Identification of Critical Speeds of Rotating Machines Using On-Shaft Wireless Vibration Measurement

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Abstract. On-shaft vibration (OSV) together with the wireless router has been used for the vibration based condition monitoring (VCM) and the method has been applied to a small experimental rig. The observations made on the measured OSV data during the rig run-up operation, in particular the identification of the rig critical speeds from the OSV run-up data are presented in this paper.

Keywords: Vibration-based condition monitoring (VCM); On-shaft vibration (OSV) measurement; Spectrum analysis, Short time Fourier transformation (STFT) analysis; Modal analysis

1. Introduction
Vibration-based Condition Monitoring (VCM) and diagnosis is a well-known tool for fault diagnosis of rotating machines. Goldman [1] and Bosmans [2] gave the summary of the vibration based techniques for identifying different faults in rotating machines. Sinha [3] gave a detailed spectrum of the vibration-based condition monitoring in rotating machines. The conventional/well-accepted VCM acquires vibration measurement generally in three directions (vertical, horizontal and axial) on each bearing pedestal that supports the rotor in a rotating machine. Hence, a large number of vibration sensors are required for a rotating machine like turbo-generator set, where the rotor is generally supported through a number of bearing pedestals. Then, a number of different signal processing procedures are employed on the measured vibration data at each bearing pedestal to identify the rotor related fault(s) [3]. All these generally need (a) substantial investment for setting a vibration-based condition monitoring system, and (b) cost related to the maintenance of the monitoring system. Hence a few number of vibration sensors with a better capability of fault(s) identification in the condition monitoring may be well appreciated by any industry. Hence, an innovative measurement scheme i.e., On-shaft vibration (OSV) is used by Elnady et al. [4] towards the modern VCM for rotating machine. This concept is expected to reduce the number of sensors and maintenance cost significantly in comparison with the well-accepted conventional VCM and moreover, the OSV data also is expected to contain enriched information of the rotor vibration which, in turn, is expected to enhance the diagnosis process with a limited vibration data. Elnady et al. [4] have used the advancement in instruments over decades for this purpose, in particular the wireless MEMS (Micro Electro Mechanical Systems)
accelerometer with its possible use in the structural health monitoring [5, 6]. Hence, a tiny and very light-weight MEMS accelerometer with a wireless sensor node mounted directly on the rotor itself was used in a small experimental rig and then a few but successful measurements were carried out at different shaft speeds in the earlier study [4].

In this paper, the OSV method has again been used on a small experimental rig. Experiments were conducted during the rig run-up and both OSV and vibration measurement using accelerometers at bearing pedestals in the horizontal and vertical directions were collected, analysed and compared. The observation made on the measured vibration response directly from the accelerometer mounted on-shaft, particularly related to identification of the rig critical speeds, during the rig run-up has been discussed here.

2. Experimental Test rig
The schematic of the rig is shown in Figure 1. The rig consists of a 20 mm diameter shaft with a span of 900 mm supported on the relatively rigid foundation through ball bearings. The shaft also carries a balanced disc of 125 mm diameter and 20 mm thickness at mid span between the two bearings of the shaft. A motor is also connected to the shaft through a flexible coupling to drive the shaft at different speeds.

![Test rig schematic](image)

**Figure 1.** Test rig.

Figure 2 shows the proposed vibration measurement scheme adopted in the present study. A small tiny micro electro-mechanical system (MEMS) accelerometer is mounted on the shaft itself. The accelerometer has a range of ±40g and sensitivity of about 200mV/g. It is assumed that the mounting of such a tiny accelerometer may not influence the rotor unbalance. The V-Link™ from MicroStrain is the wireless sensor node which is then connected to the MEMS accelerometer for wireless transmission of the vibration signals measured by the MEMS accelerometer. The V-Link module
weighs just 97gm and its mounting arrangement is also shown in Figure 2. It is mounted on a disc (denoted as disc2) as shown in Figure 1 and 2 which is kept close to the left bearing so that it should have very small effect on the rotor unbalance and influence on the dynamics of the test rig. The V-Link module can support seven external measurement channels, four differential and three single ended input channels. Presently just one single ended input channel is used for the MEMS accelerometer. It can transmit the measured data to a USB based-station connected to a PC. It uses a 12 bit analogue to digital converter and data sampling rates of 736 Hz and 2048 Hz in streaming and data logging modes respectively.

![Rig Photograph showing the vibration measurement scheme.](image)

**Figure 2.** Rig Photograph showing the vibration measurement scheme.

### 3. Modal testing

Modal testing has then been conducted on the rig by the Impulse-Response method [7] using an instrumented hammer and a tiny accelerometer in both horizontal and vertical planes. A typical frequency response function (FRF) plot in the horizontal plane and the zoomed view around the peak at 33Hz are shown in Figure 3. The 4 peaks, 31.6Hz & 33.85Hz and 154Hz & 162Hz seen in Figure 3 are identified as the machine critical speeds predominantly in the horizontal and vertical planes respectively.

![typical frequency response function](image)
5. Run up Experiment

A run-up experiment from shaft speed 0 to 1200 RPM with a linear ramp rate of 4.3 RPM/s has been conducted. The acceleration vibration data has also been collected at bearing 1 in the horizontal and vertical directions together with the on-shaft acceleration response. The measured responses are shown in Figure 4.

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**Figure 3.** A typical FRF plot in the horizontal plane, (a) Amplitude, (b) Phase, and (c) a zoomed FRF plot around 33Hz.
5.1. Data Analysis and Observations

The amplitude amplification at different speeds during run-up definitely indicates the excitation of machine critical speeds. To understand this, the short time Fourier transformation (STFT) analysis was carried out initially for the measured acceleration responses at the bearing pedestal in the horizontal and vertical directions. Typical spectrograms for the horizontal and vertical directions are shown in Figure 5. The spectrograms clearly show the presence of the frequency peaks related to the shaft RPM (1x) and its higher harmonics (2x, 3x ...) as expected. However three distinct high amplitude spots corresponding to 33Hz and 35.5Hz in the horizontal and vertical directions are also observed when the shaft speed passes through 1/3, 1/4 and 1/2 of the critical speed for both vertical and horizontal directions. Typical spectra in the horizontal and vertical directions are also shown in Figure 6 when the shaft is passing through the half critical speeds, i.e., 1002RPM and 1062RPM in the horizontal and
vertical directions respectively. As expected, the peaks at critical speeds of 33Hz and 35.5Hz are clearly observed for both directions. These values are slightly higher than the experimental modal tests frequencies of 32Hz and 33.28 Hz. This may be due to the frequency resolution of 0.015 Hz used in the STFT analysis or possible small gyroscopic effect with the speed.

With these observations, the STFT analysis has also been carried out for the on-shaft measured acceleration vibration response. The spectrogram is shown in Figure 7. As expected, the spectrogram shows the strong feature of 1x component and a few higher harmonics at lower amplitudes. In addition, the on-shaft vibration response should show peaks at both vertical and horizontal critical speeds when passing through 1/4, 1/3 and 1/2 of the critical speed. However there are no such peaks at around critical speeds of 33 and 35.5Hz as observed in the bearing pedestal responses. In spite of the apparent correlation between the on-shaft and on-bearing measurements in capturing all the amplitude amplification peaks, as can be seen in Figure 4, the respective STFTs do not show direct correlation. Hence, further investigation has been carried out to understand this behaviour.

![Typical Spectrograms for the measured acceleration vibration responses at Bearing 1 pedestal during machine run-up. (a) Horizontal direction, and (b) Vertical direction.](image_url)
5.2. Critical speeds prediction

Instead of showing a single peak when the rotor passes an integer fraction of a certain critical speed, two peaks are observed in Figure 7 for the on-shaft vibration. Hence the spectra at 1/4, 1/3 and 1/2 of the vertical and horizontal critical speeds have then been investigated further to understand the phenomena. The vibration spectra at the shaft speeds of 492RPM (8Hz) and 660RPM (11Hz), which are nearly 1/4 and 1/3 of the first horizontal critical speed respectively are shown in Figure 8. Both spectra contain a 1x peak as expected, however no clear peak at 1st horizontal critical speed has been observed. Instead two peaks at 24.3Hz and 40.7Hz for the shaft speed of 480RPM (8Hz) and two peaks at 21Hz and 44Hz for the shaft speed of 660RPM (11Hz) have been observed. The mean value of 24.3Hz & 40.7Hz is 32.5Hz, and the mean value of 21Hz & 44Hz equals to 32.5Hz too which is nothing but the 1st horizontal critical speed seen in Figure 6(a).
Similar observations are observed for the vertical critical speed as well. For clear illustration, a simple line diagram of the spectrogram shown in Figure 7 is reproduced in Figure 9 where two peaks related to the 1\textsuperscript{st} horizontal and vertical critical speeds at different shaft speeds are marked by circular and rectangular symbols respectively. The identified 1\textsuperscript{st} critical speeds in the horizontal and vertical directions are also plotted in the Campbell diagram which is shown in Figure 10. Hence the experimentally identified critical speeds are also close to the theoretical predictions. This behaviour of the on-shaft vibration measurement clearly indicates that the machine critical speeds get amplitude modulated with the shaft speed and appear as side band at frequencies \((f_{c_n} \pm f_{RPM})\) instead of a single peak at frequency \(f_{c_n}\) itself, where \(f_{c_n}\) and \(f_{RPM}\) are the \(n\)th critical speed and the shaft rotational speed in Hz respectively. Such amplitude modulation of the critical speed in the vibration response is probably due to on-shaft vibration measurement using accelerometer; hence this approach should be used to identify the critical speeds.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8}
\caption{Typical spectra of On-shaft measured acceleration response at the shaft speed (a) 480 RPM (8 Hz), (b) 660 RPM (11 Hz)}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure9}
\caption{Simplified spectrogram of On-shaft acceleration response highlighting modulated peaks, first horizontal critical speed (circles) and first vertical critical speed (rectangles)}
\end{figure}
6. Conclusions

On-shaft vibration measurement method using wireless transmission of the vibration signals has been proposed as a concept for the future condition monitoring system. It is expected to reduce the large number of vibration sensors often used in the conventional VCM. The proposed method has been applied to a small experimental rig with a flexible rotor and the experiment has been conducted during the machine run-up. OSV data have been compared with the bearing pedestal vibration used in the conventional VCM. It has been observed that the machine critical speeds are not appearing at their positions in the OSV machine run-up data, instead they get modulated at the shaft speed and appear as two side band peaks for each critical speed. Hence the identification of the critical speeds using the OSV data has been suggested based on the observation. It is now planned to introduce different faults one by one to develop the diagnosis feature which will be reported separately.

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