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An improved data fusion technique for faults diagnosis in rotating machines

Akilu Yunusa-Kaltungo, Jyoti K. Sinha *, Keri Elbhbah

School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester M13 9PL, UK

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ABSTRACT

The composite spectrum (CS) data fusion technique has been shown to simplify rotating machines faults diagnosis by earlier studies. Faults diagnosis with the earlier CS relied solely on the amplitudes of several harmonics of the machine speed, owing to the loss of phase information leading to its computation. The proposed improved CS applies the concept of cross power spectrum density for computing a poly-Coherent Composite Spectrum (pCCS) of a machine, which retains amplitude and phase information at all measurement locations. The present study compares the proposed pCCS method with the earlier CS method for faults diagnosis in rotating machines, using experimental data from a rotating rig. Results and observations show that the proposed pCCS offered a much better representation of the machines dynamics when compared to the earlier CS method and hence better fault diagnosis.

1. Introduction

Measured vibration data at individual bearing pedestals of a rotating machine have been successfully analysed with several vibration-based condition monitoring (VCM) techniques such as; spectrum analysis [1], higher order spectra analysis [2–8], wavelet analysis [9–15], artificial intelligence-based diagnosis [16–21] and model-based identification [22]. However, large and complex rotating machines with multi-shafts are often associated with numerous bearings, which imply that several vibration data measured from each bearing location, will have to be separately analysed during faults diagnosis. Therefore, the development of a VCM technique that will significantly simplify the faults diagnosis process in rotating machines is highly desirable. Earlier studies by Elbhbah and Sinha [23] proposed the use of reduced sensors (i.e. a single accelerometer per bearing pedestal) for vibration measurements in rotating machines. The study [23] also proposed the use of a single composite spectrum (CS) for the representation of the entire machine dynamics, which offered some useful faults diagnosis features in rotating machines. In the earlier technique [23], the concept of cross power spectral density (CSD) [24] was used for fusing the vibration data measured at all bearing pedestals, which did not utilize phase information from the measured vibration data at the different measurement locations. The current study however proposes the use of a poly-Coherent Composite Spectrum (pCCS) of a machine, which is also based on the concept of CSD, but has been extended to involve a number of signals. Hence, amplitude and phase information are retained for all measured vibration data, which is further explained in Sections 2–3. The computational approaches and observations from both techniques are hereby discussed in this paper. Furthermore, the present study compares the proposed pCCS method with the earlier CS method for faults diagnosis in rotating machines, using experimental data from a rotating rig. Results and

* Corresponding author. Tel.: +44 161 306 4639.
E-mail addresses: akilu.kaltungo@postgrad.manchester.ac.uk (A. Yunusa-Kaltungo), jyoti.sinha@manchester.ac.uk (J.K. Sinha), keri.elbhbah@postgrad.manchester.ac.uk (K. Elbhbah).

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observations indicate that the proposed pCCS offered a much better representation of the machine's dynamics when compared to the earlier CS method and hence better fault diagnosis.

2. Earlier composite spectrum [23]

Assuming that vibration measurements were collected from "b" number of bearing locations of a rotating machine, and the measured data in time domain have been divided into a number of equal segments (n_s) for the Fourier Transformation (FT) for each segment, then the CS for the entire machine was computed as [23];

$$S_{CCS}(f_k) = \frac{\sum_{r=1}^{n_s} X^r_{CCS}(f_k) X^{r^*}_{CCS}(f_k)}{n_s} \tag{1}$$

where $X^r_{CCS}(f_k)$ and $X^{r^*}_{CCS}(f_k)$ respectively denote the coherent composite Fourier Transformation (FT) and its complex conjugate for the rth segment of the measured time domain vibration data from "b" bearing locations at frequency, f_k. $S^r_{CCS}(f_k)$ is the coherent CS which is nothing but mean of the rth segment of measured data from "b" bearings. The component, $X^r_{CCS}(f_k)$ was thus computed as [23];

$$X^r_{CCS}(f_k) = \sqrt{\left(S^r_{x_1\gamma^2_{12}x_2}(f_k) S^r_{x_2\gamma^2_{23}x_3}(f_k) \ldots S^r_{x_{(b-1)}\gamma^2_{(b-1)b}x_b}(f_k)\right)^{\frac{1}{(b-1)}}} \tag{2}$$

where γ^2_{12}, γ^2_{23} and $\gamma^2_{(b-1)b}$ respectively denote the coherence [25] between bearings 1–2, 2–3, …, $(b-1)-b$ (where $b = 1, 2, \ldots, b$). Also, $S^r_{x_1\gamma^2_{12}x_2}(f_k)$ $S^r_{x_2\gamma^2_{23}x_3}(f_k) \ldots S^r_{x_{(b-1)}\gamma^2_{(b-1)b}x_b}(f_k)$ respectively denote the coherent cross-power spectrum between bearings 1–2, 2–3, …, $(b-1)-b$, which was computed as [23];

$$S^r_{x_1\gamma^2_{12}x_2}(f_k) = \left[X^r_1(f_k)\gamma^2_{12}X^{r^*}_2(f_k)\right] \tag{3}$$

It can be clearly seen from Eqs. (2) and (3) that all the phase information at the intermediate measurement locations will be lost due to the CSD approach adopted for the data fusion. For example, the multiplication of the FT of the rth segment of the measured time domain vibration data at frequency f_k at bearing 2 (i.e. $X^r_2(f_k)$) in the first term $\left(S^r_{x_1\gamma^2_{12}x_2}(f_k)\right)$ of Eq. (2) by its complex conjugate (i.e. $X^{r^*}_2(f_k)$) in the second term $\left(S^r_{x_2\gamma^2_{23}x_3}(f_k)\right)$ of the same equation automatically produces a real number, thereby signifying a loss of phase information between the two measurement locations (i.e. bearings 2 and 3) and so on. Similarly, Eq. (1) shows that the final CS has lost all of its phase information, due to the multiplication of the coherent composite FT by its complex conjugate.

3. Proposed poly-Coherent Composite Spectrum (pCCS)

It is has been clearly shown in Section 2 that all phase information at the intermediate vibration measurement locations is lost during the computation of CS using the earlier method. Therefore, an improved CS that provides a better representation of the entire machine dynamics is required. Hence, the improved CS is defined as;

$$S_{pCCS}(f_k) = \frac{\left(\sum_{r=1}^{n_s} X^r_1(f_k)\gamma^2_{12}X^r_2(f_k)\gamma^2_{23}X^r_3(f_k)\gamma^2_{34}X^r_4(f_k)\ldots X^r_{(b-1)}(f_k)\gamma^2_{(b-1)b}X^r_b(f_k)\right)^{\frac{1}{b}}}{n_s} \tag{4}$$

where $X^r_1(f_k)$, $X^r_2(f_k)$, $X^r_3(f_k)$, $X^r_4(f_k)$, …, $X^r_{(b-1)}(f_k)$ and $X^r_b(f_k)$ respectively denote the FT of the rth segment at frequency f_k of the time domain vibration data at bearings 1, 2, 3, 4, …, $(b-1)$ and b. Similarly, γ^2_{12}, γ^2_{23}, γ^2_{34}, …, $\gamma^2_{(b-1)b}$ respectively denote the coherence between bearings 1–2, 2–3, 3–4, …, $(b-1)-b$, while $S_{pCCS}(f_k)$ is the poly-Coherent Composite Spectrum (pCCS) at frequency, f_k. The computation of the proposed pCCS shown in Eq. (4) is also based on the concept of CSD. However, it has been extended to a number of signals instead of just two signals used in CSD, so that amplitude and phase information of signals are retained for better representation of the machine dynamics.

4. Experiments and observations

As conducted in the earlier study [23], four different conditions (healthy, misalignment, crack and rub) were simulated at two separate speeds (2040 RPM and 3000 RPM) on an experimental rig (Fig. 1). The healthy case contained some residual unbalance and possibly little misalignment. A 2 mm misalignment (in both vertical and horizontal directions) was introduced near bearing 1 for the misalignment case. In the crack case, a crack of 0.25 mm (width) by 4 mm (depth), with a 0.22 mm steel shim insert was used to simulate a shaft with a breathing crack. A Perspex sheet with a 21 mm hole was used to simulate shaft rub near bearing 1. The rig consists of two rigidly coupled shafts (1 m and 0.5 m lengths) of similar diameter (20 mm). The 1 m shaft is flexibly connected to an electric motor, while the entire shaft assembly is supported by four anti-friction ball bearings as shown in Fig. 1 [23].

Vibration data were collected from all bearing pedestals for all the experimentally simulated cases (healthy, misalignment, crack and rub) at both speeds (2040 RPM and 3000 RPM). Hence, the averaged spectra for all cases have been computed using a sampling frequency (f_s) = 5000 Hz, number of data points (N) = 8192, frequency resolution (df) = 0.6104 Hz, 80% overlap with Hanning window and 146 number of averages. Figs. 2 and 3 respectively show typical pCCS and phase plots for two cases (healthy and crack), at 2040 RPM and 3000 RPM. The healthy cases at both machine speeds (Figs. 2(a) and 3(a)) show no visible peaks, while the crack cases (Figs. 2(c) and 3(c)) are characterized by conspicuous peaks at several harmonics (e.g. 1×, 2×, 4×, etc.). Similarly, the phase plots (Figs. 2(b), (d),