

Vision Guided Laser Tracking System for Dynamic Vibrometry using a Scanning Laser Doppler Vibrometer and ArUco Marker

Aparajita Talukder, Christian Rembe

TU Clausthal, Institut für Elektrische Informationstechnik, Leibnizstraße 28, 38678 Clausthal-Zellerfeld, aparajita.talukder@tu-clausthal.de

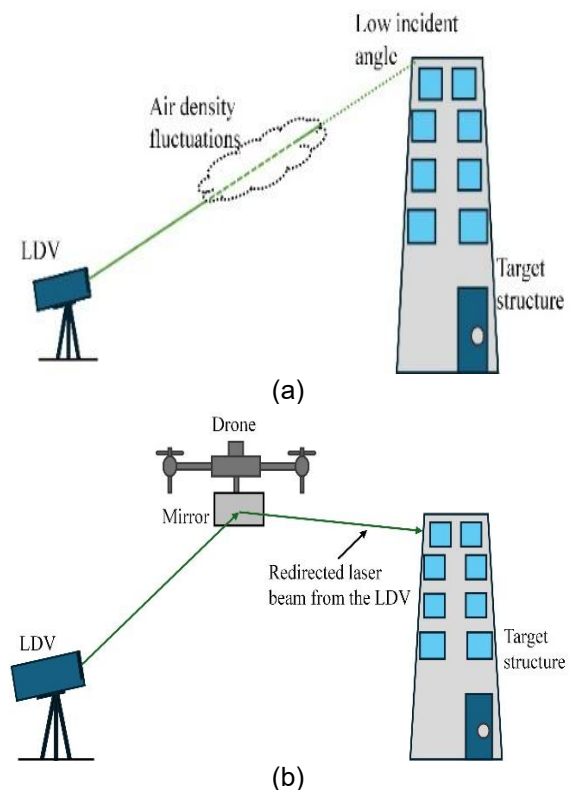
Abstract

In this paper, a vision-guided laser tracking system using a camera-based proportional feedback loop and a scanning laser Doppler Vibrometer (SLDV) is presented. An ArUco fiducial marker is used as a landmark for the system. The ArUco marker is mounted on a linear table that provides translational motion along the x -axis. The system detects the centroid of the ArUco marker at each image frame through image processing. Based on the updated centroid position, steering commands are sent to the galvo mirrors of the SLDV so that the laser beam can follow the moving target in real time. To evaluate the performance of the laser tracking system, experiments are conducted utilizing a linear table at a speed of 24 mm/s, 36 mm/s and 60 mm/s. The maximum tracking error, defined as the difference between the laser position and the marker centroid, is found to be 8 pixels (9.6 mm) at 24 mm/s, 10 pixels (12 mm) at 36 mm/s and 13 pixels (15.6 mm) at 60 mm/s speed. In addition, the root mean square (RMS) tracking error over the full measurement duration is calculated and discussed.

Keywords: Scanning Laser Doppler Vibrometer (SLDV), Image processing, ArUco marker detection, Translational Motion, Laser beam tracking.

1. Introduction

A laser Doppler vibrometer (LDV) is a non-contact measurement instrument widely used to measure surface vibrations based on the principle of optical interferometry [1, 2]. In recent years, LDV has gained increasing importance in the field of Structural Health Monitoring (SHM) [3]. However, measurements become challenging when the structure of interest is located far away from the LDV or the structure has complex geometric curves. In such cases, a ground-based LDV often cannot measure the vibration of the structure reliably [4]. This limitation mainly results from low angles of incidence and air-density fluctuations, as shown in Figure 1(a). One possible solution is to integrate a drone-mounted mirror to redirect the laser beam. This approach brings the measurement path closer to the structure and improves the angle of incidence [4, 5], as shown in Figure 1(b). To realize such a method, the measurement laser beam of the ground LDV must be able to track the drone-mounted mirror in real time during flight [5], as shown in Figure 1(c).



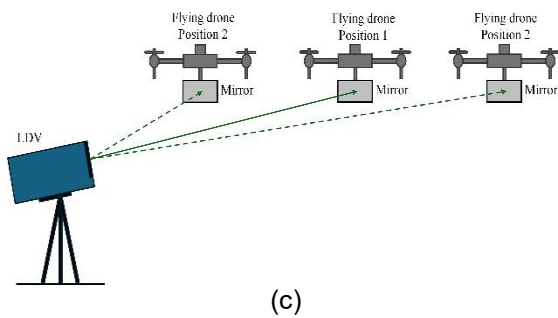


Fig. 1: (a) LDV arrangement for SHM without Flyable Mirror, (b) Introduction of Flyable Mirror to LDV arrangement, (c) Application of laser tracking in Flyable Mirror.

Several LDV configurations are available for vibration research. The choice of configuration strongly influences the design of an experiment. A conventional single-point LDV employs a stationary laser beam and measures vibration at a fixed point along the laser beam direction. A scanning LDV (SLDV) measures structural vibration at discrete points by steering the laser beam sequentially to predefined locations using two orthogonal scanning mirrors. Continuous beam motion along a prescribed path during measurement defines the continuously scanning LDV (CSLDV) mode. Active control of the measurement beam to follow the same material point on a moving object allows SLDV or CSLDV systems to operate in tracking mode [7]. In this paper, the feasibility of SLDV-based tracking is investigated through experiments on the translational motion of a linear table along the x -axis.

Conventional methods of laser tracking utilize two galvanoscanners to steer the laser beam along the x - and y -axes. Early implementations have relied on encoder-assisted synchronization and prior knowledge of the target trajectory to drive the scanning mirrors. Tracking accuracy has been evaluated in terms of the positional error between the laser beam and the target measurement point. Based on this approach, CSLDV tracking methods have been applied to rotating disks [8] and to a fan during coast-down [9] by measuring the rotational position with an encoder and synchronizing the scanning process with the rotation. In both studies, the galvanometric mirrors were driven by sinusoidal signals in the x - and y -directions generated by a digital-to-analog converter (DAC) board [8, 9]. Encoder-synchronized tracking using predefined mirror-drive waveforms was demonstrated in [10].

In [11], an encoder-based tracking system with rotor-angle feedback has been demonstrated, achieving an accuracy of ± 0.5 mm when tracking a selected point on a rotating bladed

disc. For translational motion tracking, an encoder-based laser-tracking system has been applied to measure vibrations of a pulley-driven timing belt running at approximately 4.8–5.0 m/s [12]. The target position measured by the encoder has been used to generate the set-points for two linear proportional–integral–derivative (PID) controllers that drive the scanning mirrors [11, 12].

Laser tracking without prior knowledge of the moving target has been implemented using image processing based on camera feedback. An image-based closed-loop laser tracking system has been introduced in [13], in which a charge-coupled device (CCD) camera has been employed to detect the centroid of the retroreflective tape attached to a windscreen wiper. A predictor-corrector approach has been employed to compensate for the dead time introduced by the image acquisition and processing. The study has reported a tracking accuracy of approximately ± 1.2 mm. In [14], a color-based landmark has been used to establish tracking using an SLDV. A proportional-integral (PI) control strategy has been applied to drive the mirrors. During experiments on a rotating wheel at a rotational frequency of 1\ Hz, the reported peak-to-peak error ranges from 1.8 mm to 5.2 mm. However, image-based approaches are sensitive to optical conditions. In [13], unintended bright or reflective features within the field of view of the camera can disturb the detection of the retroreflective marker. In [14], the high-intensity laser beam can alter the apparent color of the landmark when the measurement point is too close, which can compromise tracking accuracy and robustness.

This work proposes a real-time vision-guided laser tracking system that does not require encoder feedback or predefined trajectories of the moving target [12–14]. The approach is therefore suitable for objects with unpredictable motion and does not require additional sensors, since visual feedback alone is sufficient for tracking. An ArUco marker from the 4x4_50 dictionary with ID 0 is used as a landmark because its unique encoded identifier enables reliable and unambiguous detection. Consequently, the tracking process becomes insensitive to variations in laser beam intensity or spot location, as well as to the presence of other bright or similar-looking objects within the camera field of view.

This paper is organised as follows. Section 2 describes the main components used in this experiment. Section 3 presents the structure of the system. Section 4 reports the tracking results. Finally, section 5 draws a conclusion and outlines the future work of the experiment.

2. Components of the Laser Tracking System

The main component of the proposed laser tracking system is the Optomet SLDV, shown in Figure 2. The SLDV provides the measurement laser beam and enables beam steering through its internal scanning mechanism.

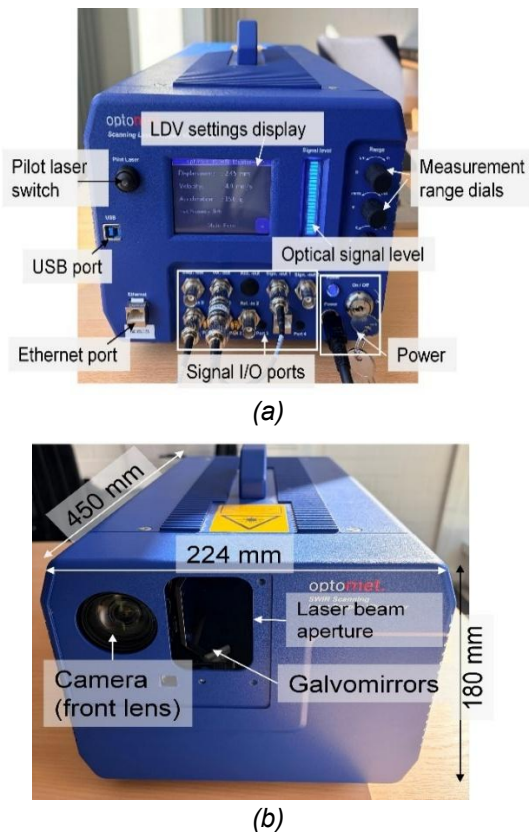


Fig. 2: Optomet SLDV (a) rear view (b) front view

The SLDV consists of two independent communication subsystems. First, an Ethernet-based subsystem provides access to the internal signal processing electronics, allowing access to the configuration of the measurement settings and transmission of the acquired measurement data. Second, a USB-based subsystem is used to interface with the peripheral components of the setup, specifically the camera, the mirror control systems, and the data acquisition unit. In this study, the USB-based subsystem has been used [15].

Figure 2(a) shows the rear view of the SLDV. It contains a touch screen display for adjusting configurations, an LED bar indicator for monitoring the optical signal level during laser focusing, and dials for selecting the displacement, velocity, and acceleration measurement ranges. The main electrical interfaces, including USB and Ethernet ports for access to the subsystems, analog signal input/output ports, a power socket, and the

on/off switch of the pilot laser, are also located in the rear panel of the SLDV.

The front view of the SLDV in Figure 2(b) shows the front lens of the integrated camera and the laser beam aperture, behind which the galvo mirrors for beam steering are located. In this paper, the integrated camera is used to provide visual feedback. It is a Complementary Metal-Oxide-Semiconductor (CMOS)-based zoom camera with full HD resolution. The camera resolution can be configured and for this experiment HD resolution has been maintained. A linear table, shown in Fig. 3, has been used to generate motion. It provides translational motion at a controllable speed and is therefore suitable for evaluating the tracking performance of the proposed system. The linear table actuator has a travel length of 400 mm and is driven by a NEMA 23 stepper motor with a screw pitch of 5 mm.

A unique landmark is required for the visual reference of the vision-guided system. A fiducial ArUco marker has been used, as shown in Figure 3. Further details of the landmark are provided in Section 3.

3. Structure of the system

The integrated camera of the SLDV provides image feedback at a frame rate of 60 fps. It continuously observes the landmark attached to the moving target and provides its position for tracking. The laser beam is steered by two galvanometer mirrors in the horizontal (x -axis) and vertical (y -axis) direction. As a visual landmark, a 4×4 , 50 mm^2 , ID-0 ArUco marker is mounted on the target. It enables reliable and unique detection of the target position. To generate controlled motion of the target, the landmark is mounted on the linear table actuator, which serves as the moving platform during the experiments. The overall configuration of the proposed system is illustrated in Figure 3.

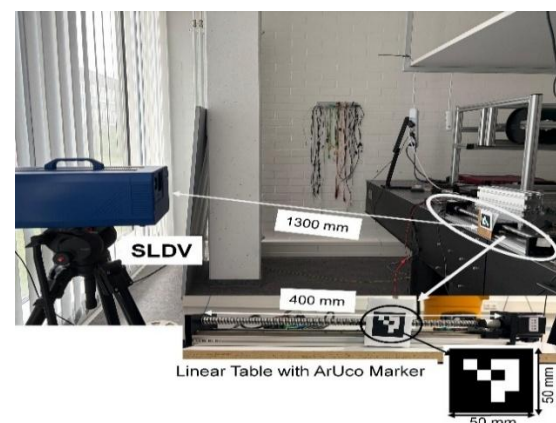


Fig. 3: Tracking system setup with the linear table and the ArUco marker.

The overall tracking integrates the following two subsystems:

3.1: image processing using computer vision

During the tracking experiments, the camera is operated in manual exposure mode to detect both the marker and the laser-beam position. For image processing, each captured image frame is first converted from blue-green-red (BGR) format to grayscale in OpenCV. A predefined ArUco dictionary provided by OpenCV is used to detect and identify the marker in the camera frame from the grayscale image. The marker centroid is used as the reference position. After detection, the four corner coordinates of the marker are extracted, and the center is computed as the mean of the corner positions. The overall image-processing procedure for ArUco marker detection is shown in Figure 4.

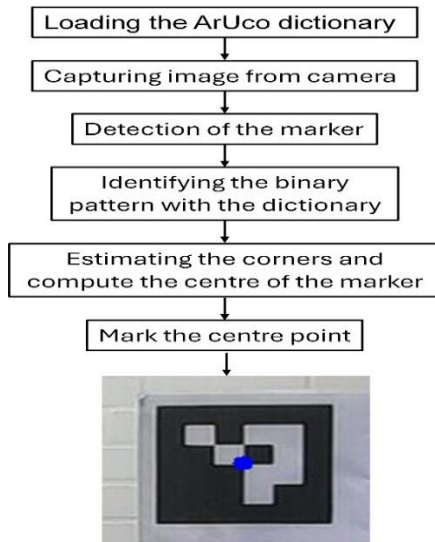


Fig. 4: Marker detection scheme

In addition, detection of the laser beam is required to verify the tracking result by comparing the laser-beam position with the marker centroid in real time. In this study, the laser-beam position is determined in each image frame by identifying the brightest pixel, while the camera exposure has been maintained at a low level to improve spot visibility. The camera is controlled via a serial interface using the VISCA protocol [16].

3.2. Mirror control

The galvo mirrors of the SLDV are precisely controlled to enable real-time tracking of the marker centroid during motion. The SLDV uses a Measurement Computing (MCC) Data Acquisition (DAQ) card to provide control output voltages to both the x -axis and y -axis mirrors within a range of ± 10 V.

Let the detected marker center in the camera image at frame k ($k = 1, 2, 3, \dots$) be,

$$\vec{P}_m(k) = \begin{bmatrix} x_m(k) \\ y_m(k) \end{bmatrix},$$

where, $x_m(k)$ and $y_m(k)$ are the pixel coordinates of the ArUco marker centroid.

If (x_c, y_c) denotes the coordinate of the image center, then,

$$\vec{P}_c = \begin{bmatrix} x_c \\ y_c \end{bmatrix} = \begin{bmatrix} W/2 \\ H/2 \end{bmatrix},$$

where, $W = 1280$ pixels and $H = 720$ pixels are the image width and height, respectively.

The ArUco marker is attached to the linear table as shown in Figure 3, so that it follows the translational motion of the table directly.

During the experiment, the displacement between the center of the detected marker and the center of the image frame is taken as the tracking error for the vision-guided control loop. The tracking error in the image plane is defined as,

$$e(k) = \vec{P}_m(k) - \vec{P}_c = \begin{bmatrix} x_m(k) - x_c \\ y_m(k) - y_c \end{bmatrix}.$$

This error is calculated in pixels. To make it independent of image resolution, the error is normalized as

$$e_x'(k) = \frac{x_m(k) - x_c}{W/2}$$

$$\text{and, } e_y'(k) = \frac{y_m(k) - y_c}{H/2},$$

Thus, e_x' and e_y' lie in the range $[-1, 1]$.

The control voltages applied to the two galvanometer mirrors are generated using proportional control:

$$V_x(k) = K_x e_x'(k)$$

$$\text{and, } V_y(k) = K_y e_y'(k).$$

Here, K_x and K_y are proportional gains where $K_x = K_y = 7$. Therefore, a proportional control strategy is implemented. Figure 5 illustrates the block diagram of the control scheme. The computed mirror-control voltages are clipped to the allowable DAQ range and subsequently converted into digital DAC commands for analog output to the scanner mirrors.

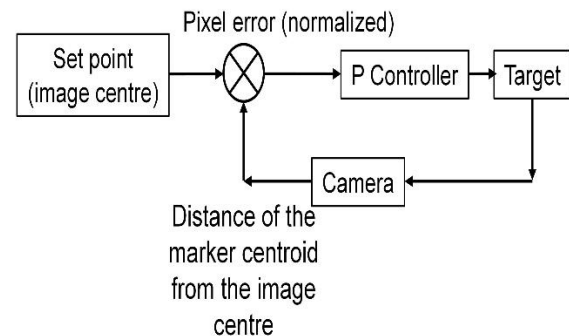


Fig. 5: The proportional control scheme.

4. Tracking result

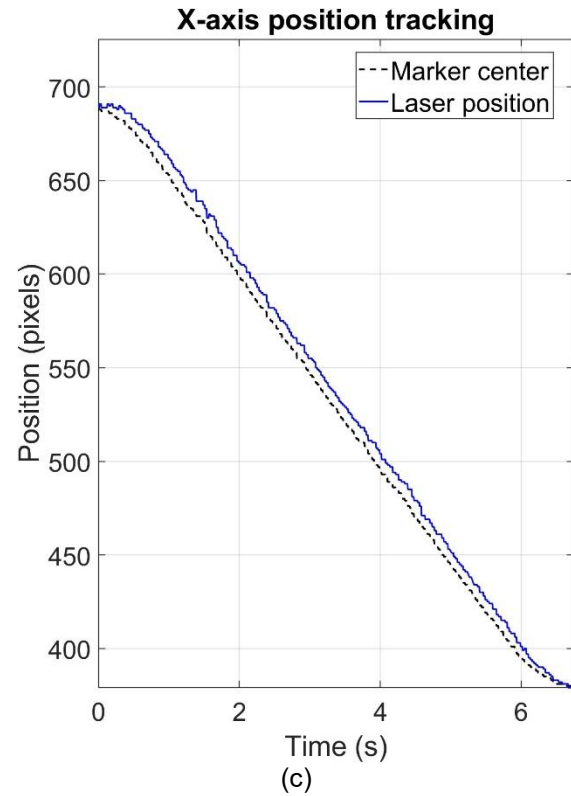
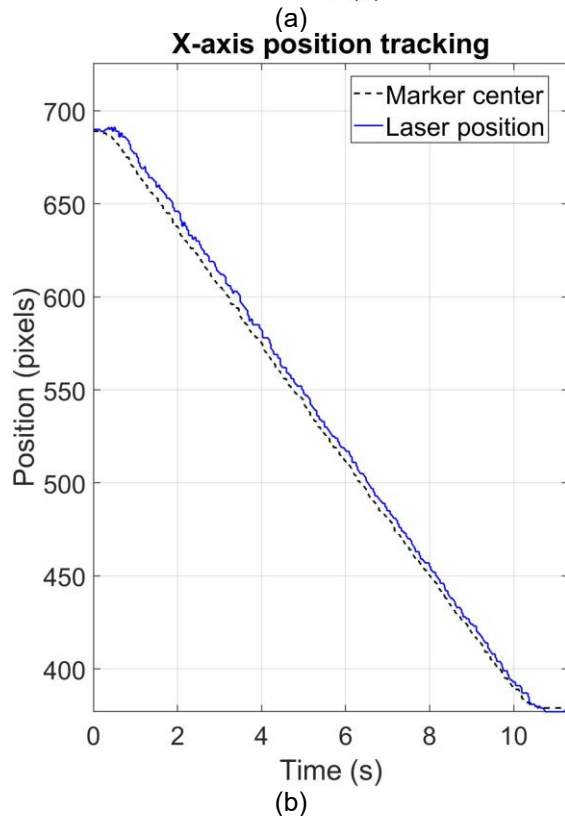
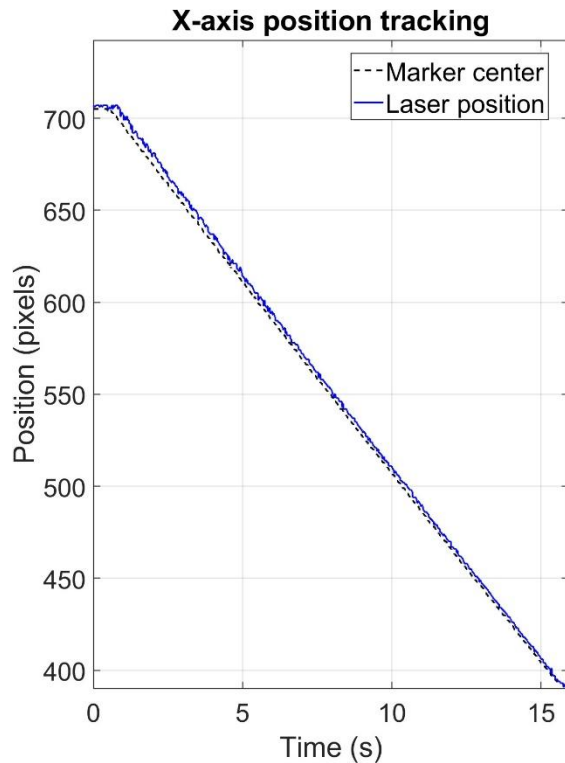


Fig. 6: Tracking performance at different translational speeds of motion - (a) 24 mm/s, (b) 36 mm/s, (c) 60 mm/s

Figure 6 illustrates the tracking performance during translational motion. The dashed and the solid lines represent the position of the center of the marker and the measured laser position, respectively, in pixels. The vertical axis in Figure 6 represents the position of the marker and the laser. The horizontal axis represents time in seconds in Figure 6. A small deviation between the target and actual laser position is visible due to the combined effect of image processing delay and mirror actuation dynamics. This deviation is defined as the tracking error. The root mean square (RMS) error is computed from the difference between the laser position and the marker position at each recorded sample during tracking. The error samples are squared to prevent positive and negative deviations from canceling each other and to assign greater weight to larger deviations. The mean of the squares is then calculated, and the square root of this mean is taken to obtain the RMS error. In the present setup, 1 pixel in the image frame corresponds to 1.2 mm in real-world distance. The marker and laser positions are recorded in integer pixels. Therefore, the tracking error is evaluated at pixel resolution.

The tracking performance is first evaluated at a linear table speed of 24 mm/s. Under this condition, the maximum tracking error is 8

pixels (9.6 mm), while the RMS error is 3.56 pixels (4.27 mm), as shown in Fig. 6(a). The experiment is then repeated at 36 mm/s, where the maximum tracking error increases to 10 pixels (12 mm) and the RMS error to 5.71 pixels (6.85 mm), as presented in Fig. 6(b). Finally, at 60 mm/s, the maximum error further increases to 13 pixels (15.6 mm), with an RMS error of 7.73 pixels (9.28 mm), as shown in Fig. 6(c). These results are obtained from the X-axis tracking data.

The summary of the tracking performance is given in Table 1.

Tab. 1: Summary of the tracking performance at different translational speed of motion: 24 mm/s, 36 mm/s and 60 mm/s

	Translational Motion		
	24 mm/s	36 mm/s	60 mm/s
Maximum tracking error, in mm	9.6	12	15.6
RMS error, in mm	4.27	6.85	9.28

5. Conclusion and Future Work

This paper has presented a vision-based laser tracking system using an SLDV, a proportional control feedback loop based on camera images, and an ArUco fiducial marker as a landmark and motorized a linear table to generate translational motion. The proportional control strategy has been successfully implemented to drive the galvo mirrors of the SLDV for laser beam steering. The result of the demonstration shows that the laser beam can follow the moving target with a small positional error. However, this approach relies on the clear and complete visibility of the landmark (ArUco marker). As a result, any short occlusion of the marker can interrupt the tracking process, which is not suitable for applications that require uninterrupted measurement with laser tracking under dynamic conditions. Future work of this study will therefore focus on the development of an advanced control strategy integrated with predictive methods to improve the accuracy of tracking at higher target speeds with enhanced robustness against temporary landmark occlusion.

References

- [1] S. J. Rothberg, M. S. Allen, P. Castellini, D. Di Maio, J. J. Dirckx, D. J. Ewins, et al., *Optics and Lasers in Engineering* 99, 11–22 (2017); doi: 10.1016/j.optlaseng.2016.10.023
- [2] P. Castellini, M. Martarelli, E. P. Tomasini, *Mechanical Systems and Signal Processing* 20, 1265–1285 (2006); doi: 10.1016/j.ymssp.2005.11.015
- [3] C. Rembe, B. J. Halkon, M. A. Ismail, *Advanced Devices & Instrumentation* 6, 0103 (2025); doi: 10.34133/adi.0103

- [4] M. Schewe, M. A. A. Ismail, C. Rembe, *Insight - Non-Destructive Testing and Condition Monitoring* 63, 280–282 (2021); doi: 10.1784/insi.2021.63.5.280
- [5] M. Schewe, M. A. Ismail, R. Zimmermann, U. Durak, C. Rembe, in: *Journal of Physics: Conference Series* 2698, 012007 (2024); doi: 10.1088/1742-6596/2698/1/012007
- [6] S. Hassani, U. Dackermann, *Sensors* 23, 2204 (2023); doi: 10.3390/s23042204
- [7] P. Chiariotti, C. Rembe, P. Castellini, M. Allen, in: R. Allemang, P. Avitabile (eds.), *Handbook of Experimental Structural Dynamics*, 1–45 (2021); doi: 10.1007/978-1-4939-6503-8_4-2
- [8] D. Di Maio, D. J. Ewins, *Mechanical Systems and Signal Processing* 24, 3013–3036 (2010); doi: 10.1016/j.ymssp.2010.06.012
- [9] M. Martarelli, P. Castellini, C. Santolini, E. P. Tomasini, *Measurement Science and Technology* 22, 115106 (2011); doi: 10.1088/0957-0233/22/11/115106
- [10] B. J. Halkon, S. J. Rothberg, in: *Proceedings of SPIE* 5503, 260–271 (2004); doi: 10.1117/12.579759
- [11] P. Castellini, N. Paone, *Review of Scientific Instruments* 71, 4639–4647 (2000); doi: 10.1063/1.1319862
- [12] P. Castellini, E. Cupido, N. Paone, E. P. Tomasini, in: *Proceedings of SPIE* 4072, 194–200 (2000); doi: 10.1117/12.386758
- [13] P. Castellini, E. P. Tomasini, *Review of Scientific Instruments* 75, 222–232 (2004); doi: 10.1063/1.1630859
- [14] D. Kim, H. Khalil, J. Nam, K. Park, *International Journal of Precision Engineering and Manufacturing* 16, 1717–1721 (2015); doi: 10.1007/s12541-015-0225-8
- [15] Optomet GmbH, *Scanning Laser Doppler Vibrometer*, <https://www.optomet.com/de/produkte/classic-serie/scanning-vibrometer/>
- [16] Sony, FCB-EV7520A Technical Manual, URL: <https://www.activesilicon.com/wp-content/uploads/FCB-EV7520A-Technical-Manual.pdf> (Accessed on 16.03.2026).