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Laser vibrometry measurements of an optically smooth rotating spindle

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Abstract

Laser doppler vibrometry (LDV) is a well-established non-contact method, commonly used for vibration measurements on static objects. However, the method has limitations when applied to rotating objects. The LDV signal will contain periodically repeated speckle noise and a mix of vibration velocity components.

In this paper, the crosstalk between vibration velocity components in laser vibrometry measurements of a rotating dummy tool in a milling machine spindle is studied. The spindle is excited by an active magnetic bearing (AMB) and the response is measured by LDV in one direction and inductive displacement sensors in two orthogonal directions simultaneously. The work shows how the LDV crosstalk problem can be avoided if the measurement surface is optically smooth, hence the LDV technique can be used when measuring spindle dynamics.

Keywords: Laser vibrometry; Crosstalk; Speckle noise; Spindle dynamics

1. Introduction

To be able to fully investigate the behaviour of a rotating system, such as a milling machine spindle, it is necessary to make measurements directly on the spindle during rotation. This can be done either by electronically or optically based non-contact measurement methods such as capacitive displacement sensors (DS) [1], laser distance sensors [2] or laser doppler vibrometry (LDV) [3]. The laser vibrometer is a powerful tool for measuring vibration velocities. The nature of the LDV system renders measurements without additional mass loading and allows a wide range of distances between the sensor head and the object (from millimetres up to several metres and scanning angles of about $\pm 20^{\circ}$). However, two major problems occur when performing LDV measurements on rotating objects; the presence of speckle noise and crosstalk between vibration velocity components. In some cases, a tracking system can be used, where the laser beam follows the rotating surface. Measurements on propellers and tiers have been demonstrated [4,5].

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Speckles are a random pattern of dark and bright spots formed in space when a diffusely reflective surface is illuminated by coherent light (laser light). This is a result of superimposing wavelets of light with different travelled path length due to the surface structure. The speckle noise from a rotating shaft is generated by the moving speckle pattern on the LDV detector. This pattern is repeated for each revolution and will create a repeated noise in the measurement signal, called pseudo vibrations [6]. Larger surface structures than half the laser wavelength will result in fully developed speckles. It has been shown by prior authors that the speckle noise level can be reduced or removed with different methods. By optimizing the target-detector separation within a laser vibrometer the noise level can be reduced but not completely removed [7]. The speckle noise in laser torsional vibrometry measurements can be removed by randomising the path that the laser light is undertaking during the revolutions, either by moving the laser along the shaft [8] or simply by adding a new surface structure. The latter can be achieved by continuously applying e.g. oil or some other substances to the surface during the measurement [9]. In theory this technique should also work in laser doppler measurements.

The crosstalk problem can be described as an error-term in the measurement caused by a velocity component due to the rotation [10–13]. The measured velocities of a rotating optically rough shaft in the two orthogonal directions, v_x, v_y, can be expressed as [13]

$$v_y = \dot{y} + \Omega(x - x_0) \tag{1a}$$

and

$$v_x = \dot{x} - \Omega(y - y_0) \tag{1b}$$

where $\dot{x}$ and $\dot{y}$ are vibration velocities, x and y are the vibration displacements, x_0 and y_0 are the distances to the spin axis due to alignment errors and Ω is the total angular velocity including torsional vibrations. $\dot{x}$ and $\dot{y}$ are the desired velocities to measure.

The methods for speckle noise reduction/removal described above cope with the specific speckle noise problem but are not able to neutralise the effect of crosstalk in a single beam LDV measurement. Consequently; the signal obtained during measurements under these circumstances will be a mix of the velocities in both directions.

A method for resolving the true vibrations in the two x- and y-direction using a set-up of two simultaneously measuring lasers in both directions and an accurate measurement of the rotational angular velocity has been developed by Halkon and Rothberg [13].

In [3], it is shown that the speckle noise in laser vibrometry can be avoided by polishing the surface optically smooth, i.e. the surface roughness is much smaller than the laser wavelength. The out of roundness was measured and showed a good agreement with a mechanical roundness measurement. However, the crosstalk was not investigated.

In this work, we investigate experimentally the crosstalk between the two directions (x and y), in laser vibrometry measurements of a rotating spindle with a polished surface. The spindle is excited by an active magnetic bearing (AMB) manufactured by SKF Revolve, and the response in the cross direction is measured by LDV and inductive DS.

2. Experimental set-up and procedure

Fig. 1(a) is a photo showing the AMB mounted in the milling machine table and Fig. 1(b) is a sketch of the AMB. The measurements were made in a Dynamite; 3-axis vertical table-top milling machine. The spindle (S) is capable of speeds of up to 7000 rpm. The dummy tool (DT) was mounted in a Collet holder (CH) with a Morse taper which was in turn mounted in the machine. The surface of the LDV measurement position (LMP) was polished optically smooth. The surface roughness was measured to $R_a = 0.021\,\mu m$, using a Wyko NT1100 optical profiler (www.veeco.com). The surface could be made temporary rough by spraying it with a developer for crack testing (paint). This paint could easily be removed without scratching the surface. The spindle was harmonically excited by the AMB in the x- or y-direction with electromagnets (EM) at a cylindrical segmented part of the dummy tool consisting of a ferromagnetic material (FM). The EM are arranged in two pairs opposite to each other. The vibrations of the spindle in the y-direction were measured by the vibrometer at LMP. Inductive DS within the AMB measured the displacements in the x- and y-direction simultaneously.