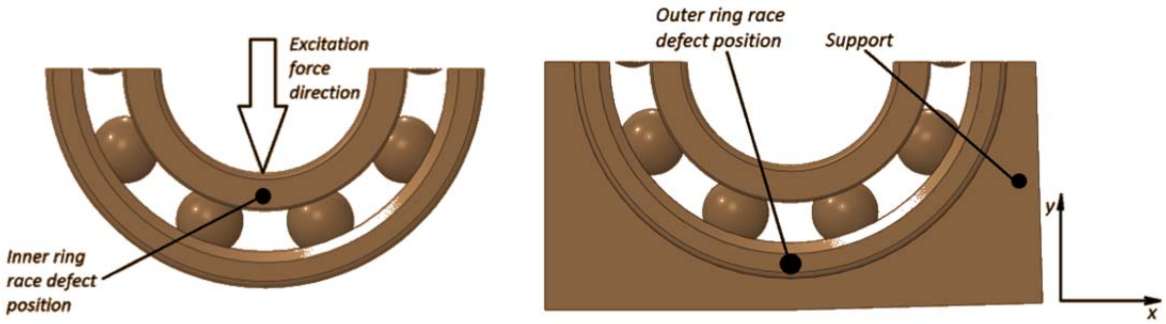


Figure 1: Test kit of the vertically positioning rotor axis with vibration accelerometers: 1xa, 1ya and 2xa, 2ya

No.	Orientation of rotor axis	Imbalance	Rolling bearing defects
1.	Horizontal	27 *g·mm*	Without
	Vertical		
2.	Horizontal	125 *g·mm*	Without
	Vertical		
3.	Horizontal	300 *g·mm*	Without
	Vertical		
4.	Horizontal	27 *g·mm*	Inner ring race defect
	Vertical		
5.	Horizontal	125 *g·mm*	Inner ring race defect
	Vertical		
6.	Horizontal	300 *g·mm*	Inner ring race defect
	Vertical		
7.	Horizontal	27 *g·mm*	Outer ring race defect
	Vertical		
8.	Horizontal	125 *g·mm*	Outer ring race defect
	Vertical		
9.	Horizontal	300 *g·mm*	Outer ring race defect
	Vertical		

Table 2. The vibration measurements order

The rotor vibration severity evaluation for the horizontal and vertical axis of rotation was provided according to different technical conditions as shown in Table 2. Initial conditions of measurements: excitation force direction same as inner ring race defect, when testing the inner ring race defect, shown in [Fig. 2a], when testing bearing with outer ring race defect, ring with defect mounted in y direction shown in [Fig. 2b]. The rotor is turning about z-axis.



a) b)

Figure 2: Initial conditions of measurements: a) position of inner ring race defect; b) position of outer ring race defect

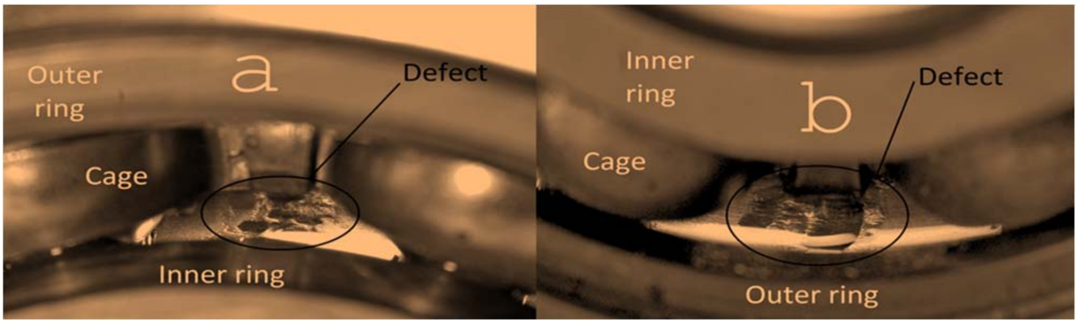


Figure 3: Defects of the deep groove ball bearing 6204 2Z/C3 P6: a - inner ring race defect; b - outer ring race defect

3 THE RESULTS AND MEASUREMENTS DATA ANALYSIS

The absolute vibration velocities data for the rotor bearing supports evaluated as root mean square values v_{RMS} and vibration velocity spectrum and cascade diagrams. The 1st and 2nd bearing was examined. The first test was performed with the brand new 1st bearing and the second and third test has been carried out with the faulty 1st bearing. The 2nd bearing was brand non-defected, later the defected bearings mounted on 2nd support in turn, non-defected bearing mounted on 1st support.

The 2nd bearing support vibration measurement data plotted in vibration velocity spectral cascade diagrams [Fig. 4 and Fig. 5] shows that the 1X frequency vibration magnitudes dominated in horizontal axis rotor at run up mode at wide rotational speed range (1000-3050 r/min). However the vertical axis of rotor with the new bearing generates 1X, 2X, 3X harmonics at wide rotational speed range and indicated existence of radial gaps as nonlinearities [Fig. 4 b]. Therefore, it is difficult to diagnose imbalance in such systems. The vertical axis rotor with damaged bearing generates 1X, 2X,…, 7X frequencies vibration harmonics from 1500 r/min [Fig. 5b]. This shows that it is difficult to diagnose the imbalance in the rotor with significant defect in bearing. The nonlinearities of radial gaps in the bearings dominated without acting gravity force as shock form.

Stationary mode at 3050 r/min analyzed using vibration velocity root mean square v_{RMS} values, as shown in [Fig.8, Fig.9, Fig.10 and Fig.11]. The statistical analysis of measurements taken at vertical axis rotor shows that the 2nd bearing support stiffness in x-direction is lower than the stiffness in y-direction (determined using FEM). Also determined that, due to additional imbalance of 300 *g·mm*, in comparison with measurements with permissible imbalance, the vibration velocity level of 1X harmonic increases from 10% to 40%, while the vibration velocity v_{RMS} values of rolling bearing defect frequency increases by only 10 - 15%.

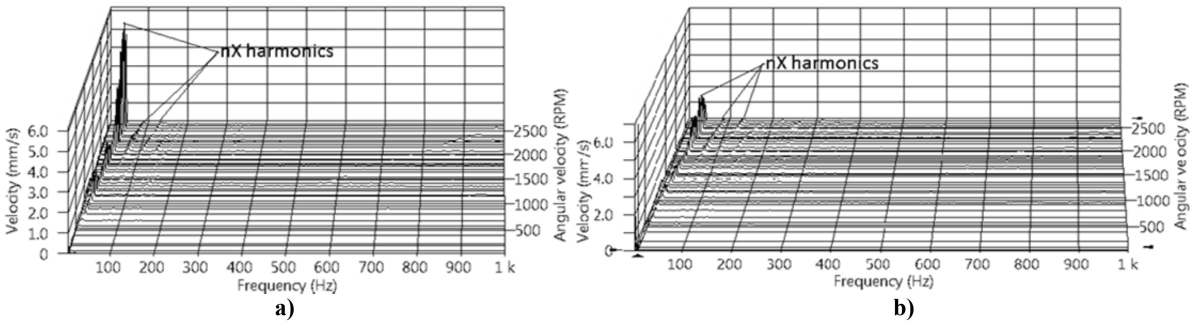
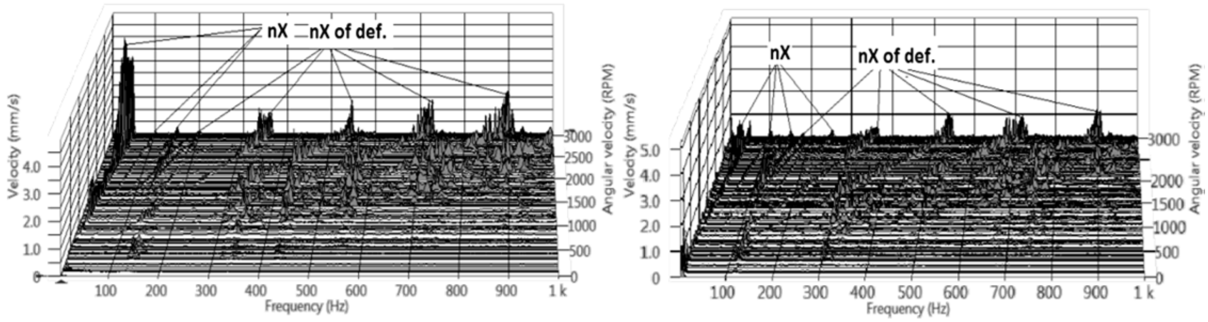


Figure 4: Vibration velocity v_{RMS} cascade plots of 2nd non defected 6004 2Z/C3 bearing measured with 2ya accelerometer, at run up mode of the rotor 300 g·mm unbalance: a – horizontal axis rotor; b – vertical axis rotor.



a) b)

Figure 5: Vibration velocity v_{RMS} cascade plots of 2nd bearing 6204 2Z/C3 with outer ring race defect measured with 2ya accelerometer, at run up mode of the rotor with 300 g·mm imbalance: a – horizontal axis rotor, b – vertical axis rotor.

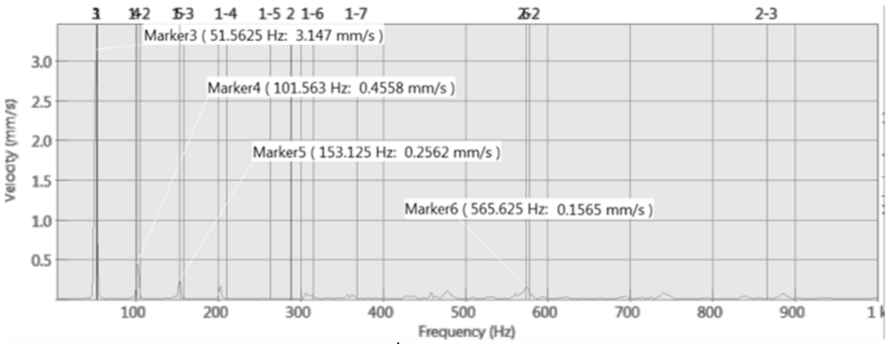


Figure 6: Vibration velocity v_{RMS} spectrum plot of 2[nd] defect bearing 6204 2Z/C3 with inner ring race fault measured using 2ya accelerometer, horizontal axis rotor

The vibration velocity v_{RMS} cascades, presented in [Fig.4] show that vertical axis rotor measured level of vibrations v_{RMS} introduces vibration noise values around the bearing defect frequency. This effect complicates diagnostics of the vertical rotor bearings, because these vibrations might cause rubbing of chain drives, shaft alignment inaccuracies, coupling defect and etc.

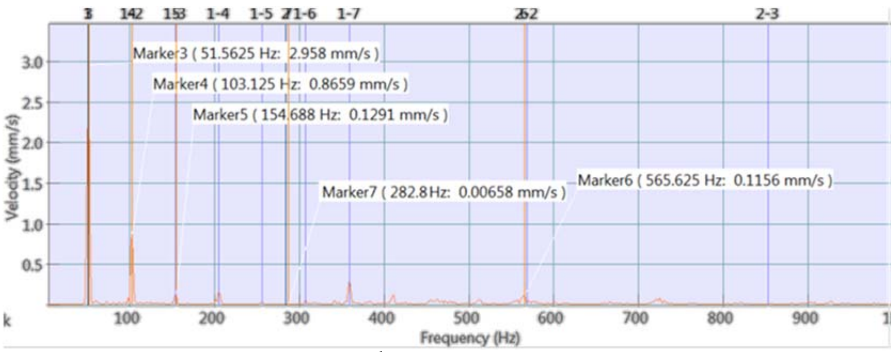


Figure 7: Vibration velocity v_{RMS} spectrum plot of 2[nd] defect bearing 6204 2Z/C3 with inner ring race fault measured using 2ya accelerometer, vertical axis rotor

The statistical vibration velocity v_{RMS} values comparison data is shown in [Fig.8, Fig.9, Fig.10, Fig.11] diagrams. The values of horizontally oriented rotor vibration v_{RMS} dominated. The v_{RMS} values in the y direction were about 2 times higher in the horizontal axis rotor, than one in the vertically oriented rotor, but the simulated stiffness of supports was about two times higher in y direction than in x direction. The physical effect stated that the rotor's gravity force augments vibrations velocity v_{RMS} values in horizontally oriented rotor, although the anisotropy of supports is significantly noticeable and stiffness of supports in y - direction is higher than in x - direction. "Ratio of bearing defect visibility (RBDV)" parameter was designed for the quantitative evaluation of the dynamics features of the vertical and horizontal rotors with deep grove ball bearings.

$$RBDV = \frac{v_{RMS\_DEF\_2X}}{v_{RMS1X}} \tag{2}$$

Where: $v_{RMS\_DEF\_2X}$ – dominant defect 2X harmonic vibration velocity v_{RMS} value, mm/s;
v_{RMS1X} – 1X frequency vibration velocity v_{RMS} value, mm/s;

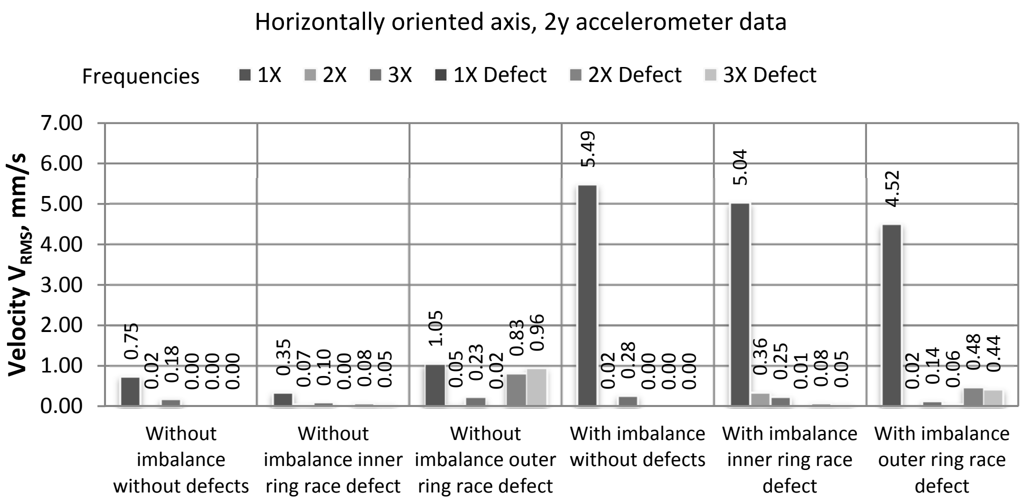


Figure 8: Horizontally oriented rotors 2y vibration velocity v_{RMS} values diagram

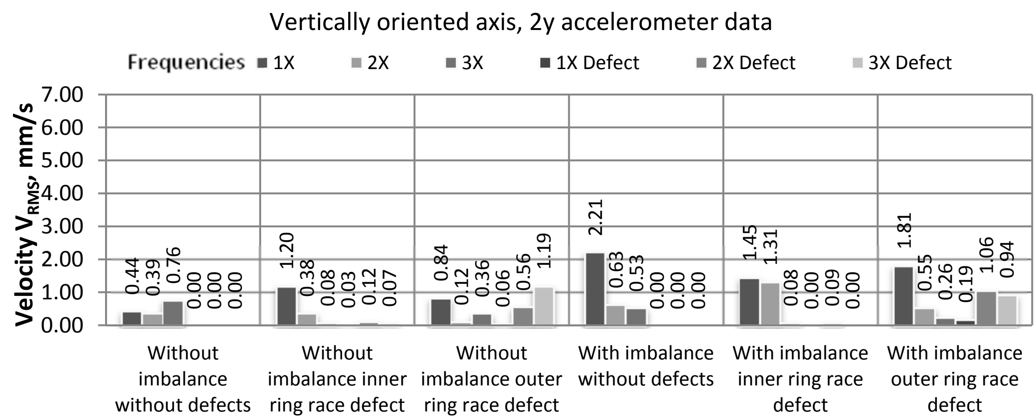


Figure 9: Vertically oriented rotors 2y vibration velocity v_{RMS} values diagram

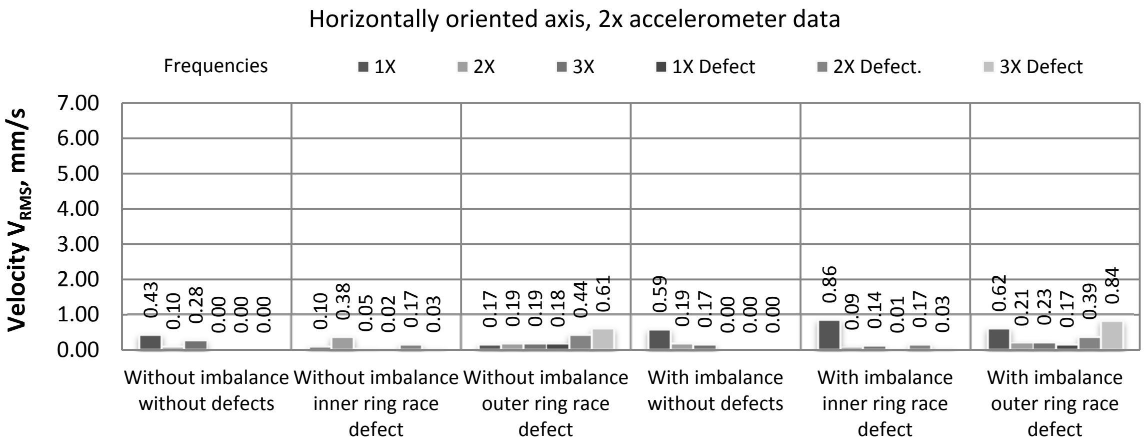


Figure 10: Horizontally oriented rotors 2x vibration velocity v_{RMS} values diagram

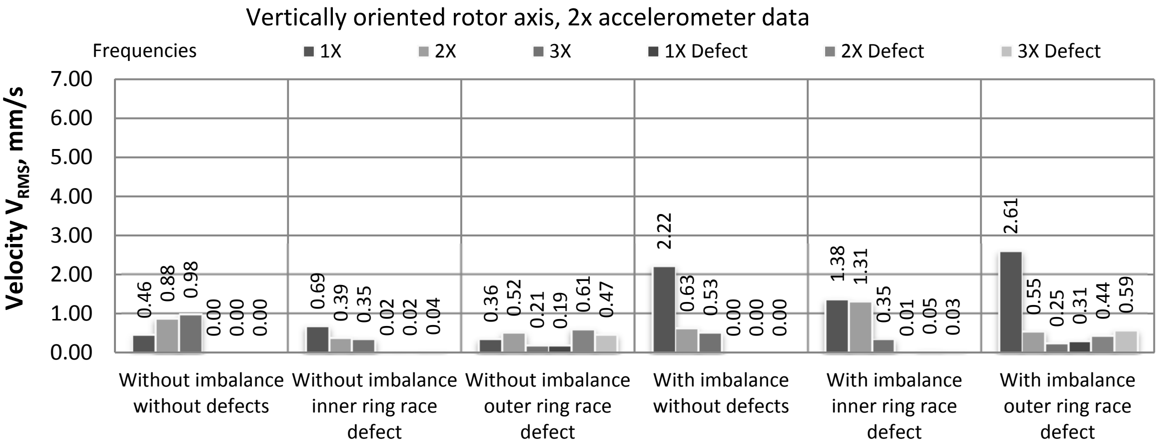


Figure 11: Vertically oriented rotors 2x vibration velocity v_{RMS} values diagram

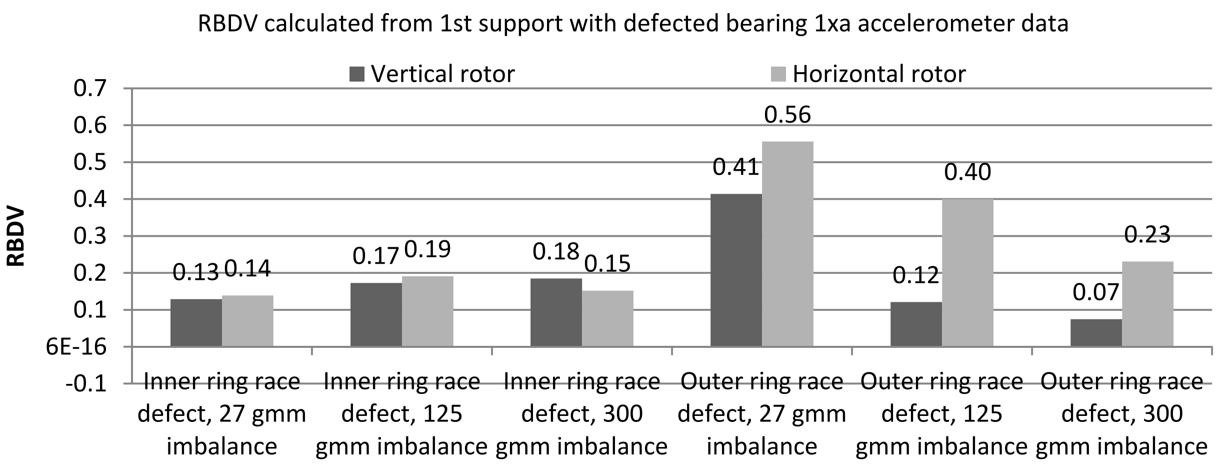


Figure 12:. Horizontally and vertically oriented rotors "RBDV" calculated form 1xa accelerometer measurements data

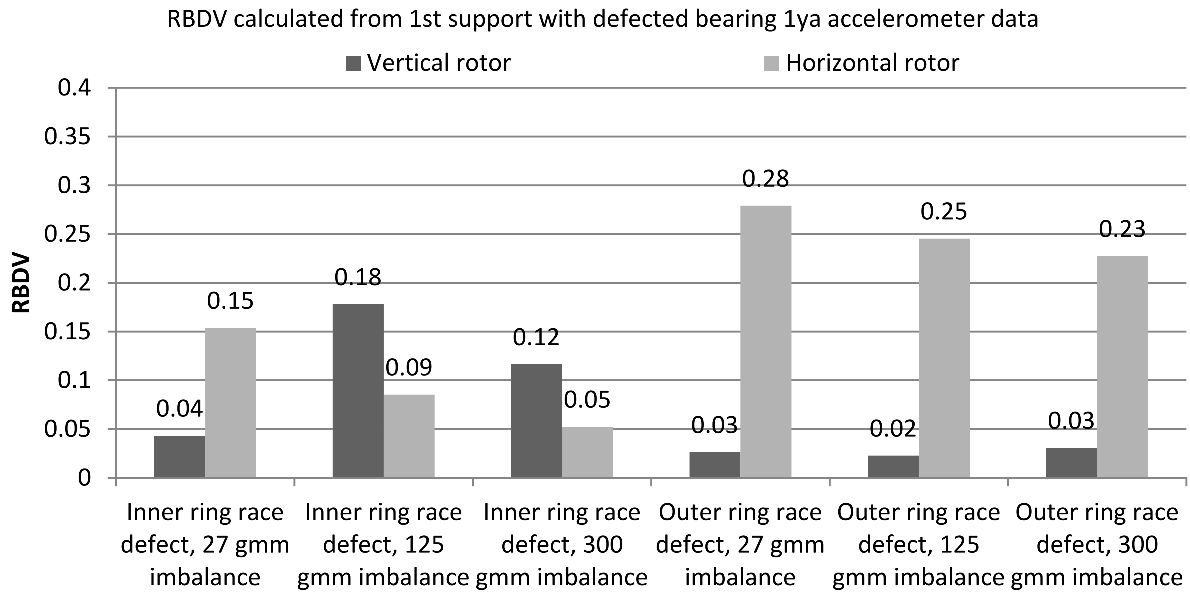


Figure 13: Horizontally and vertically oriented rotors "RBDV" calculated form 1ya accelerometer measurements data

The statistical data of dominating faulty bearing vibration velocity v_{RMS} level value divided by 1X harmonic vibration velocity v_{RMS} level values shown in [Fig.12, Fig.13] DVR diagrams. The graphs shows that, in some cases, when the rotor oriented vertically the bearing fault frequency vibration velocity v_{RMS} level is very low compared with 1X harmonic vibration velocity v_{RMS} level. It's very complicates such rotors bearing diagnostics.

The vibration velocity v_{RMS} cascade which presented in [Fig. 6, Fig.7] shows that in some cases the vertical rotor measured vibrations v_{RMS} level has a lot of vibrations noise around the bearing defect frequency. It very complicates such rotor bearing diagnostics, because those vibrations can be awaking by work chain rubbing, shaft alignment, coupling defect and etc.

The data obtained by measuring the vibration velocity v_{RMS} of the first support (the second plane data) allows only a partial determination of the second support bearing faults. When faulty rolling bearing with inner ring race defect where mounted on 2nd support, in second plane (1st support plane) kinematic bearing fault frequency harmonics cannot be detected. However when faulty bearing with outer ring race defect mounted on 2nd support, the accelerometers mounted on 1st support (second plane accelerometers) captures relatively high level of the outer ring race defect frequency 2x and 3x harmonics.

4 CONCLUSIONS

1. Vibration velocity spectrums of the vertical rotor are rich of higher level vibrations in higher order harmonics compared with horizontal axis rotors. This is due to the chaotic vertical rotor movement kinematics in radial bearing clearance.
2. Vibration intensity of horizontal axis rotor is higher in comparison with vertical axis rotor in y-direction. Due to gravitational influence to horizontal rotor in radial y-direction. Horizontal rotation axis rotor is more sensitive to imbalance that generates high level 1X frequency vibration amplitudes in comparison with vertical axis rotors that is more sensitive to the values of radial gaps in the bearings.
3. The designed RBDV values provide quantitative evaluation of horizontal and vertical rotors vibration ratio levels which enables determination how many times the defect frequency band vibration level is less than the first harmonic vibration level. It quantifies the complexity of the defect diagnosis.

4. Horizontal axis rotor is more sensitive to damaged bearing elements. That facilitates the determination of such rotor bearing defects in early stages of development. Diagnostics of vertically oriented rotors are more complicated. Imbalance has a greater influence to diagnostics of vertical rotor systems (due to imbalance RBDV value of vertical rotor with inner ring race fault and imbalance is lower).
5. The outer ring race defect of horizontally oriented rotor is more visible than vertically oriented rotor, in all measurements (that shows RBDV parameter).
6. Measurements show that, if in support where defected bearing is mounted dominated 2x defect harmonics, then in second measurements plane dominates 3X harmonics of defect (only with outer ring race defect because the inner race defect non-visible in second plane).

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