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Vibration Quantity Share of Multiple Faults with Similar Frequency Spectrum Characteristics in Rotational Machinery

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Abstract

Characteristics of the vibrations of rotational systems with misalignment and rotating looseness are well known and they are used for fault detection in the rotating machinery. For the better understanding and easier decision make in the fault removing process it is necessary to know how severe each fault is. Lack of procedures for quantification of this faults in rotational machinery is evident. In this paper is investigated the possibility for use of multiple regression analysis for determination of quantity of faults in vibration velocity signal. An experimental motor – coupling – rotor system is created and produced. These systems have capability of changing the values of misalignment and rotational looseness. Measurement of vibrational quantities were conducted on these systems by using piezoelectrical accelerometers for different combinations of fault values. All measurements were stored and processed digitally. All measurements have shown the presence of the main characteristics of introduced faults. It is confirmed that it is not possible to use RMS (root mean square) of vibration velocity, since there is a lot of other factors which has significant impact on the vibration quantity.

Keywords

misalignment, rotating looseness, rotational machinery, vibration measurement, vibration analysis

1 Introduction

Condition monitoring of rotational machinery in modern production systems could not be imagined without vibration measurement and analysis. Vibrations of the rotational machinery are the response of the rotational system on the force-induced movement. Vibrations of the rotational machinery are well known as a tool to diagnose machinery, and not only its health but also to determine the cause of the vibrations. With vibration analysis, it is possible to detect unbalance, shaft misalignment, looseness, damaged gears and bearings, etc. All diagnostic processes usually consist of frequency spectrum analysis, among other vibration diagnostic techniques.

The most common rotational machinery fault is shaft misalignment [1, 2]. Another rotational machinery fault is also common, but for this topic is interesting for something other: its frequency spectrum. Namely, severe misalignment and rotating looseness (the gap between bearing non-rotating and rotating parts) have similar frequency spectrum characteristics [3–5]. Multiple theoretical [2, 6, 7] and experimental research have confirmed the main characteristics of the vibrations caused by the faults of shafts misalignment [8–10], and rotational looseness [11–13]. As main confirmation was that both faults have similar frequency spectrums with multiples of the rotational frequency.

There are multiple types of research on how to detect faults in rotational machinery when more than one fault is present in the system. Xu and Marangoni in [2] and [9] have done theoretical and experimental research on the rotational system with misalignment and unbalance as faults. In [3] was investigated the same combination of faults. A combination of misalignment and rotational looseness is investigated in [5], and a combination of unbalance and looseness was investigated in [11].

Besides common vibration analysis procedure, multiple novel procedures were presented in different publications. In [14] was presented identification procedure of multiple faults in rotating machinery which is based on minimum entropy deconvolution combined with spectral kurtosis. Multi-component fault analysis based on decision tree and support vector machine was presented in [15], where this procedure was confirmed as suitable. Support vector machine was used as a part of the diagnostic procedure

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in combination with deep convolution neural network (DCNN) in research presented in [16]. It is shown that with improvements in DCNN it is possible to achieve very high diagnostic accuracy (over 98%). A novel procedure of multiple fault diagnosis was presented in [17]. The procedure is formed by applying ensemble empirical mode decomposition to a combined mode function. This method was confirmed as suitable for experimental and simulated signal. Multiple frequency energy spectrum and Dempster-Shafter evidence theory was used to create an approach for multiple faults diagnosis in [18]. This procedure was proved to be suitable for vibration diagnostics of multiple faults.

Detection of faults using the different techniques of vibration analysis is well known through common or novice procedures. Some of the faults are easier to repair than others, they do not require long-term machinery stoppage and procedures for repairing the faults are simpler and with lower cost. For example, misalignment could be removed by using simple tools by disassembling the coupling, realigning and then assembling the coupling again. On the other hand, dam-aged bearing requires dismantling the coupling and bearing housings and assembling them back in their place, and usually, shaft alignment is required after the bearing replacing. Sometimes machinery must be available as soon as possible. By determining the level of the impact of the fault on machinery it would be easier to "get the machine to life" by removing one of the faults, while wait a suitable time to eliminate all the faults.

Experimental research of misalignment and rotating looseness mutual interaction would be presented in this paper. The focus of the research would be put on investigating each fault impact on the quantity of vibrations, so it would be easier to decide future steps in repairing the machinery.

2 Methods

Experimental setup consists of electrical motor, a flexible coupling, and a rotor with two ball bearings, and it is shown on Fig. 1. Bearing 2 (closer to the coupling) would be bearing where rotational looseness is introduced by controlling the gap between two halves of the housing by adding the thin sheets of aluminum foil between them, as shown on Fig. 2. Misalignment (parallel and angular) is controlled in the vertical direction by adding the thin sheets of aluminum foil under the bearing housings. Initially, shafts are aligned as good as possible, with negligible residual misalignment present.

Vibrations are measured with piezoelectric accelerometers in the horizontal and vertical direction on the rotor bearings. On the shaft is also measured absolute displacement next to the bearing (approximately 10 mm from the bearing). Displacement measurements are done with inductive contactless distance sensors. Sensor locations on bearing 1 is shown on Fig. 3. Similar location is used on bearing 2.

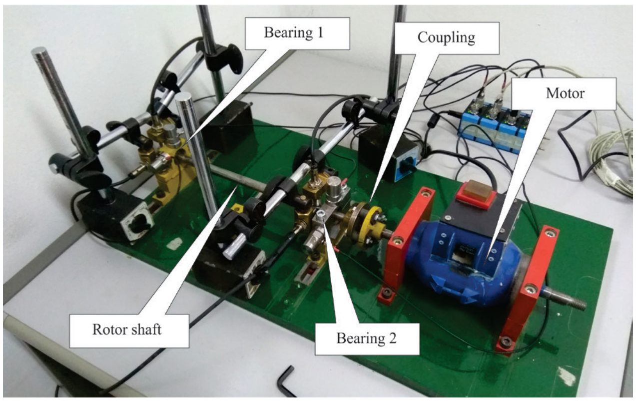

Fig. 1 Experimental rig with motor-coupling-rotor

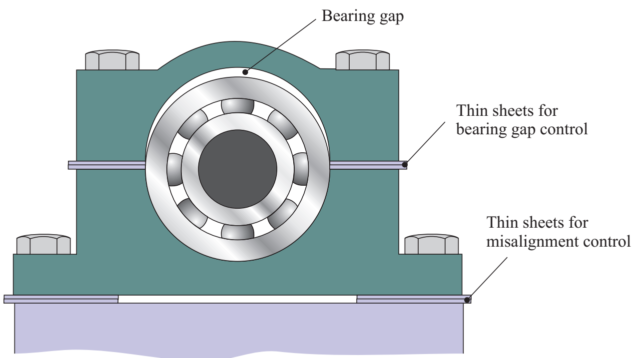

Fig. 2 Locations for thin sheets adding to control the faults size

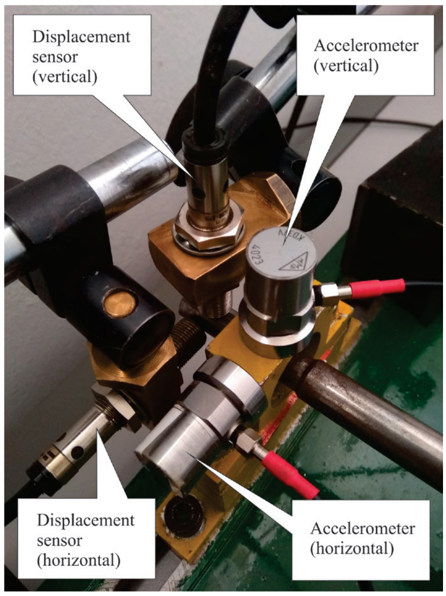

Fig. 3 Location of sensors on bearing 1

Since there are three independent variables, the experiment would be conducted with 27 combinations of variables, 3 levels each. Parallel misalignment would have values 0–0.2–0.4 mm, angular misalignment would have values 0–0.25–0.50 mm/100 mm and bearing gap would have values 0–0.1–0.2 mm.

3 Results

Obtained results have been analyzed to investigate the impact of fault size on vibration characteristics. Findings concluded from this analysis helped in defining the main part of this research. The main part of research was to determine how fault size impacts the quantity of vibrations. Impact of faults size as independent variables on vibration RMS (root mean square) quantity was analyzed by multiple regression model. Coefficient of determination (R-squared or R2) is obtained for measurements on different locations. This coefficient describes percentage of how many data fit the regression model, or it describes "goodness" of fit of data in the regression model. Statistical analysis of data was conducted in software Minitab 14.

As a first step, it would be shown that misalignment and bearing looseness is present in the experimental setup. Waveform of the measured acceleration for the bearing 1 is shown of Fig. 4. It could be seen that it consists of visible M shapes of waveform, which is common waveform shape for misalignment [5].

Frequency spectrums are obtained by Fast Fourier transform from the recorded waveforms. The presence of rotational frequency and its higher orders are noticed in all cases when misalignment is present in the rotational system. In Fig. 5, it is shown that the amplitudes of higher orders of the rotational frequency increase with the increase of bearing gap when only residual misalignment is present.

Orbital motions of the bearings are recorded by displacement sensors. Orbital motion of the bearing 1 with bearing looseness is shown on Fig. 6. It could be seen that motion is unpredictable and non-harmonic, which confirms its presence of bearing looseness.

Since it is confirmed the presence of all common characteristics of vibrations (waveform shape, frequency spectrum), it is checked how increase of independent variables

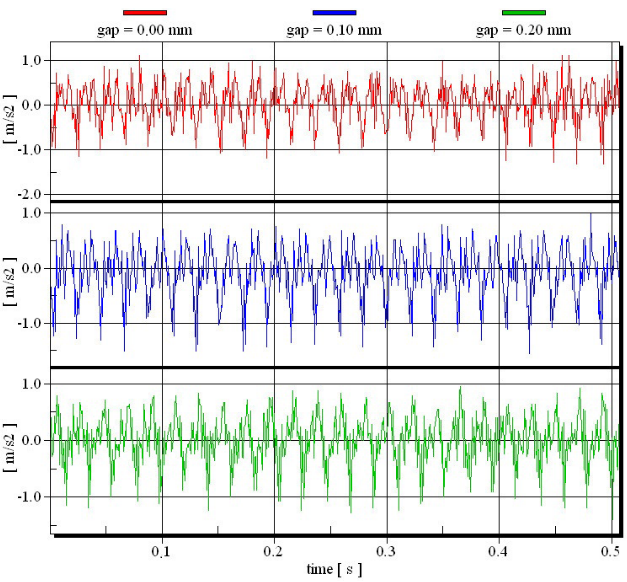

Fig. 4 Waveform of velocity measured on the bearing 1 with different size of bearing gap (α = 0.25 mm/100 mm)

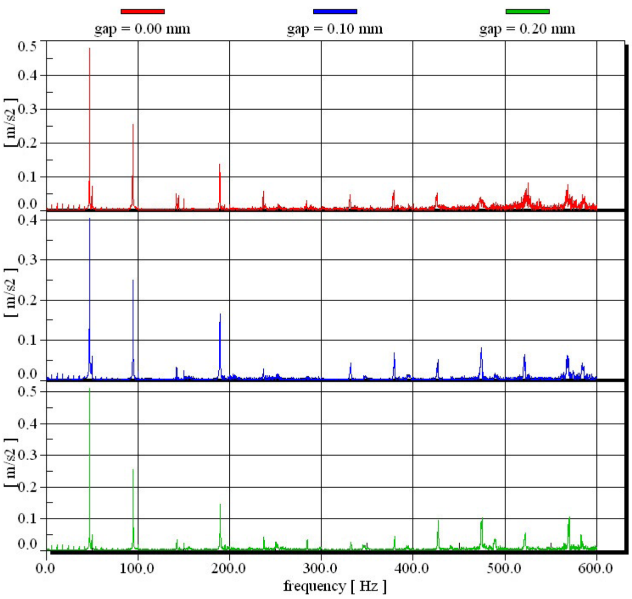

Fig. 5 Frequency spectrums for different bearing gap values measured on bearing 1

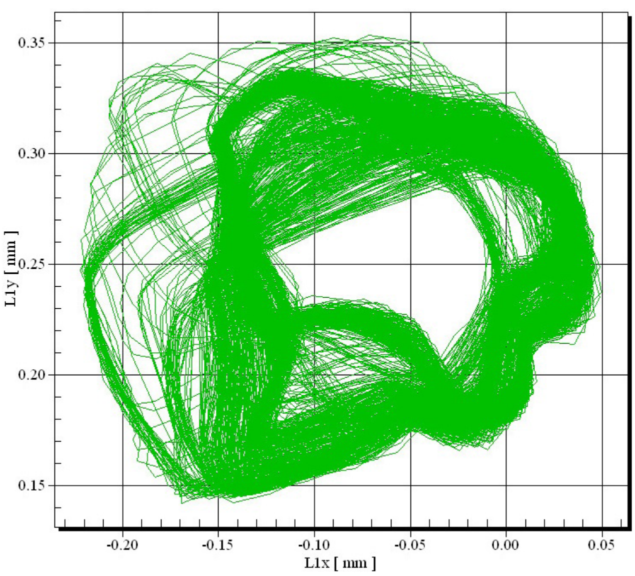

Fig. 6 Orbital motion on bearing 1 with bearing looseness

impacts the amplitudes of rotational frequency and its 2X order. It is shown that increase of misalignment is not always increasing the value of amplitudes.

Change of bearing gap impact on amplitudes of rotational frequency and 2X order is displayed in Fig. 7.

It could be seen that amplitudes of rotational frequency in the vertical direction are the greatest and increasing. Other amplitudes do not have a significant rule for increment or decrement of value.

Since it is not possible to notice any rule between faults increment to vibration characteristics value of frequency amplitudes, RMS (root mean square) of vibrations is chosen to be analyzed as vibrational quantity, since it consists of effects from all faults and frequencies. All RMS values are exported and shown in Table 1. Obtained values of RMS are analyzed by multiple regression.

Fitted Means for RMS values of vibration velocities for bearing 1 and bearing 2 measured in horizontal and vertical directions are shown in Fig. 8 and Fig. 9.

Coefficient of determination (R2) is determined for velocity values on bearing 1 in horizontal direction with its value of 15.9 %. Predictability was 0.00 %, which means that measurements on the bearing 1 could not be used to determine levels of each fault in rotational system.

Low predictability for bearing 1 in vertical direction could be also seen from regression equation, where angular misalignment has the largest coefficient value 0.1756 which is one third of the interception value 0.5056.

For vertical direction R-squared has value 31.05%, while predictability is 6.82 %. Independent variable which has the most impact in regression equation is parallel misalignment with value 0.786. Its coefficient is still lower than interception value 1.106.

Bearing 2 have a slightly better statistical value. For horizontal direction R2 is calculated 53.55 %, and predictability of 36.9 %. Greatest coefficient in the regression equation is the bearing gap, which is interesting since the bearing gap is physically introduced in the bearing 1.

The best statistical values are determined for vertical direction on bearing 2. R2 is calculated as 76.2 % with predictability of 66.27 %. Even this result is far better than other locations results, it is still low for serious consideration in practical applications because of statistical insecurity. Angular misalignment has the largest coefficient in the regression equation with value of -1.409, which is still smaller than interception (1.65).

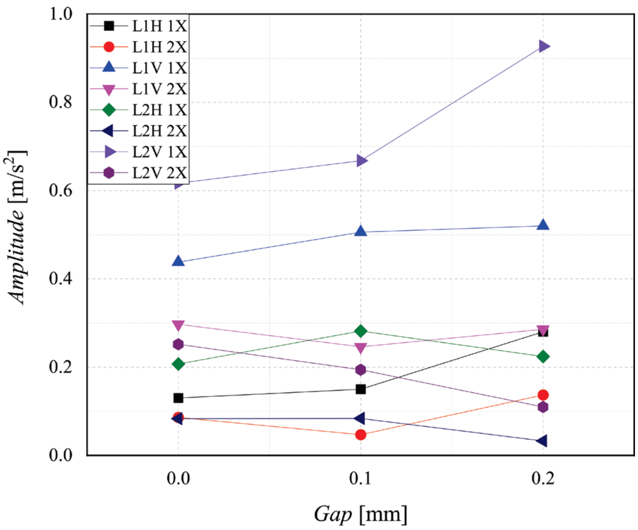

Fig. 7 Amplitudes of rotational frequency and second order harmonics for different values of bearing gap

Table 1 RMS values obtained by experimental research

No.	Paralel misalignment [mm]	Angular misalignment [mm/100 mm]	Bearing gap [mm]
1	0	0	0
2	0	0	0.1
3	0	0	0.2
4	0	0.25	0
5	0	0.25	0.1
6	0	0.25	0.2
7	0	0.50	0
8	0	0.50	0.1
9	0	0.50	0.2
10	0.2	0	0
11	0.2	0	0.1
12	0.2	0	0.2
13	0.2	0.25	0
14	0.2	0.25	0.1
15	0.2	0.25	0.2
16	0.2	0.50	0
17	0.2	0.50	0.1
18	0.2	0.50	0.2
19	0.4	0	0
20	0.4	0	0.1
21	0.4	0	0.2
22	0.4	0.25	0
23	0.4	0.25	0.1
24	0.4	0.25	0.2
25	0.4	0.50	0
26	0.4	0.50	0.1
27	0.4	0.50	0.2

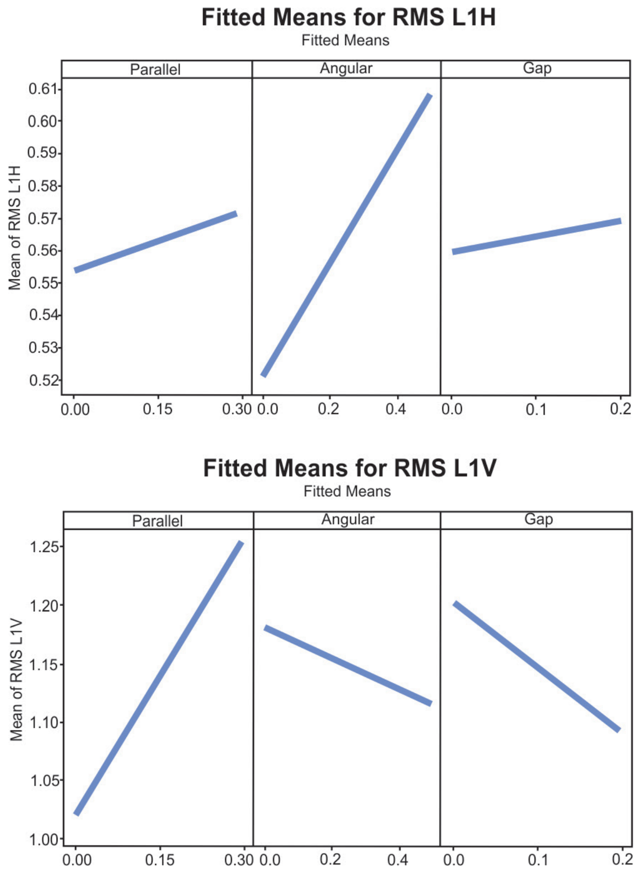

Fig. 8 Main impacts of independent variables on RMS of velocity values on bearing 1

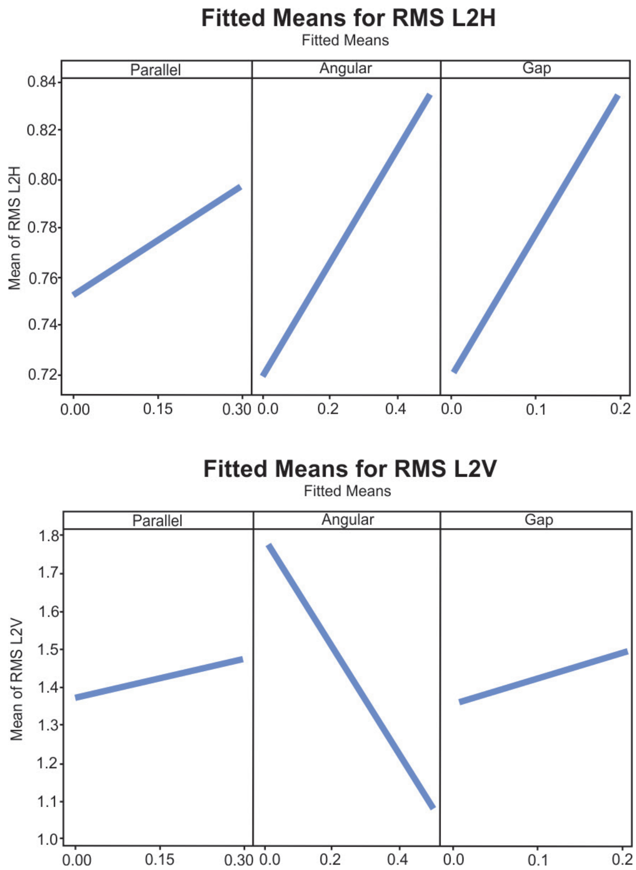

Fig. 9 Main impacts of independent variables on RMS of velocity values on bearing 2

All measurement shows that there is a lot of undescribed data in the vibration measurement, which is probably the sum of all other phenomena such as friction in bearings and coupling, motor imperfections, some residual unbalance, etc. As it could be seen from Fig. 8, Fig. 9 and regression equations, independent variables coefficients in equation does not have same sign in all locations and directions of measurement. The only variable that has the same sign for all measuring locations is parallel misalignment, but different values of coefficient.

4 Conclusions

Parallel and angular misalignment and bearing gap are the common faults in rotational machinery. Presence of more than one mentioned fault in rotational machinery could be tricky to solve, but there are multiple tools and procedures to use for detection of multiple faults. Lack of procedures for determining the severity or "quantity" of faults is noticeable.

In this experimental research is confirmed the presence of the most common vibration characteristics for analyzed faults on experimental setup of rotational system. With multiple regression analysis it is shown that it is not possible to quantify the severity of fault since there is a lot of unpredictable factors which could impact the vibration velocity values. Reason for this is because this analysis was conducted on RMS values of vibration, which consists of all internal and external effects on vibrations of a system. Quantification of the faults should be addressed at other specific values of fault characteristics, which could possibly eliminate unexpected impacts on vibrations caused by other faults than analyzed.

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