684. Remote sensing of vibration on induction motor and spectral analysis

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Abstract. This paper presents experimental vibration analysis of the induction motor by applying a short-time Fourier transform *(STFT)*, which is one of the spectral analysis methods. Vibration data of a small-sized induction motor were obtained with a laser Doppler vibrometer *(LDV)*. Experimental setup was assembled in order to register motor vibrations. Data-acquisition system was employed to register the vibrations of the induction motor. *LDV* measurement data was collected when the induction motor was operating at various speeds under no-load condition. The obtained data were analyzed by means of short-time Fourier transform method. Finally, the results of analysis were interpreted to demonstrate certain vibrational behavior of the motor.

Keywords: laser Doppler vibrometer, short-time Fourier transform *(STFT)* analysis, vibration analysis of induction motor.

1. Introduction

Electrical motors are the major prime movers in industry and are the most popular for their reliability and simplicity of construction [1].

Since the apparatus driven by induction motors has important role in industry, their safety, reliability, efficiency and performance are highly important for engineers. Although induction motors are reliable, they are subjected to some failures. Therefore in the past two decades, there has been substantial amount of research to provide new condition monitoring techniques for induction motors, mostly based on analysis of vibration signals. Therefore many commercial tools are available in this area [1–3].

Laser Doppler vibrometer *(LDV)* provide the unique ability to measure the vibrations of a surface without having to attach a transducer that might locally stiffen or mass-load the structure. They have been widely employed to measure vibration on small, lightweight structures such as hard-disk drive heads, microstructures [4–6], other systems that might be modified by attaching traditional contact transducers, and also on rotating systems where contact transducers cannot easily be attached [7]. The *LDV* has been utilized with considerable success for response measurements and modal testing [8, 9].

LDV is an interferometric technique for vibration measurements on solid bodies, which determines their instantaneous velocity by observing the Doppler effect by means of a laser beam diffused by the object surface. Vibrometers based on the *LDV* technique are devices able to measure the component of the surface velocity along the direction of the incident laser beam. The basic principle behind the *LDV* technique is the Doppler effect. Vibrometers based on this principle can remotely measure surface velocities with high spatial resolution and over a broad frequency and amplitude ranges [10].

A vibrometer is generally a two beam laser interferometer that measures the frequency (or phase) difference between an internal reference beam and a test beam. The most common type of laser in an *LDV* is the helium-neon laser [11, 12], although laser diodes, fiber lasers, and *Nd:YAG* lasers are also used. The test beam is directed to the target, and the scattered light from the target is collected and interfered with the reference beam on a photo-detector, typically a photodiode. Most commercial vibrometers work in a heterodyne regime by adding a known frequency shift (typically 30–40 MHz) to one of the beams. This frequency shift is usually generated by a Bragg cell - an acousto-optic modulator.

A schematic diagram of a typical laser vibrometer is shown in Fig. 1. The beam from the laser, which has a frequency f_o, is divided into a reference beam and a test beam with a beam splitter. The test beam then passes through the Bragg cell, which adds a frequency shift f_b. This frequency shifted beam then is directed to the target. The motion of the target adds a Doppler shift to the beam given by $f_d = 2 \cdot v(t) \cdot \cos(\alpha)/\lambda$, where $v(t)$ is the velocity of the target as a function of time, α is the angle between the laser beam and the velocity vector, and λ is the wavelength of the light [11, 12].

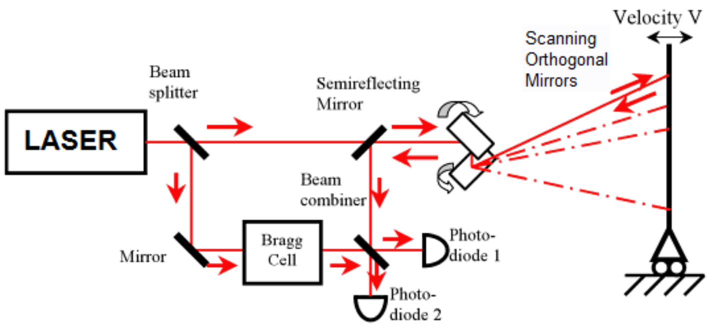

Fig. 1. Diagram of operation principle of the scanning vibrometer [13]

Light scatters from the target in all directions, but some portion of the light is collected by the *LDV* and reflected by the beam splitter to the photo-detector. This light has a frequency equal to $f_o + f_b + f_d$. This scattered light is combined with the reference beam at the photo-detector. The initial frequency of the laser is very high (> 1014 Hz), which is higher than the response of the detector. The detector does respond, however, to the beat frequency between the two beams, which is at $f_b + f_d$ (typically in the tens of MHz range).

The output of the photo-detector is a standard frequency modulated *(FM)* signal, with the Bragg cell frequency as the carrier frequency, and the Doppler shift as the modulation frequency. This signal can be demodulated to derive the velocity vs. time of the vibrating target [11, 12]. This frequency shift is then analyzed in the signal processor and is available as a velocity signal at the output in the form of an analog or digital coded voltage [10].

Unlike other remote measurement devices, the *LDV* makes the vibration measurement without mass-loading the target. It is very convenient to make non-contact mechanical vibration measurements with laser Doppler vibrometer and then perform data analysis by applying Fast Fourier Transform *(FFT)* [14-21].

2. Theory of the method and mathematical background

2.1. Laser Doppler Vibrometer

When the vibration exciter generates a sinusoidal displacement:

$$s(t) = \hat{s}\cos(\omega_1 t + \varphi_s) \quad (1)$$

The vibrometer output signal follows the relationship:

$$u(t) = \hat{u}\cos(\omega_1 t + \varphi_u) \quad (2)$$

where $\hat{s}$ and $\hat{u}$ are respectively amplitudes of the displacement and vibrometer output, ω_1 is the angular frequency of the harmonic vibration and φ_s and φ_u are respectively the initial phases of the displacement and vibrometer output [19].

The output of the two photo-detectors of the quadrature homodyne interferometer comprise an in-phase *(I)* and a quadrature *(Q)* component of the total interferometric phase:

$$u_1(t) = \hat{u}_1 \cos \varphi_{Mod}(t) \tag{3}$$

$$u_2(t) = \hat{u}_2 \sin \varphi_{Mod}(t) \tag{4}$$

where:

$$\varphi_{Mod}(t) = \varphi_0 + \varphi_M(t) = \varphi_0 + \hat{\varphi}_M \cos(\omega_1 t + \varphi_s) \tag{5}$$

is composed of the initial phase angle, φ_0, which depends on the optical path difference between the arms of the interferometer and a modulation term, $\varphi_M(t)$. Since the amplitude $\hat{\varphi}_M$ is proportional to the displacement:

$$\hat{\varphi}_M = (4\pi/\lambda)\hat{s} \tag{6}$$

and assuming that $\hat{u}_1 = \hat{u}_2$ and that there is no phase shift between the displacement $s(t)$ and the sinusoidal phase term, $\hat{\varphi}_M(t)$, a phase demodulation can be used to measure displacement [19].

2.2. Short Time Fourier transform and spectrogram

The short time Fourier transform *(STFT)* introduced by Gabor in 1946 is useful in presenting the time localization of frequency components of signals. The *STFT* spectrum is obtained by windowing the signal through a fixed dimension window. The signal may be considered approximately stationary in this window. The window dimension fixed both time and frequency resolutions. To define the *STFT*, let us consider a signal $x(t)$ with assumption that it is stationary when it is windowed through a fixed dimension window $g(t)$, centered at time location τ. The Fourier transform of the windowed signal yields the *STFT* [22-25]:

$$\mathrm{STFT}(\tau, f) = \int_{-\infty}^{+\infty} x(t) g(t-\tau) \exp[-j2\pi f t] dt \tag{7}$$

The equation maps the signal into a two-dimensional function in the time-frequency (t, f) plane. The analysis depends on the chosen window $g(t)$. Once the window $g(t)$ is chosen, the *STFT* resolution is fixed over the entire time-frequency plane. In discrete case, it becomes:

$$\mathrm{STFT}\{x(n)\} \equiv X(m, f) = \sum_{-\infty}^{+\infty} x(n) g(n-m) e^{-jwn} \tag{8}$$

The magnitude squared of the *STFT* yields the "spectrogram" of the function:

$$\mathrm{Spectrogram}\{x(t)\} \equiv |X(\tau, f)|^2 \tag{9}$$

3. Experimental setup

3.1. Induction motor specifications

In the study, a 0.37 kW three-phase asynchronous induction motor was used. The asynchronous induction motor was star connected and run under no-load condition. Its rotation speed was measured to be 2966 RPM. Label information of the asynchronous motor used in the experiment is given at the Table 1.

Table 1. Asynchronous machine label information

Motor Label Information	
3 Phase Star-Connected	Cos $\varphi = 0.83$
50 Hz	0,37 kW
2800 *d/dk*	Delta / Star**:** 220 V / 380 V Delta / Star**:** 1,7 A / 1 A

3.2. Data acquisition system

Data acquisition system was applied on a machine selected among asynchronous induction motors that can be found in Control Laboratories of Marmara University in accordance with the principal of data acquisition with *LDV*. In this study, an *OMERTON VH300 laser Doppler vibrometer (LDV)* was used.

Fig. 2. Photo from the experimental site

In Figure 2, you can see the data acquisition system of the laboratory. A schematic of the data acquisition system is shown in Fig. 3.

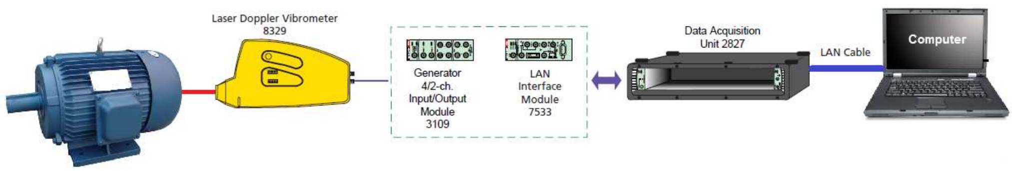

Fig. 3. Measurement scheme

4. Analysis of the system with *STFT*

The vibration of the induction motor was analyzed in the study. Data acquisition was made with *LDV* system during the analysis and the obtained data was analyzed with *STFT* and 3D apectral analysis. Fig. 4 provides the *STFT* diagram of the system. It should be noted that vibration data recorded with *LDV* are motions of a certain point on the induction motor. Furthermore, the induction motor used in the experiment was a 0.37 kW small-size asynchronous induction motor and it was run under no-load condition.

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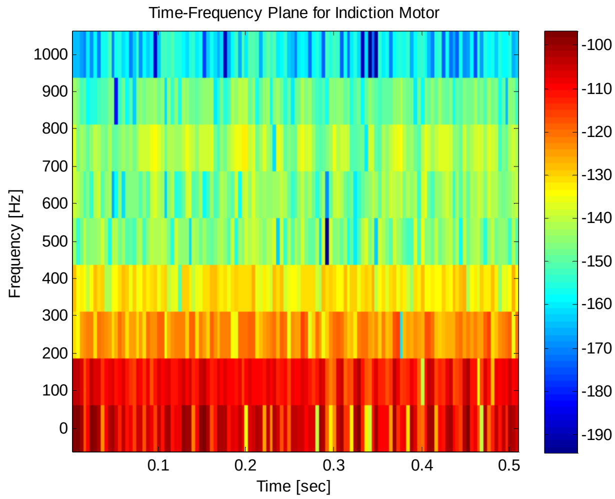

Fig. 4. *STFT* analysis of the induction motor

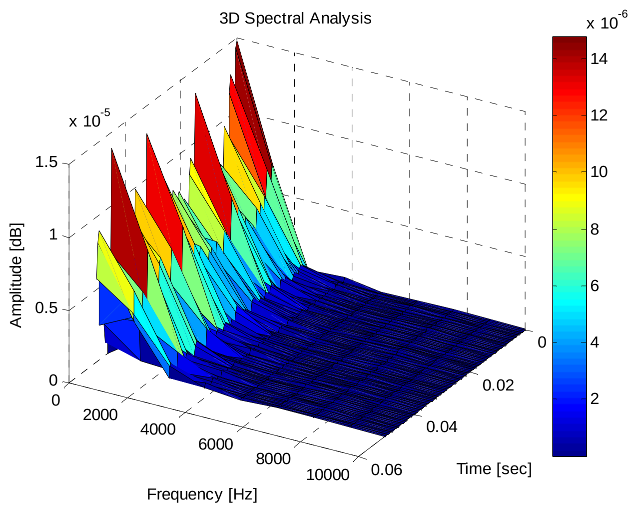

Fig. 5. 3D spectral analysis of the data obtained with *LDV*

Fig. 5 shows 3D spectral analysis of the data obtained with the *LDV*. As indicated in Fig. 1, the system does not contain any information at very high frequencies. The system oscillates at various amplitudes from 0 to 2000 Hz frequency range. Especially, on the amplitudes of 1 dB is observed that the oscillations are synchronized. At the amplitudes over 1 dB it is observed that the system oscillations are of synchronous type.

5. Conclusions

Vibration measurement with by laser Doppler vibrometer *(LDV)*, which is capable of accurately measuring point velocities from a remote position by means of interferometric techniques in mechanical systems, is one of the most effective methods. In this study, vibration data set was acquired with *LDV* when the 0,37 kW asynchronous induction motor was run under no-load condition. Obtained data were analyzed with short-time Fourier transform method. It has been determined that obtained results are meaningful and interpretations are compliance.

This study was based on two main issues. The first of these two main issues is the measurement system (measurement with *LDV*) and the second one is the analysis of data set acquired with *LDV*. During analysis, 50 Hz and the 3rd harmonic components of the asynchronous machine at basic working frequency were observed. It is concluded that other harmonics are generated by vibrations that are caused by the fixing of the machine and its run under no-load condition.

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