Vibrational analysis and diagnostics by means of laser triangulation sensor

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Abstract. Nowadays, vibrational analysis is one of the most exploited methods used in order to understand the behaviour of mechanical components, by means of modal testing, and to monitor their condition, by means of vibrational diagnostics. This kind of analysis has usually been performed through acceleration measures and there exists extensive literature about this. However, in the last few years, the original methodologies based on acceleration measurement, e.g. through piezoelectric accelerometers, came into conflict with the industrial need for time reduction. The sensors used have to be easily removable in order to speed up the control operation, for example at the end of the production line. In this scenario a valid solution is represented by the use of laser triangulation sensors that are able to measure the dynamic displacement without contact with the component surface and consequently with a very high reduction in the time needed to mount and unmount. This work is focused on a comparison of the results obtained by piezoelectric accelerometer and laser triangulation sensor both for vibrational analysis, i.e. experimental modal analysis and vibrational diagnostics of rotating machines. This paper highlights the pros and cons of the contactless displacement analysis with respect to the accelerometer measurements.

1. Introduction

Nowadays, the study of the vibrational behaviour of mechanical components plays a fundamental role in research. In particular, two of the main targets of this kind of analysis are to foresee the dynamic behaviour of mechanical components, by means of Experimental Modal Analysis (EMA), and to monitor their healthy condition, by means of vibrational diagnostics.

The EMA aims to predict the behaviour of mechanical components through measurements of acceleration, velocity and displacement as well as excitation force by means of modal parameters, i.e. natural frequencies, modal shapes and damping [1, 2].

The target of vibrational diagnostics is to detect and identify incipient faults in rotating machines directly from the acquired vibration signal. For this purpose several signal processing techniques can be exploited such as: angle domain analysis [3], time synchronous average [4], amplitude and frequency demodulation [5] and envelope analysis [6].

The vibrational analysis is usually performed by means of acceleration measurements, for example through piezoelectric accelerometers. However, in more recent years this common practice has come into conflict with the industrial need for cost reduction, directly related to time reduction and rejected products elimination, in particular during the control operations.

A possible idea to satisfy all these requests is to perform the control operations in a contactless way. In this scenario the laser triangulation sensor (LTS) can represent a valid solution, due to

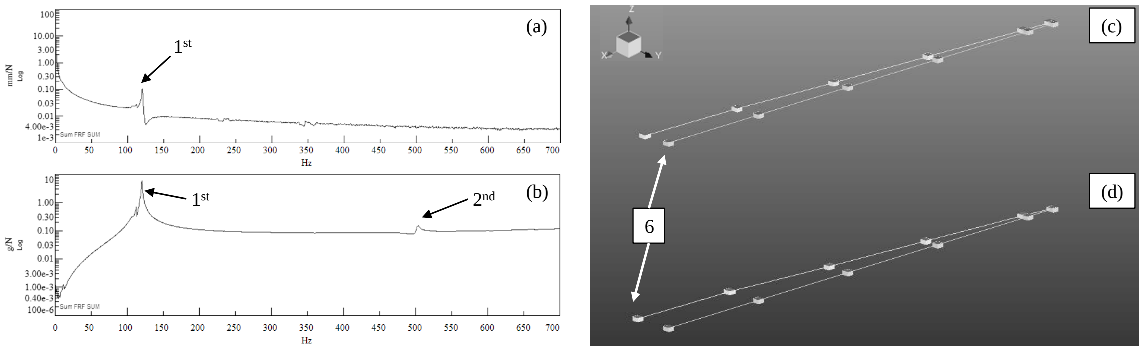

Figure 1. (a-b) FRF-sum (amplitude) and (c-d) first mode shape at 120Hz from displacement signal and acceleration signal (from top to bottom).

the fact that it is able to measure the dynamic displacement of a surface without contact.

Over the years an alternative solution has not been exhaustively studied. In this direction, Mucchi[7] proposed strain analysis as an alternative to the original acceleration analysis through a comparison between a piezoelectric strain sensor and a piezoelectric accelerometer.

This work aims to propose the LTS as an alternative to the piezoelectric accelerometer for vibrational analysis. The main purpose of this paper is to demonstrate the effectiveness of LTS for vibrational analysis through a comparison between the results obtained by the displacement analysis by means of LTS and the acceleration analysis by means of piezoelectric accelerometer in the classic vibration analysis, i.e. EMA and vibrational diagnostics.

2. Laser triangulation sensor

LTS exploits simple geometric relations in order to measure the dynamic displacement of a surface. This sensor is composed of three main components: a laser diode, a lens and a Position Sensitive Detector (PSD). The laser diode emits a laser beam directly towards the surface that reflects the beam in the direction of the PSD through the lens. Starting from the known positions of the laser source and the PSD, it is possible to calculate the distance of the surface by means of trigonometric formulas, as described by Zhang et al [8].

LTS permits the measurement of the dynamic displacement in a contactless way but inside a restricted length range depending on the transducer itself. Another issue concerning this technology is that the surface has to present particular characteristics of roughness and opacity in order to enable the correct reflection of the laser beam.

The comparison described in this work has been performed by means of a LTS model Micro-Epsilon Opto NCDT 1610-20 with a measuring range of 20 mm and a resolution of 1μm.

3. Application on Experimental Modal Analysis

In the EMA, LTS enables the measurement of the dynamic response of the system, i.e. the displacement, in a contactless way. The main issue of the exploitation of LTS for EMA is related to the fact that it does not permit the ability to perform the analysis in free conditions due to the fact that the displacement related to the system response exhibits high amplitude and may exceed the measuring range of the transducer.

The system studied is composed of a clamped circular cross section beam with a circumferential groove near one end. During the test one point at time, depicted in Figure 1(c-d), has been excited by an impact hammer (model PCB 086D05) while the response has been measured in point 6 with LTS and tri-axial piezoelectric accelerometer (model PCB 356B21) in order to extract the Frequency Response Functions (FRFs) among all the considered points.

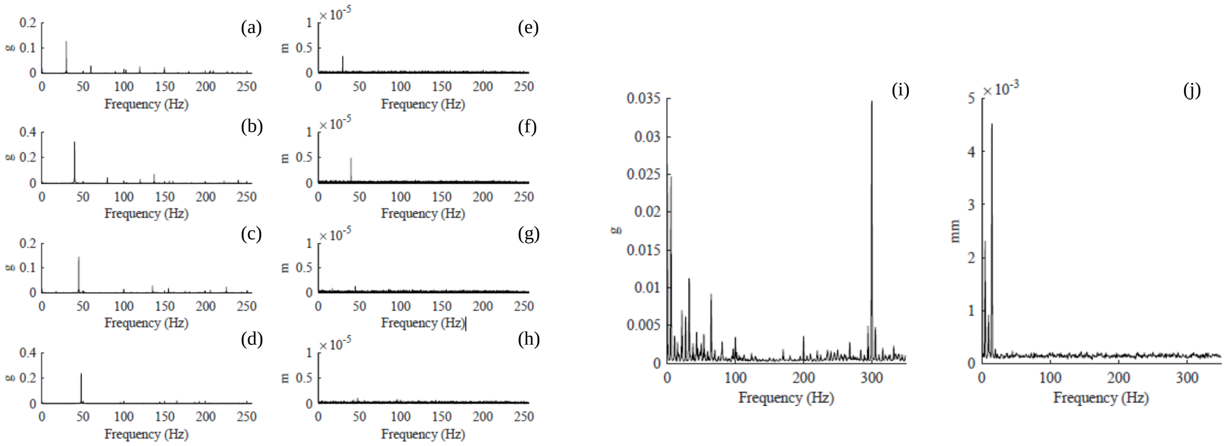

Figure 2. Spectra of (a-h) unbalanced rotor at increasing rotational frequency (from top to bottom) and (i-j) faulty gearbox from acceleration and displacement signal (from left to right).

Figure 1(a-b) report the sum of the FRFs calculated through LTS and piezoelectric accelerometer. It is possible to observe that the displacement analysis is able to extract only the first natural frequency instead of the acceleration analysis that extracts all the natural frequencies inside the considered frequency band. The comparison shows the good operation of the displacement analysis at low frequency. This restriction can be explained considering the relation between the amplitude of the spectrum of acceleration and displacement:

$$\ddot{X}(f) = -(2\pi f)^2 X(f) \tag{1}$$

where $\ddot{X}(f)$ and $X(f)$ are the spectra related to acceleration and displacement signals, respectively and f is the frequency [9]. Starting from the amplitude of the FRF-sum shown in Figure 1(b) and considering the frequency scaling factor described in eq. (1) it is possible to understand that the second natural frequency can not be detected by the LTS due to the lower amplitude of this component in the displacement spectrum with respect to the sensor resolution.

Figure 1(c-d) illustrate the modal shape related to the first natural frequency and it is possible to note that in both displacement and acceleration analysis the modal shape is represented by a bending mode along Y direction.

The value of the first natural frequency calculated by means of both displacement and acceleration analysis is around 120 Hz, as shown in Figure 1(a-c), and the two damping values are 0.68% and 0.4%, respectively. Thus, it is possible to assert that for EMA application the acceleration analysis can be replaced by the displacement analysis by means of LTS in the low frequency range, depending on the resolution of the sensor itself.

4. Application on vibrational diagnostics

The target of the vibrational diagnostics is the extraction of information regarding the healthy state of a system directly from the acquired signal. The part of the comparison presented below regards the analysis of an unbalanced rotor and a gear tooth spall made by means of both LTS and piezoelectric accelerometer (model PCB 356B21).

Figure 2(a-h) depicts the spectra calculated from displacement (e-h) and acceleration signal (a-d) at 30 Hz, 40 Hz, 45 Hz, 48 Hz. If the rotor is unbalanced, the spectrum shows the rotational frequency and its harmonics. From the comparison of the spectra in Figure 2(a-h), it is possible to note that at lower frequencies, i.e. 30 Hz and 40 Hz, the component related to the rotational frequency can be identified starting from both acceleration and displacement signal.

At higher frequencies, i.e. 45 Hz and 48 Hz, the first harmonic in the displacement spectrum is strongly masked by the background noise due to its weak magnitude.

Figure 2(i-j) compares the spectra of the faulty gearbox obtained by means of both acceleration (i) and displacement signal (j) in the range $0 - 350$ Hz. In order to perform the vibrational analysis and detect the gear fault, in the spectrum the gear mesh frequency, that for the gearbox under examination is around 100 Hz, has to be identified. It can be noticed from Figure 2(i-j) that the spectrum of the displacement is able to detect only the first harmonics of the rotational frequency but is not able to extract the gear mesh frequency. Thus the gearbox analysis can not be performed starting from the displacement signal.

In the two cases described in this section, the frequency limitation of the exploitation of LTS is related to the low amplitude of the considered component in the acceleration spectrum. Thus, according to eq. (1), the related component in the displacement spectrum exhibits a lower amplitude than the transducer resolution and consequently it can not be detected.

5. Final remarks

This work demonstrates the effectiveness on the use of LTS for vibration analysis as an alternative to the accelerometer and highlights pros and cons of this alternative sensor.

The main issue of the exploitation of LTS is represented by the relation between the transducer resolution and the frequency range in which the displacement analysis can be carried out, due to the frequency dependent correlation between the amplitude of the spectra of acceleration and displacement.

The EMA campaign demonstrates that the LTS can replace the piezoelectric accelerometer with the restrictions of the limited operative range and the need to constrain the tested object.

The same issue has been stated by the application of displacement analysis on the vibrational diagnostics. In fact, in both unbalanced rotor and gear tooth spall analysis the displacement analysis is able to identify only the low frequency components. Thus the imbalance can be detected only at low rotational frequencies and the gearbox analysis can not be performed because the gear mesh frequency can not be detected.

These problems can be overcome with higher resolution LTS or by analyzing systems with a higher amplitude response in order to extend the operative range of the transducer.

On the other hand, the main pros of the LTS regard the easier (un)mounting operations with respect to the accelerometer. Therefore it can be useful for control operations on production line, in order to meet the industrial need.

References

[1] D.J. Ewins *Modal testing: Theory,practice and application.* Taunton: Research Studies Press, (2000).

[2] W. Heylen, S. Lammens, P. Sas *Modal analysis theory and testing.* Belgium: Katholieke Univeriteit Leuven, (2003).

[3] G. D'Elia, E. Mucchi, M. Cocconcelli *On the identification of the angular position of gears for the diagnostics of planetary gearboxes.* Mechanical Systems and Signal Processing 83, (2017), pp. 305-320.

[4] P.D. McFadden, M.M. Toozhy *Application of synchronous averaging to vibration monitoring of rolling element bearings.* Mechanical Systems and Signal Processing 14, (2000), pp. 891-906.

[5] Z. Feng, H. Ma, M.J. Zuo *Amplitude and frequency demodulation analysis for fault diagnosis of planet bearings* Journal of Sound and Vibration 382, (2016), pp.395-412.

[6] R.B. Randall, J. Antoni *Rolling element bearing diagnostics - A tutorial.* Mechanical Systems and Signal Processing 25, (2011), pp. 485-520.

[7] E. Mucchi *On the comparison between displacement modal testing and strain modal testing.* Proceedings of the institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. Vol. 230, No. 19, (2016), pp. 3389-3396.

[8] Z. Zhang, Q. Feng, Z. Gao et al. *A new laser displacement sensor based on triangulation for gauge real-time measurement.* Optics and Laser Technology, Vol. 40, No. 2, (2008), pp. 252-255.

[9] J.S. Bendat, A.G. Piersol *Random Data, Analysis and Measurement Procedures.* Fourth edition, John Wiley & Sons, (2010).