VIBRATION ANALYSIS OF A LARGE ROTOR OVER INDUSTRIAL INTERNET

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ABSTRACT

Excess rotor vibration decreases production quality and causes unscheduled maintenance breaks in the manufacturing industry utilizing rotating machinery in production. Measuring and monitoring the rotor vibration levels in production conditions provides added value through decreased maintenance costs and quality variations. E.g., paper and metal manufacturing are fields where the rotor running accuracy affects directly to the quality of the final product.

In few production machines, critical components are equipped with a modern wired condition monitoring system to acquire vibration signals from the bearing housings during operation. However, upgrading a running production machine with this kind of system is expensive and requires a maintenance brake.

In the present study, a low-cost MEMS accelerometer sensor and wireless data transmitter were attached to a bearing housing of a large rotor. Measurement series was conducted to determine the subcritical vibration spectrum and the results were verified against a laboratory vibration measurement instrument. The vibration was measured during a rotor acceleration mimicking a production ramp-up.

Index Terms – Subcritical vibration spectrum, Low-cost wireless condition monitoring, MEMS accelerometer

1. INTRODUCTION

Large flexible rotors are widely used in paper and metal manufacturing, turbines, electric machines and generators. Excess vibration of a rotor reduces the lifetime of the machine. Rotating machine usage at speed ranges exhibiting intensive vibration results in increased need for maintenance, which rises production downtime and costs. In paper and metal manufacturing, minimized dynamic run-out (surface movement in radial direction) is the key factor for the quality of the final product. One component increasing the dynamic run-out is vibration observed as the rotor central axis movement in radial direction.

First step for vibration free behaviour of a rotor is balancing. Different balancing methods have been studied to achieve the wanted result [1–3]. Balancing reduces efficiently vibration caused by the unequal centre of mass and central axis of the rotor. Vibration problems caused by the unbalance increase with rotor angular frequency and the maximum is reached at rotor critical speed. However, balancing is only one aspect related to the vibration behaviour of the rotor. Bending stiffness variation of the rotor is another remarkable source of vibration excitation. When rotor bending stiffness is not constant, it bends differently in different angular positions. Bending stiffness variation can be caused, e.g., by uneven material distribution in tube rolls [4]. Bending stiffness variation excites the rotor twice per rotation leading to 2nd harmonic subcritical vibration at twice the rotation frequency.

Another feature contributing to the rotor vibration is the bearing assembly. The raceway surface of the bearing has a certain roundness profile with waviness components (lobes) of different orders and amplitudes. These undulations cause considerable vibration at the subcritical harmonic resonance frequencies. For example, one undulation per revolution causes resonance when the rotation frequency is approaching the natural frequency of the rotor. Two undulations per revolution cause resonance when the rotation frequency is half of the natural frequency etc. Generally, the subcritical resonance vibration is observed, when the rotating frequency of the rotor approaches fraction of the natural frequency e.g. 1/2, 1/3, 1/4… 1/N times the natural frequency.

Since many of the large flexible rotors in industry are designed to operate below the critical speed, the subcritical vibration spectrum of the rotor must be measured in production conditions to discover the optimal vibration free production speed. In some cases, some modifications to the supporting elements of the rotor system can be done to achieve the eligible non-vibrating velocity range for a rotor.

To measure the vibration spectrum, different methods can be used, but many of them are expensive and need a certain setup to make the measurement possible. In existing factories, implementing an extensive wired condition monitoring (CM) or vibration measurement system is laborious, requires a maintenance break and usually is considered too expensive. In addition to CM systems based on accelerometers, some of the vibration measurements are done by measuring the distance variation of the rotor surface (dynamic run-out) in vertical and horizontal direction. The measurement can be done with noncontact sensors, for example Eddy-current sensors [5], Laser displacement sensors [6], or Laser Doppler Vibrometry (LDV) [7].

Various researchers have investigated cost-effective and low-power Micro Electro Mechanical System (MEMS) accelerometers usage in rotor vibration measurements and machine CM [5,8–11]. Chan and Huang [8] investigated sampling frequency and jitter of low-cost standardised MEMS accelerometer. They noticed that in their system, the data storage delay and the UART (Universal Asynchronous Receiver Transmitter) bridge delay were the factors that limited their sampling frequency. Hence, selecting the communication protocol and data storing method needs to be considered, when a certain sampling frequency is required.

Jiménez et al. [5] measured vibration of a laboratory scale rotor using a MEMS accelerometer. They inserted their measurement instrument inside a hollow rotor. Since the accelerometer rotated with the rotor, the angular velocity and rotation angle of the rotor could be measured utilizing the gravitational force.

Feng et al. [9] investigated CM of a compressor by attaching a MEMS accelerometer on the rotor surface. Based on the results, CM with their methods was possible. Elnady et al. [10] compared FE and experimental modelling of on-shaft vibration measurement. Furthermore, they researched [11] the same field and have compared vibration measurements from bearing housing and on-rotor during run-up of the rotor. Their results suggested that it is possible to use on-rotor MEMS accelerometers to measure critical speeds and conduct CM.

In this study, an easy-to-implement and cost effective method for subcritical vibration spectrum measurement is analysed using MEMS accelerometer and Internet of Things (IoT) microcontroller with a built-in WLAN chip. Using this self-built wireless vibration measurement instrument (WVMI), it is possible to measure the subcritical vibration spectrum

during the production ramp-up. No specific measurement setup is needed, making the process easier and interfering the production as slightly as possible. Laboratory-level accelerometers are used to compare and verify the results.

2. MATERIALS AND METHODS

2.1 Rotor vibration measurement setup

Measurements were conducted using a paper machine roll as a test rotor. The rotor length was 5000 mm, the roll diameter was 320 mm and the shell thickness of the roll was 16.5 mm (Figure 1).
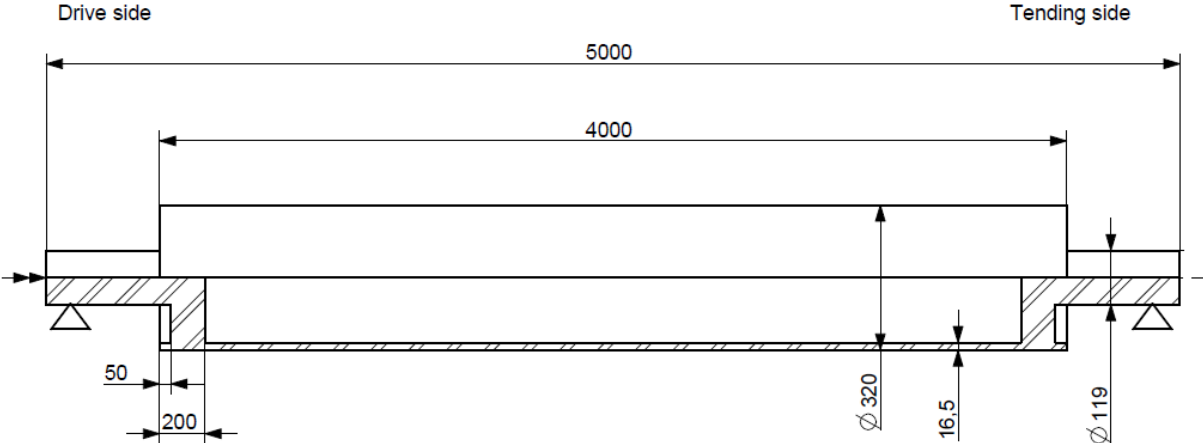

Figure 1 Dimensions of the test rotor.

The rotor was driven with a CNC-controlled roll grinding machine. The complete test setup is presented in Figure 2. The rotor was supported by two row spherical roller bearings on both ends. WVMI and reference accelerometers were attached to the tending side bearing housing (Figure 3). Both vertical and horizontal axis were measured.

Figure 2 Test rotor and the measurement setup in the tending side bearing housing.

Vibrations were measured during the acceleration of the rotor, which imitated a typical production ramp-up acceleration. Moreover, when measured during the acceleration, the subcritical vibration properties at angular velocities from 0 rpm to accelerated rpm could be observed. In this study, the acceleration was set from 0 rpm to 950 rpm.
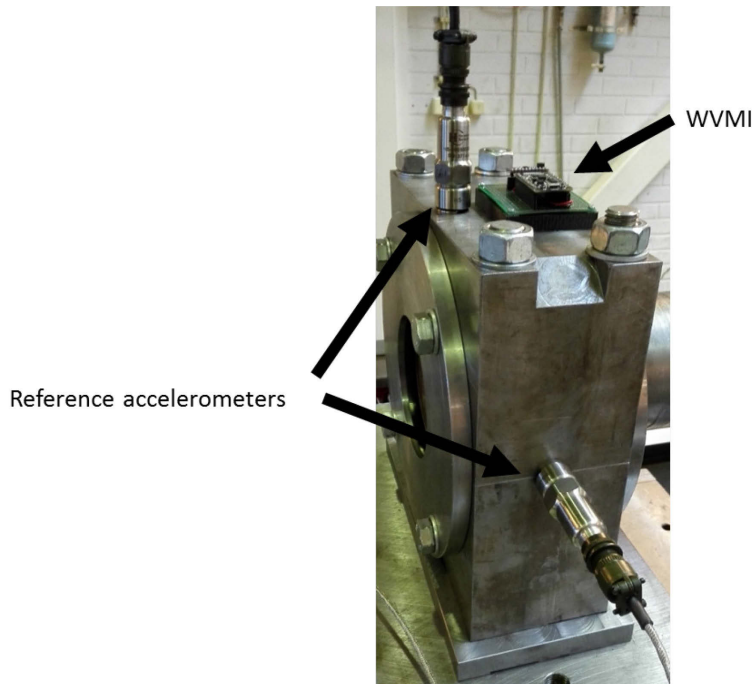
Figure 3 Bearing housing with the Wireless Vibration Measurement Instrument (WVMI) and reference accelerometers.

2.2   Wireless vibration measurement instrument

The wireless vibration measurement instrument (WVMI) developed in this study was built using a MEMS accelerometer (LIS3DSH, STMicroelectronics) and a NodeMCU microcontroller based on ESP8266 (Espressif Systems). ESP8266 connected the device to a wireless network, which allowed a remote access to the WVMI and wireless data transmission. Serial Peripheral Interface bus (SPI) was used to communicate between the LIS3DSH and microcontroller. SPI allowed a maximum sampling frequency of 1000 Hz.
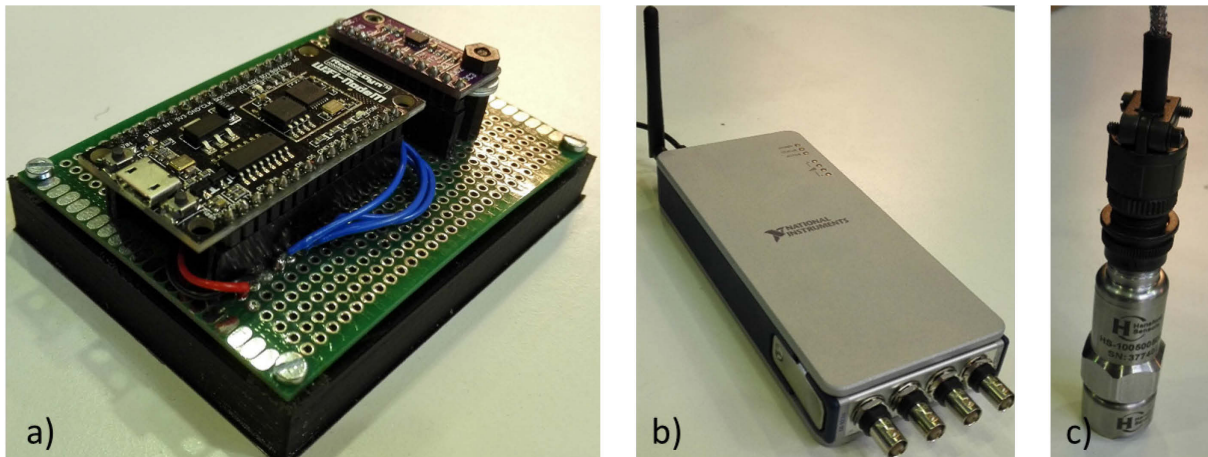

Figure 4 a) Wireless vibration measurement instrument (WVMI) b) National Instruments' cDAQ-9191 wireless data acquisition unit and NI-9234 sound and vibration input module and c) Hansford Sensors' HS-1005005001 accelerometer.

LIS3DSH was able to measure the acceleration in all three dimensions. The anti-aliasing low-pass filter built into the accelerometer was set to 50 Hz since the maximum investigated natural frequency was 30 Hz. The output of the sensor was a 16-bit integer which was converted to acceleration (m/s^2) afterwards using Matlab. To verify and compare the results, 2 piezo-based accelerometers (Hansford Sensors' IEPE HS-1005005001) and National Instruments' wireless

data acquisition chassis equipped with a sound and vibration input module were used (cDAQ-9191 and NI-9234). WVMI, and the reference devices are presented in Figure 4. The specifications of the accelerometers and the used configurations during the measurements are presented in Table 1.

Table 1 Specifications of the accelerometers

Accelerometer	LIS3DSH		HS-1005005001	
	Specifications	Used	Specifications	Used
Measurement range	(±2, ±4, ±6, ±8, ±16) g*	±2g*	±16g*	±16g*
Sensitivity	(0.06, 0.12, 0.16, 0.24, 0.73)** mg*/digit	0.06 mg*/digit	500mV/g*	500mV/g*
Sample rate	3.125 Hz – 1600 Hz	1000 Hz	2 Hz – 10 kHz	1650Hz
Number of axis	3 (x, y and z)	2 (y and z)	1	1

*g = gravitational force
** Depending on the measurement range

Communication between the WVMI and the computer was resolved with User Diagram Protocol (UDP) over Wireless Local Area Network (WLAN). However, UDP features no handshaking between the devices to ensure that the data has reached its destination. Due to data transmission or WLAN errors, some of the data may be lost during the measurement.
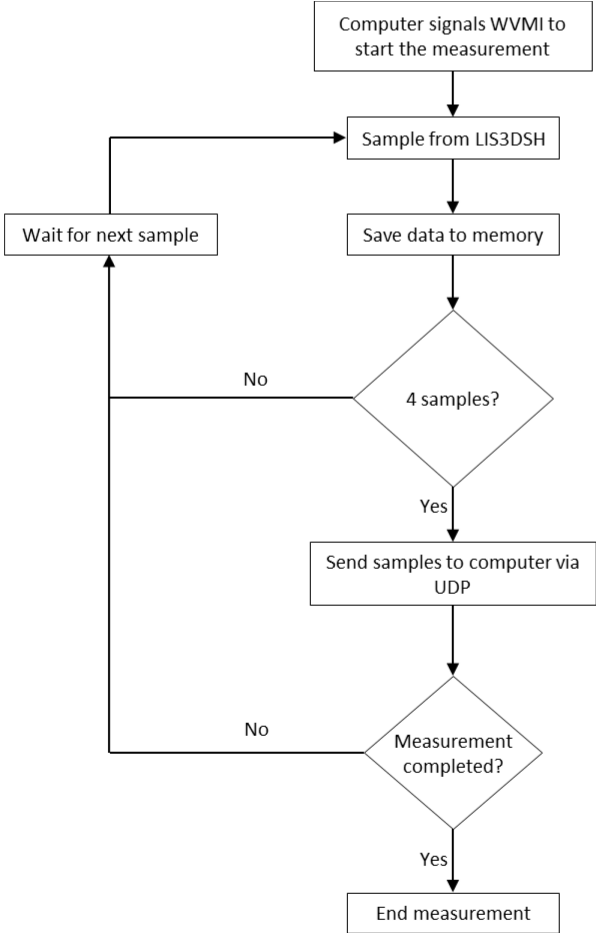

Figure 5 Block diagram presenting the measurement procedure in the WVMI

The measurement procedure and the overview of the program is presented in Figure 5. The communication between the computer and the WVMI was started by connecting them to the same WLAN. The IP-address and UDP port of the WVMI were provided. Python program on the computer started the measurement by sending an UDP packet to the WVMI. WVMI saved 4 measurement values from the accelerometer and the timestamps of each measurement and sent them as one UDP packet to the computer. The sampling clock was realized with a microcontroller timer since the samples needed to be taken in even intervals.

Python program on the computer saved the UDP packets in to a string. After the measurement ended, the string was saved to a file and a Matlab script was used to manipulate the data. The data was converted to gravitational units by using conversion rate of 0.00006 g/digit from LIS3DSH datasheet. Finally, the data was multiplied by 9.81 m/s^2 to get the SI unit.

2.3   Analysis methods

The analysis of the measurement data was performed using spectrograms based on Fast Fourier Transform (FFT) and short-time Fourier transform (STFT). Fourier analysis is used to transform time domain data into the frequency domain or vice versa. Through Fourier analysis, the measurement data is decomposed into simple trigonometric functions revealing the harmonic components of the vibration. The amplitude and frequency of each component are easily determined. FFT is a computation algorithm that calculates the Fourier analysis faster by exploiting complex numbers [12]. When it is important to know how the frequency of the signal changes over time, Short-time Fourier transform is useful [13]. STFT divides the original data in segments with certain amount of measurement samples.

Fourier analysis assumes the data periodic. The measurement data during the acceleration of the rotor was not periodic leading to Fourier analysis results harder to interpret. However, using a windowing function, the data can be manipulated to mimic periodic signals making the Fourier analysis more feasible. In this study, Hanning windowing was used.

Spectrogram is popular in speech or sound analysis [14–16]. Exploiting spectrograms, the frequency domain data can be visualized as a 3-dimensional plot presenting the frequencies (Hz), normalized power (dB/Hz) and time (s) during the measurement.

3.   RESULTS

Results from the measurements are presented in Figure 6 and Figure 7. The 1X, 2X 3X and 4X presented in the figures are the harmonic components of the rotor vibration. 1st harmonic component (1X) equals the rotor rotating frequency; 2nd harmonic component corresponds to vibration occurring twice per revolution etc.

Figure 6 presents the measurement results in the horizontal direction. The natural frequency of the rotor system in horizontal direction can be observed from both spectrograms, resulting in 21.51 Hz in Figure 6a and 21.58 Hz in Figure 6b.
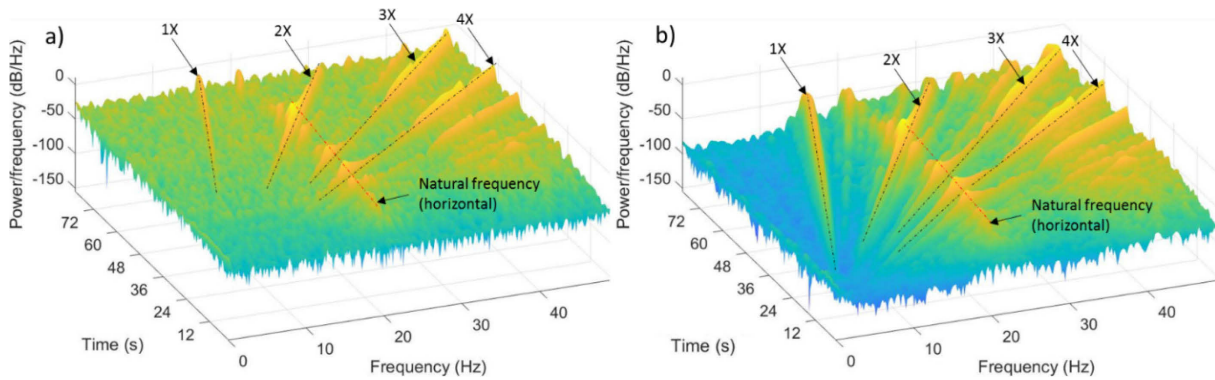
Figure 6 Spectrograms of the horizontal direction vibration measurements: a) WVMI b) Reference device.

In vertical direction, the WVMI had difficulties to separate the harmonic components from the data. However, the 2X, 3X and 4X responses can barely be seen in addition to natural frequencies both in horizontal and vertical directions (Figure 7 a). Reference instrument was able to measure and separate all the harmonic components (1X - 4X). The vertical natural frequency interpreted from the Figure 7a is 30.1 Hz and from Figure 7b 29.84 Hz. The horizontal natural frequency is also visible in Figure 7. In Figure 7a, the horizontal natural frequency is little lower, 21.43 Hz, than in Figure 6a. Figure 7b yields 21.58 Hz for the horizontal direction natural frequency, equalling the result from Figure 6b.
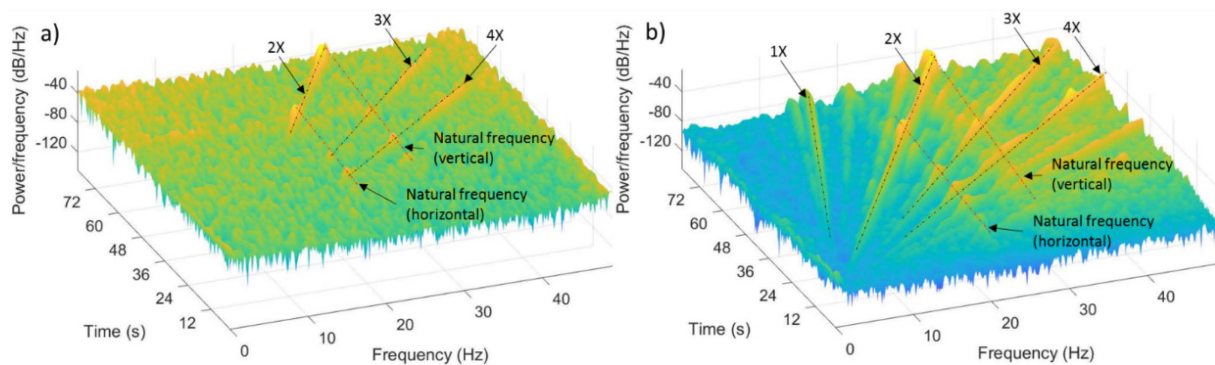

Figure 7 Spectrograms of the vertical direction vibration measurements: a) WVMI b) Reference device.

During the measurements, some of the UPD packages were lost (0.05 % on the measurements in Figure 6a and Figure 7a).

4. DISCUSSION

Comparing the spectrograms based on the measurement results by the WVMI and the reference setup, the reference device was able to detect vibration with lower amplitudes more accurately. However, the natural frequency in horizontal direction (Figure 6) is observed as clearly in both the spectrograms. The measured (WVMI) horizontal direction natural frequency is 21.51 Hz, which agrees well with the previous research value 21.6 Hz. The next region with higher vibration is c. 40 Hz, which is assumed to be related to the next bending mode natural frequency. The measurement in horizontal direction with the WVMI was obviously accurate enough to detect the subcritical vibration free rotation frequency ranges.

In Figure 7a, the WVMI has difficulties to detect the harmonic components. 1X harmonic component cannot be identified from the spectrogram at all. Other harmonic components from

2X to 4X can be observed being significantly less apparent as in spectrogram based on the data of the reference device (Figure 7b). Natural frequencies are visible in both spectrograms in Figure 7, albeit observing them from the reference device data is more obvious. The horizontal direction natural frequencies can be detected from the spectrograms as well. Furthermore, the measured (WVMI) vertical natural frequency (30.1 Hz) agrees with previous research (30 Hz).

The possible reason for the less precise measurement in vertical direction may be the small amplitudes (significantly smaller in vertical than in horizontal direction), which are not high enough for the MEMS accelerometer to detect among the vibration noise. Gravity may reduce the precision of the measurement as well. To experiment the gravity interference, the WVMI was placed to the side of the bearing housing for different orientation of accelerometer axes. The results were similar, featuring the axis in vertical direction detecting the vibration spectrum vaguely. Some UDP packet loss occurred during the measurements but the loss percentage was negligible and did not affect the results.

The WVMI and the reference setup both established a wireless communication with the computer. However, the compact WVMI proved to be easier to set up during tests, since the single unit measured both the axes and transferred the measurement data contrast to the two accelerometers connected with cables to the separate wireless data acquisition unit in the reference setup.

The results suggest that a wireless vibration measurement system connected to a rotor is a feasible and low-cost alternative to a wired condition monitoring system. Subcritical vibration spectrum was acquired precisely enough in horizontal direction to observe the superharmonic resonance peak frequencies of the rotor. This information can be used in optimizing the production speed of the production line, especially if the subcritical vibration spectrum of virtually every rotor is known, which is an achievable goal considering the device developed in this study. The wireless properties of the device support the applications in existing machine lines to decipher the present frequency properties and improve the runnability.

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