Data fusion of acceleration and velocity features (dFAVF) approach for fault diagnosis in rotating machines

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Abstract. Earlier research studies have suggested the unified vibration-based approach for fault diagnosis (FD) in identical machines with different foundation flexibilities and multi-rotating speeds. Intially the acceleration-based features were used for this approach then further work optimised the approach by combining acceleration and velocity features from vibration data for analysis. However the optimised approach was only tested on the identical machines rotating at different speeds below the machine's first critical speed. The current paper tends to observe the optimised approach when applied to a test rig operating below and above the machine's first critical speed.

1   Introduction

A number of the fault diagnosis (FD) approaches for differentiation of various machine operating conditions (healthy and faulty) with varying degree of foundation flexibilities, changing speeds as well as data combination has been investigated in recent studies [1-7]. These studies considered various FD techniques in order to obtain an efficient and reliable system. Amongst the proposed approaches are the unified multi-speed (UMA) [3], poly-coherent composite spectrum (pCCS) [5] and composite spectrum (CS) [7] with analysis of data obtained from machines installed on various rigid foundations using single accelerometer per bearing pedestal to measure vibration signal. In a bid for an improved method where diagnosis of an extensive range of faults encountered by rotating machines can be achieved, Luwei et al. [1] optimised the unified multi-speed approach, by fusing acceleration and velocity features (dFAVF) from time and frequency domain parameters where good fault classification was achieved during diagnosis. However, these earlier analyses [2-7] were carried out using acceleration data while all studies were done with machine operating below the first critical speed.

The design of most machines operating with high speeds is such that they pass through several critical speeds at which high vibration level is encountered [8]. Assuming we have the same machine on the same foundation, machine may be observed to either run below or above critical speeds. Based on this, some recent studies were examined where dynamic

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characterisation to identify critical speeds and mode shape at various critical speeds with challenges in FD for such scenario is presented [8-10, 12].

The present study extends from earlier studies [2-3] with the aim of carrying out fault diagnosis on vibration data measured below and above the machine's first critical speed using data fusion of acceleration and velocity features (dFAVF) analysis. This paper presents the test rig, faults simulated, experiments conducted, data analysis and observations made from this study.

2   Experimental rig and fault simulation

The test rig for current study as shown in Figure 1 is located in the Dynamics Laboratory at The University of Manchester (UK). In order to foster direct comparison between previous studies [2-7] and current one, the experimental rig used is quite similar to that used in previous studies [2-7] with regards to component location i.e motor, bearings (Bg1 – Bg4), couplers (C1 and C2) and sizes in discs (125mm diameter and 14mm thick) and shaft (1000 mm long, 500 mm short, and both having 20 mm diameter). However, as opposed to the rigid flange bearing mounting of the anti-friction bearing in earlier studies, the current study used 4 flexible springs connection thus increasing foundation flexibility as can be seen in Figure 2**.**
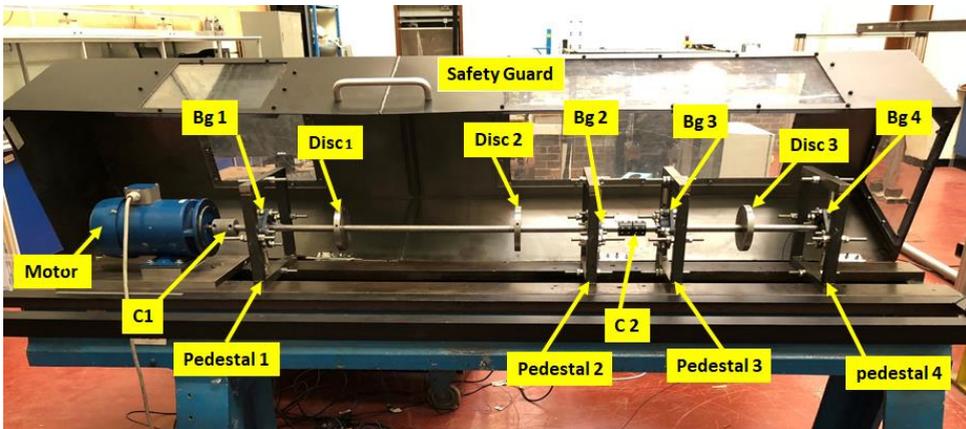

Figure 1. Experimental rig in dynamics laboratory at The University of Manchester
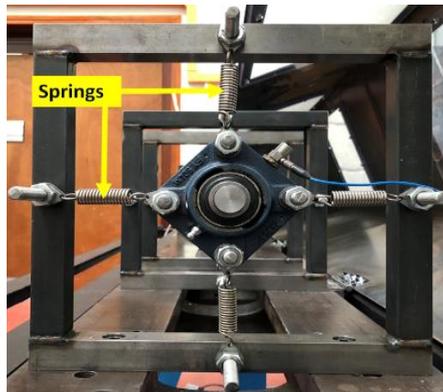

Figure 2. Bearing pedestal showing spring connections

A dynamic characterisation of the test rig was carried out by conducting modal tests [12]. The first five bending natural frequencies identified by the modal tested are 11.52 Hz, 18.62Hz, 30.75 Hz, 49.13 Hz and 85.83 Hz. A typical frequency response function (FRF) plot derived from the modal tests is shown in Figure 3.
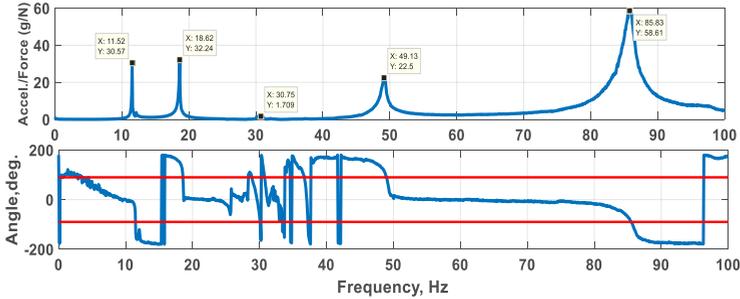

Figure 3. A typical Frequency Response Function (FRF) plot of the measured acceleration response at a location to the applied force in the modal tests

Considering the natural frequencies, three running speeds were selected; one below and two above the first critical speed i.e. at 450 RPM (7.5 Hz) below the first critical speed, 900 RPM (15 Hz) above the first critical speed and 1350 RPM (22.5 Hz) above the second critical speed. Six conditions were simulated during the tests which are sumarised in Table 1. Each condition was tested independently of the other at the three selected speeds. The vibration responses at each bearing pedestal were collected using single accelerometer mounted on each bearing for these tests for further analysis. The accelerometer was mounted at 45 degree from the horizontal and vertical direction and vibration data was collected for the test conditions listed in Table 1.

Table 1. List of different tests conditions

No	Condition	Code	Description
1	Residual Misalignment Residual Unbalance	RMRU	Reference healthy case having some residual misalignment and residual unbalance
2	Unbalance	Unb	1.5×10^{-3} kgm at 30^0
3	Misalignment	M	Parallel Misalignment with Bg1 displaced 0.8mm in vertical direction
4	Crack near Bearing1	CBg1	0.34mm wide x 4mm deep notch with 0.33mm shim glued (on rotor near Bg1)
5	Crack near Bearing2	CBg2	0.34mm wide x 4mm deep notch with 0.33mm shim glued (on rotor near Bg2)
6	Rub near Disc1	RubD1	Perspex blade on rotor near Disc1

3   Data analysis and observation

Typical spectra for acceleration and velocity (RMRU and different faulty conditions) computed from the measured acceleration vibration signals for the test rig at rotating speed of 900 RPM (15 Hz) are shown in **Figures 4-5.**
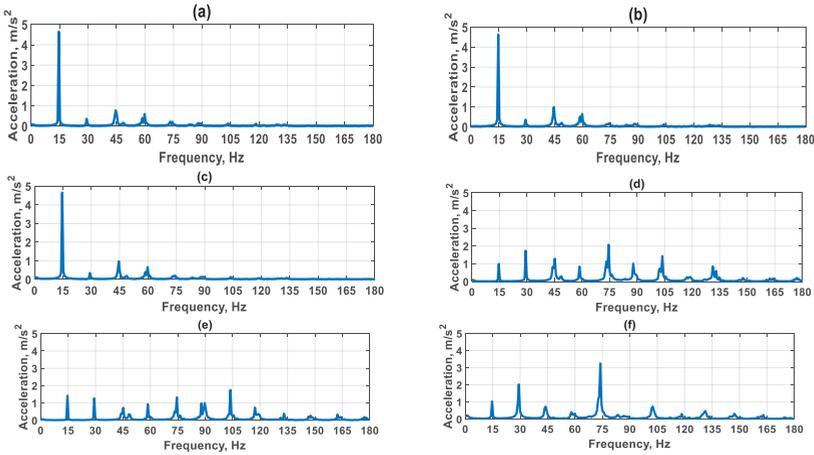
Figure 4. Measured acceleration spectra plots at Bearing 3 (a) H (b) M (c) Unb (d) CBg1 (e) CBg2 (f) RubD1
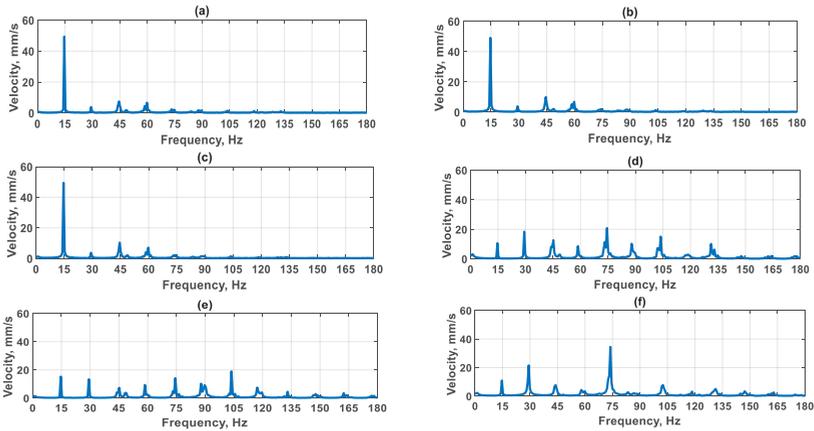

Figure 5. Measured velocity spectra plots at Bearing 3 (a) H (b) M (c) Unb (d) CBg1 (e) CBg2 (f) RubD1

The spectra in Figures 4-5 show some differences but based on the spectrum analysis it is generally difficult to do the diagnosis unless the trended data are not available. Besides these inadequacies, there is also the challenge of generating several spectra for FD. Hence the earlier optimised approach for the FD is applied again on the current experimental data.

Features were extracted from time and frequency domain parameters as suggested earlier studies [2-3]. The root mean square, crest factor and kurtosis were computed as the time domain features from the measured acceleration data as the acceleration is a good indicator of impulsive and high frequencies content in the signal. Similarly, the spectrum energy and the amplitudes at 1x to 5x harmonics which formed the velocity spectrum were considered as the frequency domain features. The velocity parameters are generally considered as good indicators for the rotor related faults. These time domain and frequency domain analysis features were then adopted in developing a data matrix which was further inputed into principal component analysis (PCA) for classification of machine condition. The aim of PCA is to achieve dimensionality reduction of a data set where large and complex variables are transformed to new sets of uncorrelated variables called principal components (PCs) with the first set of PCs carrying a larger variance of the overall data [3,11].

Given a data matrix **F**, with features F_1, F_2, $F_3...F_{36}$ per set of data from *D1 to D20* with C_1 representing a particular machine condition and at a particular rotating speed S_1, a mathematical representation of individual features used in building the data matrix at a particular condition (C_1) and a particular speed (S_1) is presented in eq. (1) as:

$$F_{C_1 S_1} = \begin{bmatrix} F_{1_{D_1}} & \cdots & F_{36_{D_1}} \\ \vdots & \ddots & \vdots \\ F_{1_{D_{20}}} & \cdots & F_{36_{D_{20}}} \end{bmatrix}_{C_1 S_1} \tag{1}$$

$$\mathbf{F} = \begin{bmatrix} F_{C_1 S_1} & \cdots & F_{C_1 S_3} \\ \vdots & \ddots & \vdots \\ F_{C_6 S_1} & \cdots & F_{C_6 S_3} \end{bmatrix} \tag{2}$$

Eq. (2) shows the computation of the overall data matrix with all features including all simulated machine conditions and all rotating speeds. In this analysis, 9 features per bearing were used and with 4 bearings (Bg1 – Bg4) the total number of features, *F* is equal to 4 x 9 = 36. Similarly, the number of data set per machine condition is 20 and there are 6 machine conditions ($C_1 – C_6$) so that the total number of data sets for all cases is equal to   20 x 6 = 120. Thus, fusion of acceleration and velocity features at all speeds and all experimentally simulated test conditions gave a 120 x 108 data matrix. So that a plot of PC1 versus PC2 that was carried out presented useful insight and clear classification between each simulated machine condition as shown in Figure 6.
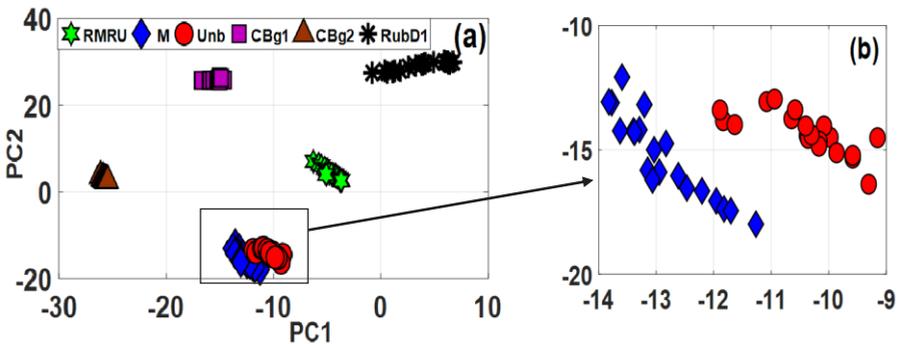

Figure 6. Classification of test rig healthy and faulty conditions (a) all experimentally simulated conditions (b) zoomed view of misalignment (M) and unbalance (Unb) conditions.

Figure 6 is a typical representation of PC1 versus PC2 plot computed from the dFAVF approach. In Figure 6(a), all experimentally simulated test conditions are seen to have very good clustering of individual cases and exceptional separation from other test conditions except between the unbalance (Unb) and the misalignment (M) conditions. However, the zoomed view in Figure 6(b) shows clear separation between the Unb and M indicating their independent clustering. This observation reveals that the dFAVF approach is also useful for effective diagnosis in fault classification of rotating machine operating below and above the machine first critical speed.

4   Conclusion

The current paper clearly demonstrates the usefulness of the data fusion of acceleration and velocity features analysis (dFAVF) approach in the machine FD. Notwithstanding the fact

that current demonstration covers only rotor related defects, observation shows that it further widen the application of the unified vibration-based fault diagnosis approach using the dFAVF approach when the machine rotating speeds are below and above machine first critical speed with measured vibration data collected using only one accelerometer per bearing pedestal.

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