Fault detection based on instantaneous angular speed measurement and variational mode decomposition

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Abstract. Rotating machinery encounter throughout their lifetime various problems. Among them, a rotor–stator rubbing problem is one of the most common. This paper proposes a procedure, which applies the instantaneous angular speed (IAS) measurement as a starting step for rotor-stator partial rub detection. There are various approaches regarding counting techniques and processing of signal. In this paper, an application of analog signals from toothed wheel encoder or zebra tape encoder is considered at low to moderate sampling rates. As the rubbing process is nonlinear, this paper is proposing a variational mode decomposition (VMD) as the second step of the detection procedure. The VMD is relatively new method with promising results especially interesting for machinery fault detection. Detection tool is tested on laboratory test rig at two different rotor operating conditions *i.e.* without rotor–stator rubbing and with light partial rotor–stator rub. Measurements were performed with non-contact eddy current displacement sensors pointed to toothed wheel encoder. Results are presented in the shape of rotor orbits, IAS signals, FFT spectra of IAS signals and VMD spectrograms. Developed fault detection procedure based on IAS measurement and VMD decomposition was successfully tested on laboratory test rig for no rubbing and light rotor to stator partial rub condition.

1 Introduction

Rotor–stator contact or rubbing is occasional problem faced by rotating machines especially during startups and shut downs when passing through their critical speeds. Depending on rotor and stator structure configuration rotor-stator rubbing phenomena can be classified in rigid rotor disc-rigid stator rubbing [1-3], bladed disc-stator rubbing [4] and rotor-stator rubbing in retainer bearings of the active magnetic bearings [5, 6].

From a data acquisition point of view [7-10], rotor vibrations are usually measured by accelerometers at bearing pedestals or with non-contacting probes relatively from bearing pedestals to shaft in two radial directions (horizontal, vertical) and if needed in axial direction too.

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Recently, a measurement of Instantaneous angular speed (IAS) [11-13] is recognized as a promising technique for fault detection. The idea is to use rotor encoder signal and try to determine new vibration condition patterns to improve overall detection capabilities especially for those machines which experience change in speed during normal operation. If measurements have to be performed on toothed wheel encoder or zebra tape encoder with analog signals and acquired with a general purpose ADC system at low to moderate sampling rates, such a system can experience problems with non-uniformity of encoder segments geometry. In such cases a correction procedure has to be performed using of normalized time passage ratio [14].

The vibration generated by rotor-stator contact always contains nonlinear and non-stationary signals. Recently, a number of new methods have been proposed to analyze such signals. One of the promising methods is the Empirical Modal Decomposition (EMD) [15-17]. It decomposes the data into a set of intrinsic mode functions (IMF's), not assuming linearity, stationarity, or any a priori bases for decomposition. Although popular, IMFs of original version of HHT (EMD) suffer from the lack of mono-component property for the real signals containing noise. Bearing this in mind Dragomiretskiy and Zosso have recently proposed a new approach called Variational Mode Decomposition (VMD) [18].

This paper considers IAS measurement with an optical encoder with 30 segments at 20 kHz sampling frequency. To decrease the error caused by low sampling frequency, raw signal is up-sampled by a factor 50 performing cubic spline interpolation. To resolve another source of error *i.e.* geometric non-uniformity, a correction procedure was performed using normalized time passage ratio of encoder segments. To test detection possibility of technique based on IAS measurement and VMD a partial rotor-stator rub failure is considered. Rubbing situation is connected with presence of fractional sidebands of rotor speed in frequency spectra. It can be concluded that VMD spectrogram can detect light partial rotor-stator rub condition and give clear difference between no-rubbing and rubbing condition.

2 Instantaneous angular speed measurement

In [11] authors gave review of all kinds of angular speed measurement methods. They can be divided into two groups; timer/counter methods and ADC based methods. The first one can be further divided on methods measuring an elapsed time between successive encoder pulses or counting encoder pulses during the prescribed time. The ADC based methods were not very attractive to researchers of condition monitoring until recent remarkable increase of speed and memory capacity of modern computers and general purpose data acquisition systems. Because ADC based method treat encoder signal as any other analog signal, there is elegant solution for software upgrade of measuring system originally built for lateral vibration measurements. This paper is focused on ADC method and discusses various techniques for signal conditioning.

While minimum measurable speed is affected by memory capacity of the acquisition system or length of the record for a given sampling frequency and encoder resolution, maximum measurable speed, theoretical speaking, is determined by the ratio of sampling frequency and encoder resolution.

Although resolution of the modern encoders can range from one to many thousands, for condition monitoring applications, a sensor with dozens or hundreds of pulses per revolution is sufficient for most machinery monitoring and diagnosis [11].

Based on paper [14], sampling frequency could be as low as 20 kHz but the raw signal should be up-sampled/interpolated to virtually get approximately the same sampling frequency as proposed in [13].

The concept of IAS measurement is applicable for both constant and variable running speed so it is more flexible diagnostic tool then Time interval measurement of torsional vibration as explained in [14].

3 Variational mode decomposition

In EMD method it was observed that actual IMF in real signal application often is not a desired mono-component function. To overcome this problem, Dragomiretskiy and Zosso proposed another scheme, VMD [18]: (1) for each mode, compute the associated analytic signal by means of the Hilbert transform in order to obtain a unilateral frequency spectrum; (2) For each mode, shift the mode's frequency spectrum to "baseband", by mixing with an exponential tuned to the respective estimated center frequency; (3) The bandwidth is now estimated through the H^1 Gaussian smoothness of the demodulated signal, i.e. the squared L^2 norm of the gradient.

The resulting constrained variational problem is solved by separate minimizations with respect to $\{\omega_k\}$ (all modes) and with respect to $\{u_k\}$ (corresponding center frequencies). Complete optimization of VMD algorithm can be summarized as follows:

- At the beginning chose how many modes K are significant,
- Initialize $\{\hat{u}_k^1\}, \{\omega_k^1\}, \hat{\lambda}^1, n = 0$
- Repeat following loop $n = n + 1$
for $k = 1: K$

Update $\hat{u}_k$ for all $\omega \geq 0$:

$$\hat{u}_k^{n+1}(\omega) = \frac{\hat{f}(\omega) - \sum_{i < k} \hat{u}_i^{n+1}(\omega) - \sum_{i > k} \hat{u}_i^n(\omega) + \frac{\hat{\lambda}^n(\omega)}{2}}{1 + 2\alpha(\omega - \omega_k^n)^2}$$

Update ω_k :

$$\omega_k^{n+1} = \frac{\int_0^\infty \omega |\hat{u}_k^{n+1}(\omega)|^2 d\omega}{\int_0^\infty |\hat{u}_k^{n+1}(\omega)|^2 d\omega}$$

end for

Dual ascent for all $\omega \geq 0$

$$\hat{\lambda}^{n+1}(\omega) = \hat{\lambda}^n(\omega) + \tau \left(\hat{f}(\omega) - \sum_k \hat{u}_k^{n+1}(\omega) \right)$$

Until convergence condition is met

$$\sum_k \left\| \hat{u}_k^{n+1} - \hat{u}_k^n \right\|_2^2 / \left\| \hat{u}_k^n \right\|_2^2 < \varepsilon .$$

4 Test rig

Experimental evaluation of the proposed algorithms for light rubbing detection at constant and variable speed condition is performed on a laboratory test rig shown in Figure 2. The test rig, originally built for rotor – stator contact dynamics investigation, consists of a rotor supported by two roller bearings and connected via elastic coupling to induction motor with

speed controller. The stator is made of annular plate elastically suspended on four circular beams.

The measurement system used for this purpose was based on National Instruments PCI card NI 4472. While first encoding device had toothed wheel with 24 teeth/segments, the second one consisted of a disc with zebra stripes with alternating 30 black and white stripes.

Although acquisition card offered a higher sampling rate, selection of non-contacting eddy current displacement probe as a sensing device recommended sampling rate up to 20 kS/s. Proposed procedure works as an off-line system because raw analog signal is first acquired with a simple LabVIEW application and then processed using a Matlab routine.

Measurements and simulations [8] showed that first critical speed of the rotor is at 27.8 Hz, while the first natural frequency of the stator is at 90 Hz. Radial clearance between the rotor and stator was 0.4 mm. Previous analysis showed better measurements with optical encoder device so those measurement results will be presented below.

Figure 2. Laboratory test rig

5 Experimental analysis and results

To test light rub detection capabilities of IAS measurement in combination with VMD, two tests will be presented, one without rotor-stator rubbing and one with rotor-stator rubbing. During tests rotor had slight unbalance ($5e-5$ kg m). First test was performed starting at 25.7 Hz speed without establishing contact between rotor and stator. After that, speed was increased up to 27.6 Hz when light rotor – stator rubbing started and another test was recorded. Figure 3 presents rotor disc orbit at $n = 25.73$ Hz (without rub – red dashed circle present clearance between rotor and stator) and rotor disc orbit at $n = 27.55$ Hz (light partial rub). Furthermore Figure 4 presents difference between a) FFT of IAS signal at $n = 25.73$ Hz (without rub), d) FFT of IAS signal at $n = 27.55$ Hz (light partial rub). And finally, VMD spectrograms of IAS signal for no rubbing and rotor-stator rubbing is presented in Figure 5. FFT spectrum of IAS signal (Figure 4a) for no rubbing condition beside dominant 2x harmonic has also 1x harmonic but with much lower amplitude.

In corresponding VMD spectrogram (Figure 6a) only oscillation about 2x harmonic is clearly seen. In case of light partial rotor-stator rubbing in FFT spectrum of IAS signal a fractional harmonic has appeared, especially $3/2x$ and $5/2x$ with its sidebands, Figure 4b. In VMD spectrograms of IAS signal (Figure 5b) for rubbing case there is clear indication of $3/2x$ harmonic together with 1x harmonic of rotor speed.

Figure 3. Rotor disc orbits, a) no rubbing, b) rotor-stator rubbing

Figure 4. FFT of IAS signal, a) no rubbing, b) rotor-stator rubbing

Figure 5. VMD spectrograms of IAS signal, a) no rubbing, b) rotor-stator rubbing

According to Muszynska [19] and Peng [20] if partial rotor–stator rub is happening there must exist stable fractional vibration with frequencies equal to exact fraction of the rotating speed. Most often this fraction is 1/2 harmonic and higher fraction harmonics e.g. 3/2 and 5/2.

6 Conclusion

This paper presents possibility of fault detection based on Instantaneous Angular Speed measurement and Variational Mode Decomposition. For this purpose two measurements are performed on the specially designed test rig. First measurement presents subcritical rotor operation without rotor–stator rubbing. FFT spectrum of IAS signal for no rubbing condition beside dominant $2x$ harmonic has also $1x$ harmonic but with much lower amplitude. In corresponding VMD spectrogram only oscillation about $2x$ harmonic is clearly seen. In case of light partial rotor-stator rubbing in FFT spectrum of IAS signal a fractional harmonic has appeared, especially $3/2x$ and $5/2x$ with its sidebands. In VMD spectrograms of IAS signal for rubbing case there is clear indication of $3/2x$ harmonic together with $1x$ harmonic of rotor speed.

It can be concluded that VMD spectrogram can detect light partial rotor–stator rub condition and give clear difference between no-rubbing and rubbing condition. Future research will be focused on indication of different intensity of partial rubbing and different measurement of IAS signals.

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