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CORRECTION OF OBLIQUE-ANGLE OSCILLATION FOR LASER DOPPLER VIBROMETRY

The paper proposes a correction method of the oblique-angle vibration for laser doppler vibrometry. It briefly discusses the key mathematical approach considering the surface of the analysed object to be a reference plane and gives a practical example of the method proper application. The proposed correction method is practically verified by laboratory measurement of natural frequencies and mode shapes for vibrations of high voltage transformer housing. The results are further compared to equivalent accelerometer measurement.

Keywords: *laser, doppler, vibrometry, measurement, prototype, oblique-angle, correction*

1 Introduction

Laser Doppler Vibrometry (LDV) has been primarily used in medicine [1-3] but offers a wide range of technical capabilities also in engineering applications involving contactless vibration measurement [4-8]. It has been introduced as a very sensitive method applicable for measurements that assess movements of high-dynamic components. This method is particularly important for applications where physical contact with analyzed device is not technically possible, typically rotating machines in operation, measurement of hot surfaces or surfaces under high voltage.

Commercially available LDV are typically constructed with a single beam to measure radial and axial vibrations or with parallel beams to measure pitch and torsional vibrations. Therefore, they can only collect data at one point at a time. In such a case, performing a complex modal analysis to obtain an operational deformation shape is usually a relatively long process. This problem is even more difficult for larger structures or for low natural frequency structures, such as aircraft, space structures or civil structures [9-16].

As stated in [17], the market offers several types of laser-scanning vibrometers allowing multiple points to be measured simultaneously, but they are usually very expensive and complicated. The authors of the same work [17] presented their own design of a three-dimensional measuring system visible on Figure 1 and consisting of a single point vibrometer that can redirect the laser beam using computer-controlled mirrors. The only disadvantage of the proposed system was the lack of an observation angle correction algorithm when measuring large surface from one position.

This study extends the authors' original work [17] with presenting a simple method of correcting observation angles that can be used generally for any other similar application.

2 Oblique-angle correction

In engineering, most projects require vibration measurements of relatively large technical surfaces, such as a transformer housing, building walls or similar structures. Often, there is insufficient space to install the measuring system at a suitable distance. Therefore, the laser beam senses the vibrations at the specific measuring point under a large angle. This angle changes according to measured point coordinates and the consequent correction is not an easy task.

A practical example is shown in Figure 2. The aim is to investigate natural frequencies and mode shapes for vibrations of high voltage transformer housing. The matrix of investigated points is marked with red dots. The position of the laser vibrometer is considered to be at coordinates $[x0,\ y0,\ z0]$. The arms $r1$ - $r4$ represent the distances measured (with a laser) between the vibrometer lens and all of the transformer housing corners.

As obvious, the oscillations scanned at different positions must be accordingly recalculated prior the final evaluation. The triangle seen in Figure 3 proposes the method to determinate necessary correction coefficient for any evaluated point.

Considering the surface of the transformer housing to be the reference plane, it is possible to determine the observing position by solving the set of Equations (1).

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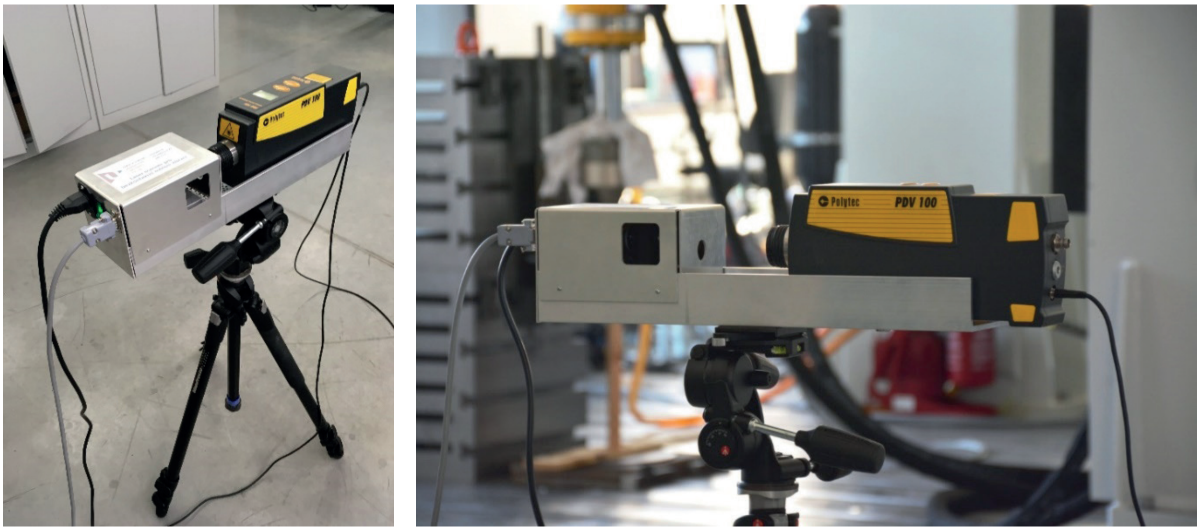

Figure 1 LDV with XY scan head [17]

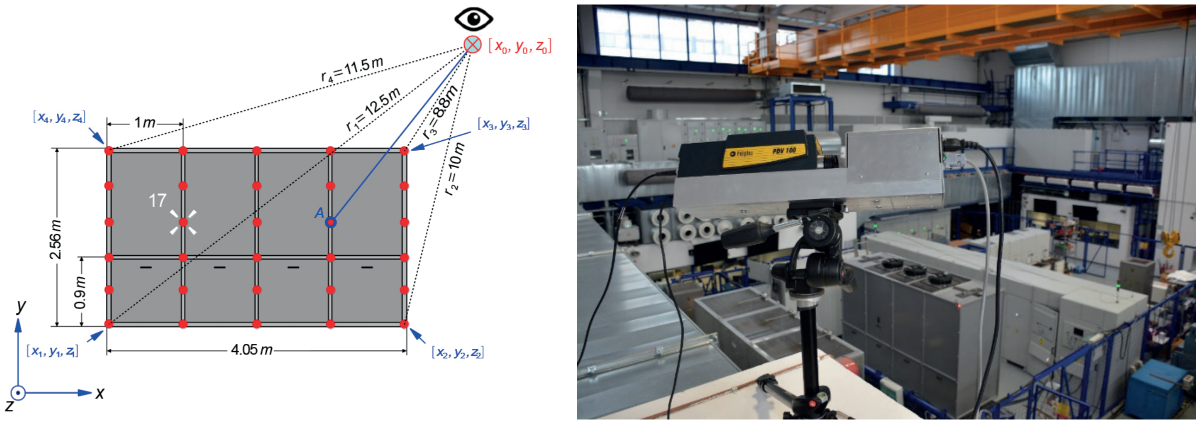

Figure 2 Practical example for the method application

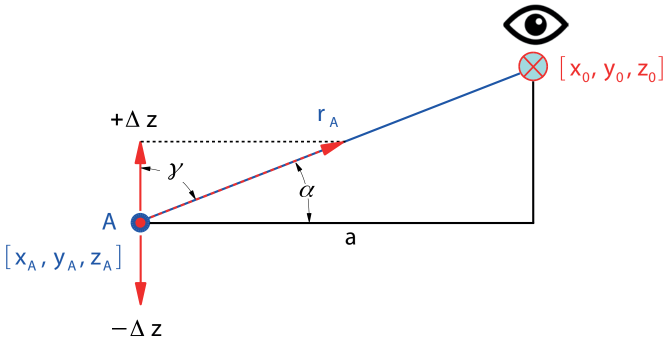

Figure 3 Correction factor determination

$$
\begin{aligned}
&(x_0-x_1)^2+(y_0-y_1)^2+(z_0-z_1)^2-r_1^2=0\\
&(x_0-x_2)^2+(y_0-y_2)^2+(z_0-z_2)^2-r_2^2=0\\
&(x_0-x_3)^2+(y_0-y_3)^2+(z_0-z_3)^2-r_3^2=0
\end{aligned}
\tag{1}
$$

In this case, Equation (1) can be rewritten according to Figure 2 into a simpler Equation (2).

$$
\begin{aligned}
&x_0^2+y_0^2+z_0^2-r_1^2=0\\
&(x_0-x_2)^2+y_0^2+z_0^2-r_2^2=0\\
&(x_0-x_3)^2+(y_0-y_3)^2+z_0^2-r_3^2=0
\end{aligned}
\tag{2}
$$

Assuming $x_2=x_3$, Equation (2) changes into Equation (3).

$$
\begin{aligned}
&x_0^2+y_0^2+z_0^2-r_1^2=0\\
&(x_0-x_2)^2+y_0^2+z_0^2-r_2^2=0\\
&(x_0-x_2)^2+(y_0-y_3)^2+z_0^2-r_3^2=0
\end{aligned}
\tag{3}
$$

By solving the Equation (3) we get the coordinates (4)-(6).

$$
x_0=\frac{x_2^2+r_1^2-r_2^2}{2x_2}
\tag{4}
$$

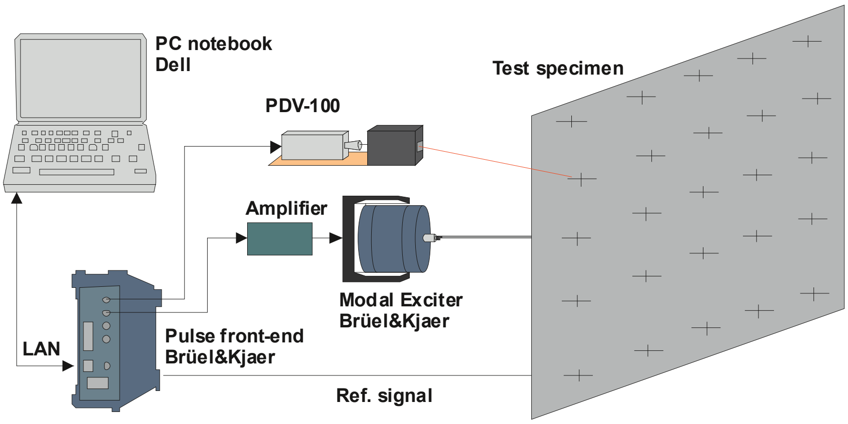

Figure 4 *Block diagram of the experimental setup*

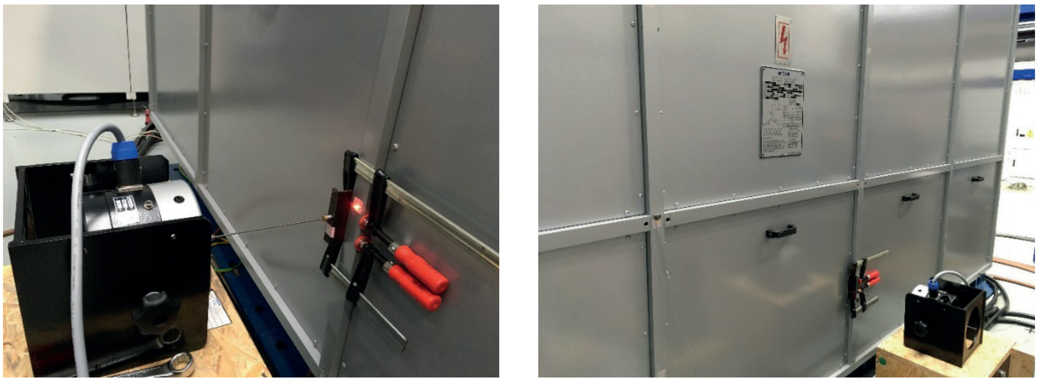

Figure 5 *Vibration generator (left), position of excitation point on transformer housing (right)*

$$y_0 = \frac{y_3^2 + r_2^2 - r_3^2}{2y_3} \tag{5}$$

$$\begin{aligned} z_{01} &= \frac{\sqrt{-x_2^4 y_2^3 - y_2^3 (r_1^2 - r_2^2)^2 - x_2^2 \left[y_3^4 + (r_2^2 - r_3^2)^2 - 2y_3^2 (r_1^2 + r_3^2) \right]}}{2x_2 y_3} \\ z_{02} &= \frac{\sqrt{-x_2^4 y_2^3 - y_2^3 (r_1^2 - r_2^2)^2 - x_2^2 \left[y_3^4 + (r_2^2 - r_3^2)^2 - 2y_3^2 (r_1^2 + r_3^2) \right]}}{2x_2 y_3} \end{aligned} \tag{6}$$

The position of the observation point is then $[x_0, y_0, z_{01}]$. Further, if the length a seen in Figure 3 is calculated as Equation (7)

$$\alpha = \sqrt{(x_0 - x_A)^2 + (y_0 - y_A)^2}, \tag{7}$$

then the angle α is given by Equation (8) and the angle γ is obtained from Equation (9).

$$\alpha = \operatorname{atan}\left({}^{z_{01}}\!/_{a} \right) \tag{8}$$

$$\gamma = {}^{\pi}\!/_{2} - \alpha \tag{9}$$

Finally, the correction factor is according to Equation (10).

$$k_r = \cos\gamma \tag{10}$$

The method can be used for any complex shape by dividing the whole surface of the analyzed object into smaller but simpler regions and applying it repeatedly. It is similar to application of the finite element method.

3 Experimental Measurement

The validity of the proposed correction method is practically demonstrated by laboratory measurement of natural frequencies and mode shapes for vibrations of high voltage transformer housing shown in Figure 2 right. A block diagram of the measurement system is shown in Figure 4.

During the experiment, the transformer housing was mechanically excited by the dynamic vibration generator (Type 4824) in the frequency sweep mode (1-100 Hz). It is a lightweight modal exciter capable of exciting oscillations

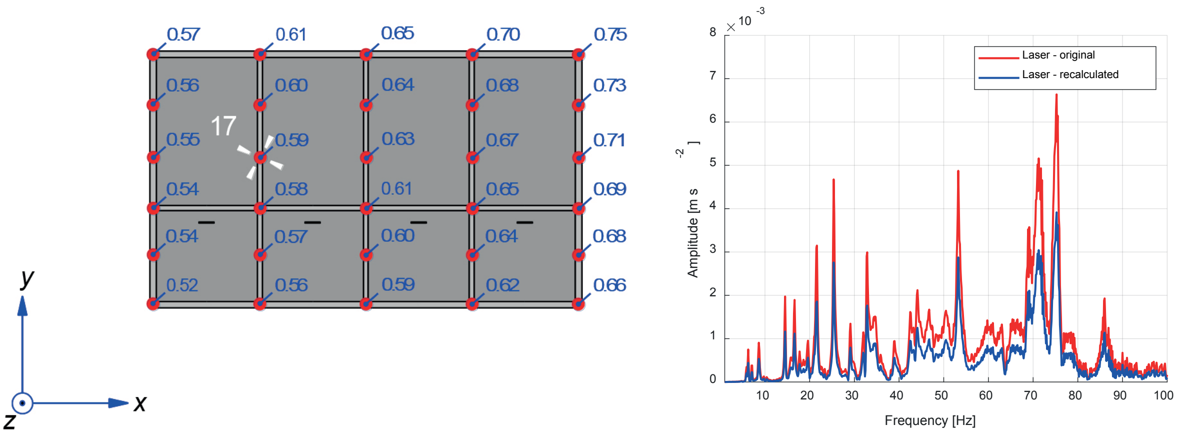

Figure 6 *The correction factors calculated for evaluated measuring points (left), the measured vibration spectrum valid for the measured point "17" (right)*

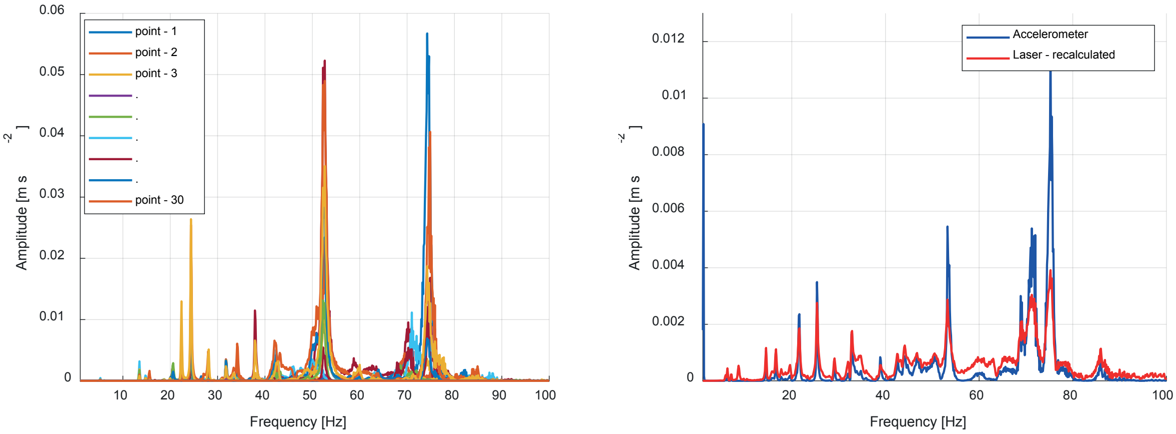

Figure 7 *Vibration spectrum measured with accelerometer at all tested points (left), comparison between LDV and accelerometer measurement performed at point "17" (right)*

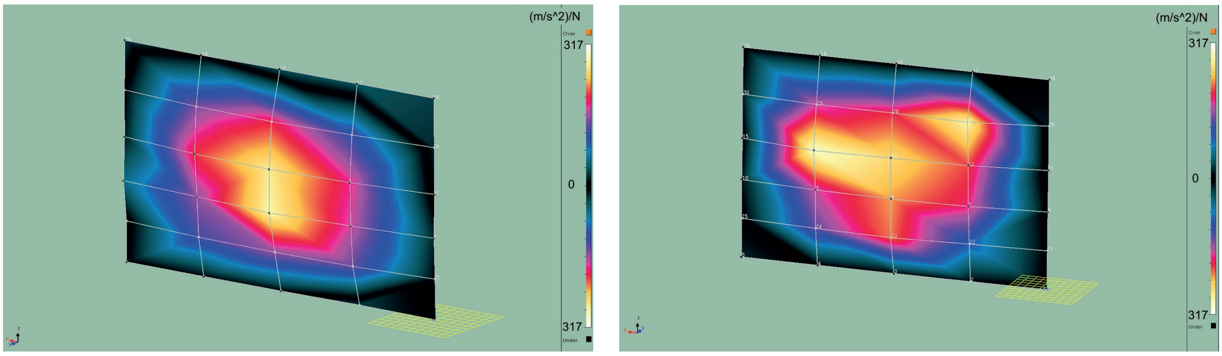

Figure 8 *Mode shape of the transformer housing at first significant frequency 5.25 Hz; accelerometer (left), laser vibrometer (right)*

with a force of 100 N. Figure 5 shows the location of the exciter along with the transformer housing being analyzed.

Measurements were repeated four times in a sequence and subsequently averaged. The transformer housing from the viewpoint of the laser vibrometer (laser targeting to the upper right corner) is shown in Figure 2.

The resulting correction factors calculated using Equations (1)-(10) are listed in the left side of Figure 6. The vibration spectrum measured at the measuring point "17" can be seen in the right side of the same figure.

An additional equivalent accelerometer measurement was performed to validate the presented results as this method is usually considered to be a reference in a given scientific field. Comparison between LDV and accelerometer measurement is shown in Figure 7. For this purpose, a constant current line drive accelerometer (4533-B) was a perfect choice due to high sensitivity, wide frequency range and low noise.

Minor inaccuracies in the frequency domain are caused by the non-linear response of the transformer housing, whose frame is manufactured from a set of aluminum structural beams interconnected with a plastic clutch assembly. Another slight difference manifested mainly at higher frequencies may be caused by the accelerometer mass. This additional weight can cause slight distortion in both amplitude and spectral regions by shifting individual antinodes.

The qualitative comparison between transformer housing mode shapes derived from results of accelerometer measurement and the LDV measurement is shown in Figure 8.

4 Conclusion

The paper has given a brief discussion on the technical background and the most important benefits of using laser Doppler vibrometry. It has proposed a correction method of the oblique-angle vibration for a vibration measurement with a laser beam. The study has brought a simple mathematical description of the analyzed geometrical problem and has shown a practical example of its proper usage. Moreover, it could be used for any complex shape by dividing the whole surface of the analyzed object into smaller but geometrically simpler regions and applying it repeatedly.

The method has been verified by a laboratory measurement performed on the high voltage transformer housing. The results have shown very good agreement between corrected LDV and the equivalent accelerometer measurement. Therefore, the proposed correction method should be considered as valid.

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