Experimental Investigation of Rotor Vibration by Using Full Spectra from Shaft Mounted Piezoelectric Patches

Mateusz KOZIOŁ
AGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics, al. Mickiewicza 30, 30-059 Kraków, makoziol@agh.edu.pl

Piotr CUPIAŁ
AGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics, al. Mickiewicza 30, 30-059 Kraków, pcupial@agh.edu.pl

Abstract

The work considers the applicability of signals coming from rotor-mounted sensors in machine diagnostics. In the experiments, such sensors were implemented by piezoelectric patches bonded to the surface of a shaft. The laboratory stand also included more common sensors: laser sensors that measured the displacement of the central disc, as well as accelerometers mounted on the supports. The signals measured are analysed using the so-called full FFT method and the spectra are compared. The results show that the signals from piezoelectric sensors can be processed so that their spectral content is similar to typical spectra obtained using stator-mounted sensors.

Keywords: rotor dynamics, piezoelectric patches, frequency spectrum, signal processing, diagnostics

1. Introduction

Many types of rotating machinery are required to work continuously for a long time. Since the functioning of these devices is very often crucial for society, condition monitoring becomes important, even if it results in additional costs. As one of the symptoms, a vibrational signal carries information about the health condition of a machine. However, proper diagnostics depends on many factors, among others on the type of sensors and their placement, appropriate signal processing techniques, as well as expert knowledge.

The condition monitoring systems of rotating machinery currently used incorporate mainly displacement and acceleration sensors that measure the vibrations of the shaft and bearing supports [1, 2]. There have been many studies that search for vibrational indicators of most common rotor problems, such as misalignment [3, 4], cracks [5], rubs [6], etc. In general, in these studies the stator-mounted sensors are utilized, mainly because mounting such sensors on non-rotating parts is easy and reliable. The signals obtained from such sensors will be considered as referenced to an inertial or stationary reference frame (SRF). Studies where the sensors are mounted directly on the shaft are less common, as an example, papers [7, 8] can be mentioned. In this paper the signals obtained from rotor-mounted sensors will be used and throughout the paper they will be referred to as referenced to a rotating reference frame (RRF). Generally, in such configurations a slip ring assembly has to be used, which is an important element of such a solution.

With technological advances in MEMS, it becomes reasonable to use rotor-mounted sensors more widely. By applying the currently available communications technology and telemetry systems, wireless measurements can meet high requirements, and some rotor-related problems can be better observed using sensors fixed directly to the shaft. Therefore, such an approach is recently getting more attention from scientists. As an example, in reference [9] the authors use a MEMS-type accelerometer mounted on to the surface of a circular shaft. This work concentrates on the torsional vibrations arising from misalignment, so that only the tangential to shaft surface component of the acceleration is being analysed. The radial component is taken into account in reference [10], were a MEMS sensor is mounted as before, and additional stationary referenced accelerometers are used. The study includes the run-up conditions as well as the passage through the first critical speed. In publication [11] it is showed that axially mounted MEMS accelerometers can be used to measure the unbalance response. The authors also propose a method of estimating the rotational speed, which is based on a gravity component of accelerometer signals.

In general, rotor-mounted sensors generate signals referenced to a rotating frame, and in most cases these signals are qualitatively different from those measured in a stationary (inertial) frame. By analysing a standard spectrum plot for signals from RRF, it may be difficult to assess the full meaning and significance of different vibration spectrum components. The current work shows that the use of the so-called full FFT [1] (or complex FFT [12]) for signals from RRF can be beneficial. This approach requires two sensors, which measure the motion in two perpendicular directions. The paper will compare the use of full spectra for experimental signals referenced to stationary (SRF) and rotating reference frame (RRF), and the similarities and differences will be emphasized. The experimental tests were performed on a laboratory stand, equipped with piezoelectric patch sensors mounted on a rotating shaft, that is also used to test active control of flexible rotors.

2. Test facility

The experiment has been conducted on a laboratory stand presented in Fig. 1. The elastic rotor made of aluminium is horizontally mounded in two supports. The supports consist of lathe chucks and ball bearings. There is a steel disc in the middle of the length of the rotor. Eight piezoelectric patches (PZT26) are glued to the surface of the shaft near the rotor ends. The polarisation of all elements is away from the shaft surface. Two piezoelectric patches placed on the same surface are connected in parallel, so that all patches are connected into four pairs (marked by the same hatching in Fig. 1). The piezoelectric signals from the rotational reference frame are transferred by a classic slip ring assembly (not shown). To achieve higher gains and lower phase shifts for low frequency components of the PZT signals, two charge amplifiers have been used. The displacement of the disk is measured by two perpendicular laser triangular sensors. Additionally, acceleration in two perpendicular directions is measured on each support, and the encoder of the motor is used as the absolute phase marker (the so-called key-phasor). The rotor speed is constant and it is equal to 540 rpm. All signals are sampled and acquired simultaneously, using one master clock, FPGA chip and the LabView software.

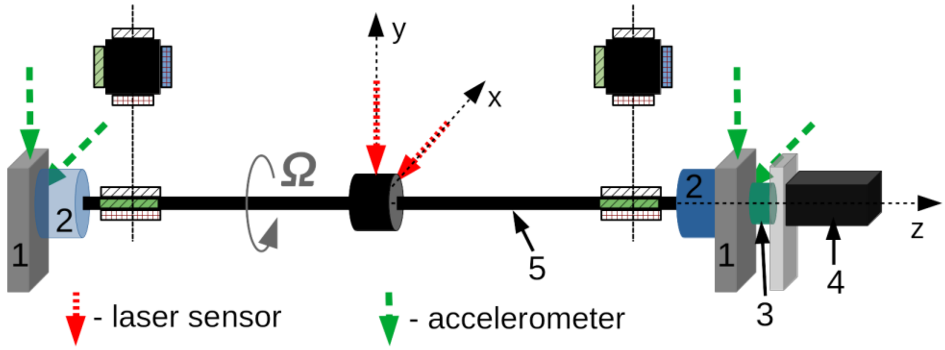

Figure 1. The scheme of the laboratory stand: 1 – support, 2 – lathe chuck, 3 – flexible coupling, 4 – motor with encoder, 5 – shaft with bonded piezoelectric patches and a disc

3. Data processing

The main advantage of applying full FFT is that it provides information about the phase correlation between the two measured channels. In the experimental set-up, sensors were mounted perpendicular to each other. The phase correlation between the channels is not lost thanks to the use of a complex signal, the real part of which is the signal measured in one direction and the imaginary part is that measured perpendicularly to it [12]. When the Fourier transformation is performed on such a complex signal, it is possible to distinguish the direction of rotation of individual frequency components, which in not true with the standard Fourier spectrum calculated using a single real signal. A very intuitive explanation of this feature can be found in reference [13]. The full frequency spectra were calculated using the FFT function of the MATLAB software. In order to minimize spectral leakages, time series of duration corresponding to an integer multiple of the number of turns are being used.

To allow for a comparison of the results obtained using different signals, the latter will be scaled to the same engineering units (e.g. to mm or m/s^2), before the Fourier transformation. The signals from piezoelectric sensors are scaled by using the laser sensors. When the structure does not rotate, the first mode of vibration is excited and the responses of the sensors are measured. Then, using a laser sensor as reference, the scaling factor is determined. This procedure was performed separately for each direction of rotor motion, to account for mounting imperfections.

4. Results and discussion

Before the analysis of the results, the directional information of the frequency components should be systematised. Let us assume that there are two sensors (x, y) referenced to SRF, and two additional sensors (ξ, η) referenced to RRF. All sensors measure signals in the directions shown in Fig. 2a, and the shaft rotates counter clock-wise (CCW).

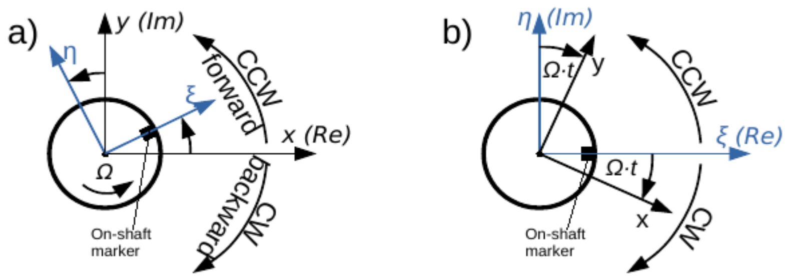

Figure 2. Interpretation of full spectrum directivity information: a) in SRF, b) in RRF

The double-sided spectrum of a complex signal (x + *i*y) has the following interpretation: the components with a positive frequency have CCW direction of rotation (in reference to SRF), and since they are consistent with the direction of the rotation of the shaft, they are called the forward components (Fig. 2a). The components with negative frequencies are called backward, because they rotate opposite to the shaft, that is in the clock-wise (CW) direction. Similarly, using the full spectrum approach for the RRF-referenced complex signal (ξ + *i*η), the components with a positive frequency will have CCW direction (in reference to RRF), and those with negative – CW (Fig. 2b). It implies, that a static force acting in SRF, e.g. the gravity force, will have a CW component in RRF. Usually, in the literature, the full spectra of SRF referenced signals are presented in such a way that the forward frequency components are always positive, regardless of the direction of the rotation of the rotor or positions of the sensors. Thus, the full spectrum obtained for RRF referenced signals will always have a gravity related component with negative frequency (-1X, i.e. -1 times the frequency of rotation), for any direction of rotation.

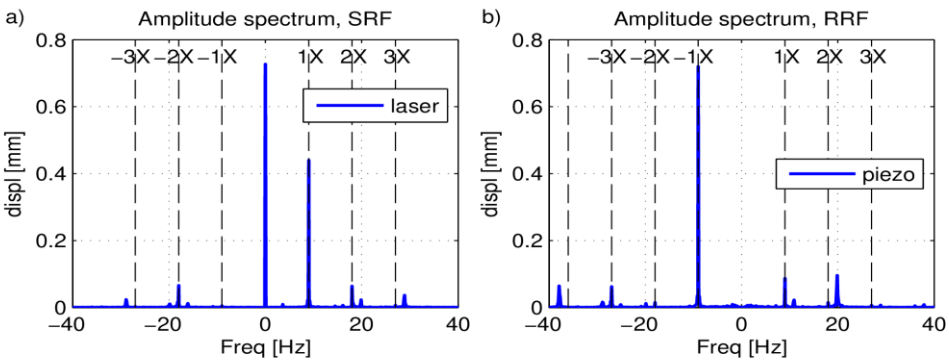

Figure 3. The obtained full spectra for: a) the laser sensors, SRF spectrum,
b) the piezoelectric patches, RRF spectrum

The two main components of the SRF spectrum (Fig. 3a) are 0X and +1X, which are due, respectively, to the gravity force and to the combination of the unbalance and a possible shaft bow. The RRF spectrum has only one significant peak (Fig. 3b), due to gravity, as discussed above. The unbalance and bow related deflections are absent from the RRF spectrum, because the piezoelectric patches are unable to measure constant static strains (the static charges are slowly discharged by measurement instrumentation). It may be difficult to measure the shaft deflection due to the gravitational force using a laser sensor, since the undeformed shaft position is usually not known. On the other hand, the -1X component of the RRF spectrum can be conveniently used to estimate the deflection of the shaft caused by gravity. To this end, the amplitude of this component was measured by the piezoelectric sensors for several rotational speeds of the shaft, and the obtained values were averaged. Using this value the reference undeformed shaft position was established, which allowed the measurement of the static component in Fig. 3a.

By taking a closer look at the other components, further similarities can be observed. There is a simple relationship between the spectra, the RRF components are shifted by 1X to the left relative to SRF, and vice versa. Using this principle, a plot in Fig. 4 has been obtained, showing a comparison of the spectra obtained with different sensors. It can be seen that the signals obtained from different types of sensors contain nearly the same components, except that the unbalance information cannot be obtained using piezoelectric sensors that rotate together with the shaft. Two important conclusions follow from this observation: firstly, the typical symptoms, which are well established and described for sensors working in SRF can also be used for signals that come from the shaft-mounted sensors. Secondly, the use of a one-side full spectrum for signals from RRF would cause averaging of components that do not correspond to each other. For example, when a one-sided view were used to signals presented in Fig. 3b, the amplitudes of components -1X and 1X would be averaged. When one looks at these components from the SRF perspective, it turns out that 0X and +2X components are averaged, which clearly disrupts diagnostic information carried by the signals.

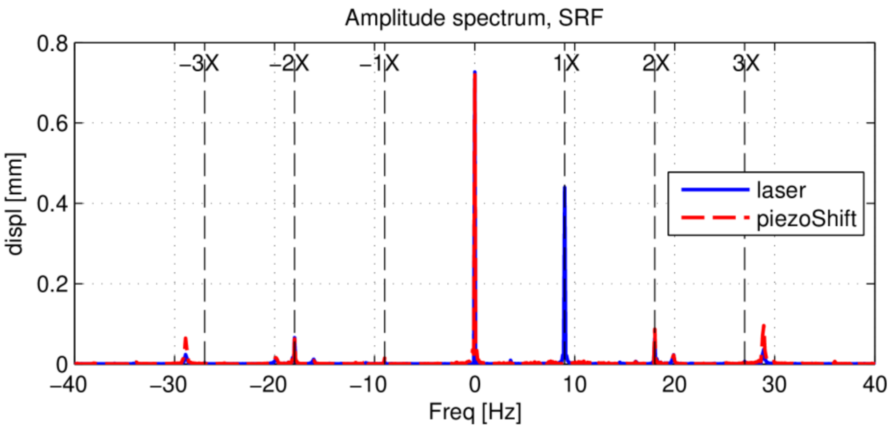

Figure 4. The comparison of the spectra, when RRF spectrum is shifted by +1X

The full spectra for signals obtained from the accelerometers are presented in Fig. 5b. The previously dominating components are less pronounced, because acceleration is measured, so that the higher- frequency components become better visible. The two main components in Fig. 5b are non-integer multiples of the frequency of rotation, what is typical of vibrations generated by ball bearings [12]. Two 3204 2RS bearings were used in the laboratory stand, for which one can calculate the outer race order, which is about 3.2X. The experimental results are in good agreement with the calculated value. The same components can be found in the shifted spectrum (Fig. 5a) obtained using piezoelectric patches. Even though the sensors rotate with the shaft, the components related to bearings can be clearly observed after proper data processing.

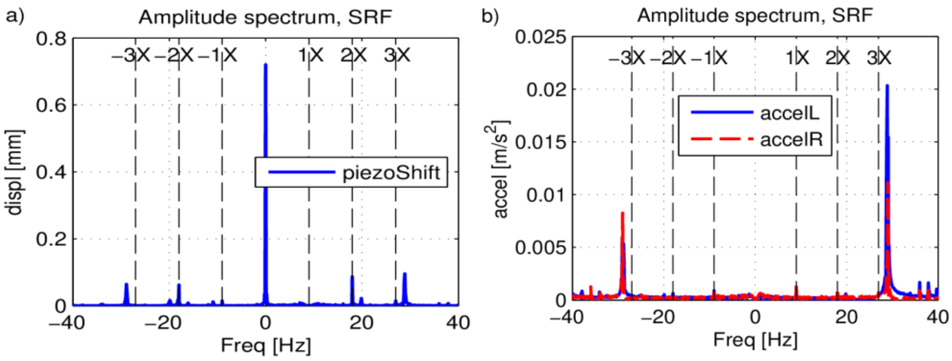

Figure 5. The full spectrum of signals from: a) piezoelectric patches, shifted by +1X, b) accelerometer on bearings supports

Piezoelectric patches also preserve the phase information that exists in the vibrational signals. As an example, the orbit plots [1] for SRF and RRF sensors are compared in Fig. 6. The displacements from the laser sensors have been filtered using band-pass filter with centre frequency that corresponds to 3.2X (Fig. 6a) and zero phase shift. The signals generated by piezoelectric patches must be first transformed to SRF and then filtered using the same filter as earlier. The plots (Fig. 6) show 4 revolutions of the shaft, and the red dots mark that 0° absolute angular position of the shaft is crossed (as measured by the motor encoder). The orientation of semi-major and semi-minor axes in both ellipses, as well as the phase relations with respect to the absolute phase marks are in good agreement.

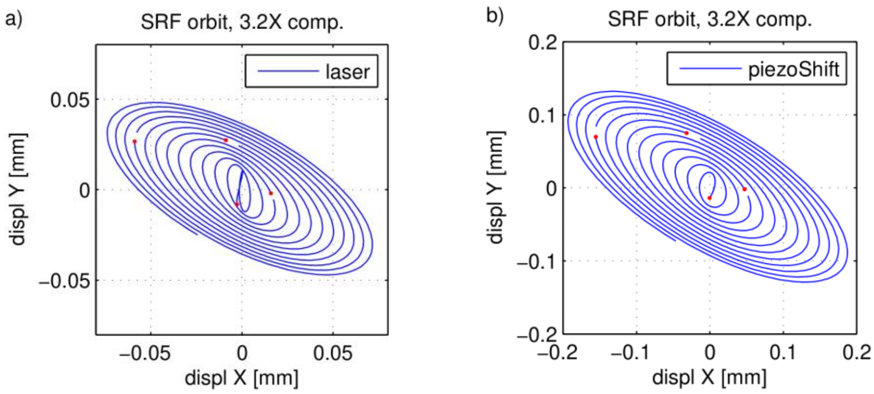

Figure 6. 3.2X-filtered orbits based on displacements from: a) the laser sensors, b) transformed (shifted) piezoelectric patches

5. Conclusions

The paper has discussed experimental results, obtained for an elastic rotor that has a constant rotational speed. Piezoelectric patches bonded to the shaft have been used as one of the sensors measuring vibrations. As expected, the static strains that are generated in rotating shafts are lost by piezoelectric sensors. The work shows that PZT patches are capable of measuring the other significant information, however it requires proper data processing to compare it with other sensors that do not rotate with the shaft.

As the results show, the use of the full spectrum is especially advisable to process signals that come from RRF. With a RRF spectrum, the one-side view (which has been used in the literature to analyse signals form sensors referred to a rotating frame) can be inadequate, since it averages unrelated components. Using the approach discussed in this paper, the fact that the sensors rotate with the shaft ceases to be relevant, and the full SRF referenced spectrum can be easily reconstructed . It has the advantage that the well-studied SRF spectra signatures of rotor problems (like misalignment, rub, rotor crack) can be adapted to signals that come from rotor-mounted sensors.

Acknowledgments

The first author would like to acknowledge the support of the Dean of the Faculty of Mechanical Engineering and Robotics of AGH UST under grant number: 16.16.130.942/Kozioł.

References

1. A. Muszyńska, *Rotordynamics*, CRC Press, Boca Raton, 2005.
2. J. Kiciński, *Dynamics of Rotors and Sliding Bearings* (in Polish), IMP PAN, Gdańsk, 2005.

3. M. Monte, F. Verbelen, B. Vervisch, *The Use of Orbitals and Full Spectra to Identify Misalignment*, in: A. Wicks (Ed.), *Structural Health Monitoring*, Springer International Publishing, Cham, **5** (2014) 215 – 222.
4. R. R. Da Silva, E. S. Costa, R. Oliveira, A. Mesquita, *Fault diagnosis in rotating machine using full spectrum of vibration and fuzzy logic*, Journal of Engineering Science and Technology, **12** (2017) 2952 – 2964.
5. A. A. Cavalini Jr, L. Sanches, N. Bachschmid, V. Steffen Jr, *Crack identification for rotating machines based on a nonlinear approach*, Mechanical Systems and Signal Processing, **79** (2016) 72 – 85, doi:10.1016/j.ymssp.2016.02.041.
6. M. A. Abuzaid, M. E. Eleshaky, M. G. Zedan, *Effect of partial rotor-to-stator rub on shaft vibration*, Journal of Mechanical Science and Technology, **23** (2009) 170 – 182, doi:10.1007/s12206-008-0717-x.
7. H. Kunze, M. Riedel, K. Schmidt, E. Bianchini, Vibration reduction on automotive shafts using piezoceramics, in: E. H. Anderson (Ed.), San Diego, CA, 2003: p. 382, doi:10.1117/12.483891.
8. P. J. Sloetjes, A. De Boer, *Vibration Reduction and Power Generation with Piezoceramic Sheets Mounted to a Flexible Shaft*, Journal of Intelligent Material Systems and Structures, **19** (2008) 25 – 34, doi:10.1177/1045389X06072753.
9. L. Arebi, F. Gu, A. Ball, *A comparative study of misalignment detection using a novel Wireless Sensor with conventional Wired Sensors*, Journal of Physics: Conference Series, **364** (2012) 012049, doi:10.1088/1742-6596/364/1/012049.
10. M. E. Elnady, A. Abdelbary, J. K. Sinha, S. O. Oyadiji, *FE and Experimental Modeling of On-shaft Vibration Measurement*, Proceedings of the 15th International Conference on Aerospace Sciences & Aviation Technology, (2013) 1 – 18.
11. S. Jiménez, M. O. T. Cole, P. S. Keogh, *Vibration sensing in smart machine rotors using internal mems accelerometers*, Journal of Sound and Vibration, **377** (2016) 58 – 75, doi:10.1016/j.jsv.2016.05.014.
12. Y. Ishida, T. Yamamoto, *Linear and Nonlinear Rotordynamics: A Modern Treatment with Applications*, Wiley-VCH, Weinheim, 2012.
13. M. Owen, *Practical Signal Processing*, Cambridge University Press, 2012.