Remote 3D Laser System for Measuring Object Vibrations with Parasitic Vibration Correction

Margarita A. Deneva[1], Marin N. Nenchev[1] and Valyo N. Nikolov[2]
[1] Sci. Lab. "Quantum and Optoelectronics" and Sci. Lab."Optical and laser technologies in the automotive industry" at IMEESST
[2] Department of Transport and Aviation Engineering and Technologies
Technical University of Sofia, Branch Plovdiv, 25 Tcanko Djustabanov Str., 4000 Plovdiv, Bulgaria
deneva@tu-plovdiv.bg

Abstract – A laser-based system that enables remote detection of vibrations and displacements in structures (transport bridges, rock masses, buildings, etc.) over distances from meters to kilometers is presented. Measurements are performed in three orthogonal axes (Z – laser beam, Y – vertical, X – horizontal) using interference wedge structures. The system incorporates a high-sensitivity technique for identifying parasitic vibrations, which can be addressed either by temporary suspension of data acquisition or through post-processing methods, including signal subtraction or elimination via oscilloscope-supported filtering and analysis techniques.

Keywords – **remote 3D vibration registration; parasitic vibration correction; interference wedge system; water mirror; laser-based sensing.**

I. Introduction

We present the development of a laser-based system for remote registration using a directed laser beam to measure mechanical vibrations and translational displacements of objects - transportation bridge structures, rock formations, and buildings near road networks - at distances ranging from meters to kilometers. The system enables three-dimensional (3D) measurements by independently capturing motion components along three mutually orthogonal axes. The used for the purpose three beams are formed within internal emitter sub-block of the system and are emitted in parallel as a common bundle directed towards an opto-mechanical secondary unit block, which is rigidly connected to the vibrating object.

The three incident laser components - each aligned with one of the spatial directions - and their corresponding reflected beams, modulated with vibration information, are directed back from the respective sub-block to Block B1 – Receiver's part. This reflective return enables the extraction of vibration data from each individual component according to its directional alignment (Z, X, Y).

A key novel contribution of the present work is the introduction of a water mirror as a highly sensitive medium for vibration detection. As we demonstrate, this method enables accurate registration of the intrinsic vibrations of the object of interest, effectively minimizing interference from external sources. A major challenge in vibration measurement is the presence of parasitic signals - vibrations caused by environmental or anthropogenic activity at the location of the emitter-receiver subsystem within the measurement device. These parasitic influences can significantly distort the recorded signal, leading to a superposition of the true response of the object and the external noise.

979-8-3503-8064-4/25/$31.00 ©2025 IEEE

To address this challenge, we propose a differential measurement strategy that enables the extraction of the object's pure vibration. This approach involves a two-stage recording process. In the first stage, the total signal - consisting of both the object's vibration and the parasitic component - is registered. In the second stage, the parasitic vibration alone is recorded, under comparable conditions but without excitation of the object. Both signals are converted into electrical form using standard electronic instrumentation, and the parasitic component is subtracted from the total. The result is an accurate reconstruction of the object's genuine vibrational response. Modern dual-channel oscilloscopes provide the necessary technical functionality for implementing this method, enabling synchronized acquisition and precise signal processing in real time.

The effectiveness of this method depends on the accurate and temporally aligned registration of both signals. This requirement is fulfilled through the application of the proposed water mirror technique, which offers not only high sensitivity but also rapid response dynamics. These characteristics make it particularly suitable for use in complex experimental environments, where temporal resolution and signal integrity are critical.

A. Parasitic Vibrations in Precision 3D Sensing

To better understand the complex process of developing an effective system with both practical and scientific significance, we briefly present the current state of its main component. This component plays a key role in vibration sensing of the objects under study and holds potential for future enhancement and functional expansion.

As previously mentioned, a major challenge in vibration measurement lies in the influence of parasitic external factors that arise at the emitter–receiver section of the system. These undesired vibrations are superimposed on the main (useful) signal and lead to distortion in the registration of the actual object-specific vibration data.

In this context, the development of a highly reliable and accurate system requires specific measures to mitigate parasitic effects. This work proposes a targeted solution to that problem, focused on isolating and registering only the vibrations of the studied object. The proposed method incorporates a water mirror as a system element that helps suppress undesired disturbances.

A simpler but significantly less effective alternative is the temporary deactivation of the system during the occurrence of parasitic vibrations. Although technically possible, this approach leads to data loss and disrupts continuous recording.

A more advanced and efficient method involves separate detection of the useful and parasitic vibrations, converting both into electrical signals and subsequently eliminating the parasitic component through electronic subtraction. Modern dual-channel oscilloscopes provide the necessary technical means for implementing this approach.

To ensure the required accuracy in detecting parasitic vibrations, we have implemented a specialized technical solution that, in our view, offers particularly high effectiveness. The system integrates high-sensitivity instrumentation with the ability to initiate and terminate signal registration rapidly. Central to this configuration is the use of a water mirror, functioning as a highly sensitive vibration detection element. Further details on the system architecture are presented in the following sections.

B. Overview of the Proposed 3D Vibration Measurement System

The operating principle of our measurement system relies on the use of Interference Wedges (IWs) [1-3] as core sensing elements, with one IW employed along each of the three orthogonal spatial axes. The uses of IW as resonance structure, as construction and action, and the approach, previously proposed and described by us in earlier works [4-7], underpins our developed 3D vibration registration system. An implementation variant of the system is schematically illustrated in Fig. 1 and Fig. 2. A more detailed optical diagram of the measurement setup was originally presented in [7].

The system shown in Fig.1 comprises an emitter-receiving unit, designated as Block B1, which generates a bundle of three narrow laser beams, each ~ 1.5 mm in diameter. The incident laser bundle, denoted as Bundle, is emitted with horizontal or near-horizontal propagation and, by the system's design, is directed onto the vibrating object under investigation. The direction from the emitting-receiving apparatus to the registration object is defined as the Z direction. The bundle consists of three parallel laser beam components - BX, BY, and BZ emitted along the Z-direction. Vibration detection along the Z-axis is performed using beam component BZ, while detection in the two orthogonal directions perpendicular to Z is carried out vertically along the Y-axis with beam BY, and horizontally along the X-axis with beam BX. The registration of vibrations in all three spatial directions is performed by a secondary unit, referred to as Block B2, which is rigidly attached to the vibrating object VO, as shown in Fig. 1.

Each of the three sub-blocks of Block B2 – SbB21, SbB22, and SbB23 – possesses a corresponding optical structure incorporating an IW as its primary element. The appropriate spatial orientation of each wedge in its sub-block enables independent measurement along one of the three orthogonal directions. In each sub-block, the respective IW operates in reflection for the incident optical beam: IW1 in SbB21, IW2 in SbB22, and IW3 in SbB23. IW1 and IW2 function via direct reflection of the incoming beam, while IW3 is integrated within a more complex opto-mechanical structure of SbB23 [7].

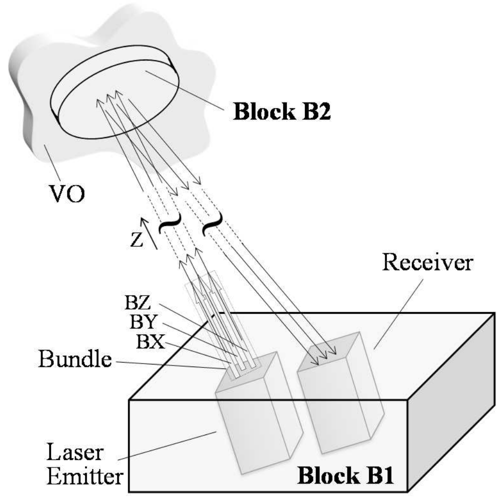


Fig. 1. Block diagram of the remote 3D vibration measurement system. VO – vibrating object; BX, BY, and BZ – parallel incident laser beams, propagating in the same direction as part of a common bundle, and directed toward the corresponding sections of Block B2 for the independent registration of vibrations along the three orthogonal spatial axes.

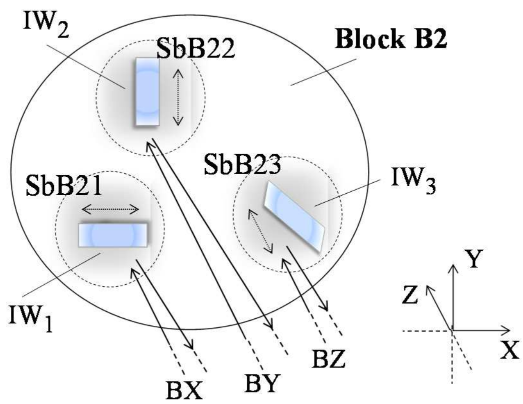
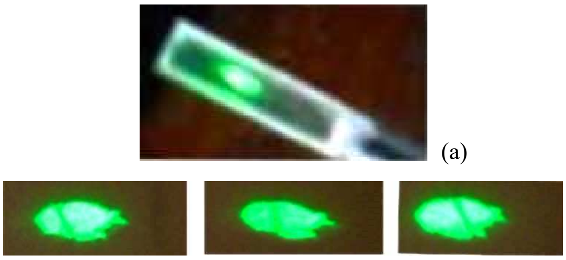


Fig. 2. Block diagram of Block B2, illustrating the incorporated sub-blocks responsible for vibration measurement along each of the three spatial directions. Each sub-block includes a corresponding interference wedge, oriented according to the respective measurement axis. BX, BY, and BZ – incident laser beams used for vibration analysis.

The IWs used (IW_1, IW_2, and IW_3) are manufactured using a conventional, well-established technique [8]. Each wedge is fabricated on a high-optical-quality quartz flat plate with typical dimensions of approximately 1–2 mm thickness and 25 × 70 mm width and length. The fabrication process involves the deposition, via vacuum sputtering or evaporation, of a dielectric mirror with ~80% reflectivity onto the quartz substrate. Over this, a transparent layer with sub-millimeter thickness and a small angular separation between its two surfaces (on the order of $\sim 10^{-5}$ rad) is deposited. A second flat dielectric mirror, also with ~80% reflectivity, is then applied to the opposite surface of the wedged transparent layer. The resulting assembly of mirror - transparent wedge - second mirror constitutes the respective interference wedge.

When illuminated by a probing monochromatic laser beam, the described IW structure forms one or more narrow (approximately 1 mm wide) indicator resonance transmission lines within the illuminated spot. These lines, dark in the reflected light, act as key markers. Depending on the specific IW configuration, either one or two resonance lines may form. In our setup, for a working wavelength of 0.57 µm, are formed two lines and the spacing between them is approximately 4 cm. These resonance lines serve two main functions: the position of a single line indicates the location of the incident beam on the wedge, while the distance between a pair of lines establishes a linear scale for remotely measuring the displacement or vibration of the wedge.

The reflected beam, now containing the dark resonance line(s), returns to the receiving unit (Block B1). Any movement of the VO leads to a corresponding displacement of the IW and, consequently, of the resonance line(s) within the illuminated spot. This shift provides information about the vibration-induced motion, as evidenced by the changing position of the resonance line within the stationary illumination spot. This dynamic is illustrated in Fig. 3, which shows consecutive positions of the reflected spot from the wedge.



(a)

(b)

Fig. 3. Photographs illustrating the optical behavior of the interference wedge (IW): (a) IW illuminated by a laser beam; (b) three consecutive reflections of the laser spot from the IW, demonstrating the dynamic motion of the object to which the IW is attached.

The registration is performed in reflection, by observing the displacement of the reflected laser spot - a method also employed in the present work. The shown example corresponds to translation along one spatial direction; analogous approaches are used for the remaining two directions.

In the arrangement, the illuminating beam from Block B1 maintains a fixed position, while the IW moves relative to it due to the object's vibration. The resonance line's shift within the reflected spot thus directly corresponds to the motion of the vibrating object. This configuration facilitates non-contact optical monitoring of vibrations through beam-based detection. The same principle applies to detecting vibrations along the Y-axis, using a configuration analogous to that used for the X-axis. In this case, vertical displacement of the resonance line within the reflected beam image indicates vibration in the orthogonal direction. The altered position of the resonance line, now shifted vertically, encodes the vibration data, which is processed by Block B1 to determine motion along the Y-axis of the investigated object. Due to the more specific way of registering vibration along Z, the direction of the incident working beam, IW_3 is in a complex configuration [7, 9, 10].

C. Approach for the detection and suppression of parasitic vibrations

In the context of remote high-precision 3D vibration registration, the presence of parasitic vibrations at the emitter–receiver stage introduces distortions that compromise the accuracy of the measured object translation. These undesirable disturbances, generally resulting from external mechanical or environmental factors, are superimposed on the useful signal and have the potential to obscure or modify the true vibration data.

To ensure the reliability of the measurement process in a remote sensing setup, a dedicated approach for detecting and suppressing such parasitic effects is required. This section outlines the conceptual basis and justification for implementing a separate registration and compensation method, which enables the isolation of the target vibration signal from interfering components.

A significant contribution of the present work lies in the proposed solution - described in detail below - for enabling separate and remote 3D vibration registration in the presence of a common undesired (parasitic) vibration occurring at the location of the three-directional laser emitter–receiver instruments of the system. A critical aspect of this approach is the accurate detection of the parasitic vibration itself. In this study, we achieve this by employing a novel technique developed by the authors: a water mirror–based solution, which has proven to be both efficient and reliable.

Parasitic vibrations present at the emitter–receiver stage introduce undesired superposition of additional vibration signals onto the probing radiation, thereby distorting the measurement of the actual motion of the remote object under investigation. These disturbances significantly affect the accuracy of the acquired data, potentially masking or altering the real vibration characteristics of the object.

A core objective addressed in this work is the extraction of a clean vibration signal - i.e., the vibrations of the target object alone, free from contamination by parasitic motion. Achieving this requires a two-part solution:

First, it is necessary to obtain a precise measurement of the total vibration, which represents the sum of both the desired (object-related) and the undesired (parasitic) components.

Second, the approach must include an independent and accurate registration of the parasitic vibration at the location of the emitter–receiver system. Only through this separation can the actual vibration of the object be isolated with high reliability.

The combined presence of both vibrational components on the return signal leads to distortion of the actual object's response and compromises the integrity of the remote measurement. However, in principle, the true object vibration can be recovered by subtracting the recorded parasitic signal from the total measured vibration. This differential method is only valid if both measurements are carried out with sufficient accuracy and synchronization.

One feasible strategy involves simultaneous registration of both the total and parasitic vibrations. In some implementations, it may be necessary to suspend the recording of the object's vibration signal at the onset of a parasitic event and resume it only after the disturbance ceases. Nevertheless, such an approach introduces data loss during the transition period.

Alternatively, modern measurement systems - such as dual-channel oscilloscopes - offer the possibility of electronic subtraction or digital processing of the two signals, allowing precise compensation without interrupting the acquisition. In all cases, the key requirement is the accurate and time-synchronized registration of both the total and the parasitic vibrations, including their initiation and termination moments.

In the following section, the practical realization of this approach is presented, including the system configuration and the specific implementation of the parasitic vibration registration using the water mirror technique.

D. Implementation of parasitic vibration suppression

In this section, we present the practical realization of our proposed solution for the precise detection and registration of parasitic vibrations in a 3D remote vibration sensing system. The method is based on a high-sensitivity water mirror technique developed by the authors. This approach offers multiple advantages, including significantly enhanced sensitivity and virtually inertia-free initiation and termination of the registration process. Importantly, the technique can be implemented using readily available, non-specialized equipment, which is discussed in detail below.

The core vibration registration configuration is technically accessible and can be readily implemented in practice. A working realization with visual display is illustrated and described here. For demonstration purposes, the system utilizes a compact semiconductor laser that emits a narrow green beam (wavelength 0.532 µm), with milliwatt-level power and a beam diameter of approximately 1.5 mm. To facilitate 3D registration, either three identical lasers can be used - each aligned with a spatial axis - or a single laser source can be integrated with an optical system of beam splitters and mirrors to produce three beams. Each beam is directed along one of the X, Y, and Z axes toward the target object for vibration sensing.

The registration method is demonstrated in detail for the vertical (Y-axis) vibration detection using a water-based reflector. The basic setup is shown in Fig. 4 (a photograph combining the principal structural elements of the system).

The water container was selected from a series of containers tested for optimum sensitivity and spread of the incident laser beam reflected from the water mirror surface. Its top water surface acts as the reflective medium – water mirror. The lightweight container, made of plastic and weighing only a few grams, has an open top, a height of 7 cm, and a square cross-section of 6 × 6 cm. It is filled with 6 cm of water, leaving 1 cm of free space above the waterline.

A flat glass plate (1.6 mm thick, 26 mm wide, and 76 mm long) is placed horizontally on the edges of the container, positioned 1 cm above the water surface. This plate plays a critical role in separating and comparing the reflection behaviour of rigid and fluid surfaces. A narrow green laser beam, with a circular spot of 1.6 mm, is directed at the beginning of the glass plate at an incidence angle of approximately 45°, resulting in a reflected beam that travels toward a screen. The portion of the incident beam that passes through the plate is reflected by the water mirror surface and falls directly onto the same screen, forming a second, highly visible spot (shown in the upper region of the image in Fig. 4, adjacent to the reference scale).

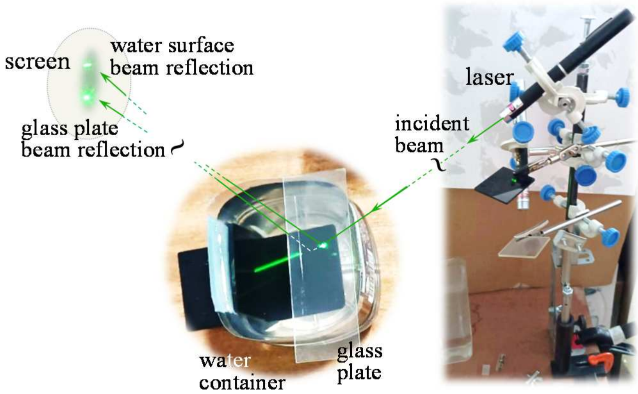


Fig. 4. Schematically presentation with the main constructing elements (laser source, water container with a glass plate, as a solid state reflector, on top of it, screen for visualisation) of the implementation scheme for registration of the parasitic vibration, shown for one direction vibration.

The entire container is rigidly attached to the vibrating object (i.e., a table top). The complete implementation for parasitic vibration registration is shown in Fig. 5, which includes all main components. A mechanical vibrator is connected to the table to simulate parasitic vibrations.

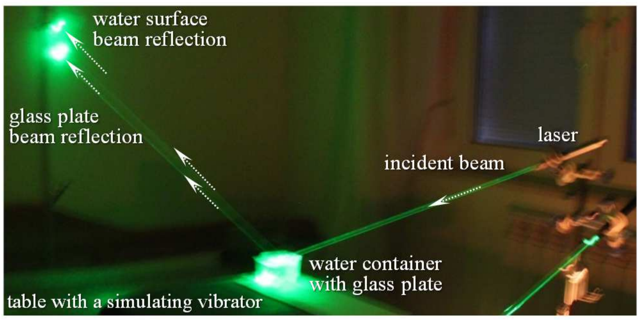


Fig.5. Photograph of the practically implemented setup for registering parasitic vibration in the vertical (Y) direction. The system includes a water container with a glass plate on top, forming part of the real experimental configuration. Laser reflections from both surfaces are projected onto a screen for visual detection of vibrational displacement.

The laser beam spot reflected from the glass plate appears in the lower part of the screen and serves as a reference, indicating the stable position of the rigidly connected container. The second spot, reflected from the water mirror surface, is clearly visible above it. When the vibrator is activated, the upper spot - corresponding to the reflection from the water mirror - begins to shift vertically.

This displacement, caused by the water mirror surface's response to the vibration, is distinctly observed in the sequential images shown in Fig. 6.

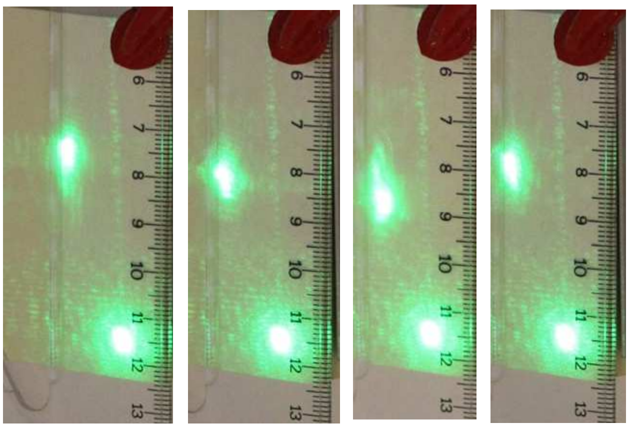


Fig. 6. Successive photographs showing the displacement of the laser beam spots during vibration. The lower spot, reflected from the rigid glass plate, remains fixed and serves as a reference for the container's position. The upper spot, reflected from the water mirror, exhibits clear vertical displacement corresponding to the object's vibration, demonstrating the high sensitivity of the water mirror to vibrational motion.

It is clearly observed that the laser beam reflected from the glass plate does not change its angle of incidence, and thus does not follow the vibrations of the container or the vibrating base. This confirms that, due to rigid coupling and low surface response, the glass reflection does not register any vibration under these conditions.

In contrast, the reflection from the water mirror shows distinct displacement, indicating its high responsiveness to vibration. Under identical conditions, the water mirror exhibits sensitivity over 10 to 20 times greater than that of the glass reflector. The laser spot from the water mirror surface undergoes visibly measurable movement, while the glass-reflected spot shows practically no deviation.

This result highlights a fundamental point of the present work: the water mirror surface acts as an extremely sensitive vibration reflector, enabling effective detection of parasitic motion. The screen-registered spot displacement provides a clear and quantifiable measure of vibration amplitude, derived from known geometric parameters such as the angle of incidence and the screen distance.

To quantify this sensitivity, an experimental procedure was implemented: a screen placed 8 meters from the reflection point registers the position of the laser spot reflected from a glass plate within the experimental setup. Subsequently, a specially selected second parallel glass plate - with only a reflective surface and a precisely defined thickness of 1.5 mm, placed on the first plate - is introduced. The distance between the two reflected laser spots on the screen defines a scale; under vibration-free conditions, this corresponded to 3.5 mm on the screen for a 1.5 mm change in level. During a set of vibration measurements, the water mirror's reflected laser spot exhibited a deviation span of 8.2 mm on the screen, corresponding to an estimated water surface level variation of approximately 3.5 mm.

The configuration with the water mirror enables highly sensitive detection of the vibrational behaviour of the entire system (in this case, the table top with the attached water container). Additional experiments with containers of various shapes and water levels demonstrated measurable responses, though with varying sensitivity. The selected 6 × 6 cm container, with a 6 cm water column, consistently produced the strongest response. Taller containers, with similar cross sections but increased height, resulted in weaker reflected beam spread and smaller amplitude. Wider containers (e.g., 10 × 15 cm base and 2–5 cm water column) yielded even smaller deflections - on the order of 1 mm - under otherwise identical conditions.

These findings confirm the optimality of the chosen container configuration in terms of vibration sensitivity. They also demonstrate how the water mirror technique can substantially enhance the vibration detection capabilities of mechanical systems. To further validate the robustness of the liquid mirror principle, additional experiments were performed using alternative fluids such as alcohol-based solutions and antifreeze mixtures. These alternatives exhibited comparable optical behaviour and provided improved freeze resistance under low-temperature conditions. Nevertheless, water remains the preferred medium due to its superior stability, safety, and ecological advantages in typical environmental settings.

Beyond the accurate determination of vibration amplitude, two additional important observations emerge from the behaviour of the reflected laser spots:

- Higher Sensitivity: Under identical experimental conditions, the water mirror demonstrates significantly greater sensitivity - by more than an order of magnitude - compared to the glass reflector that is rigidly coupled to the vibrating object. This means that even small vibrations produce a clearly visible and measurable response when reflected from the water mirror surface, while the rigid glass surface often registers little to no displacement.
- Faster Response Time: Careful observation of the laser spot displacement reveals that the registration from the water mirror begins and ends much more rapidly than that from the rigid glass reflector. In practical terms, this indicates that the water mirror is capable of responding to changes in vibration nearly instantaneously, whereas rigid reflective elements exhibit a noticeable delay due to inertia and mechanical coupling. In our experiments, the water mirror showed a response time estimated to be at least an order of magnitude faster.

These characteristics - particularly the combination of high sensitivity and fast dynamic response - demonstrate the potential of the water mirror as a highly effective tool for registering parasitic vibrations. Despite its compact dimensions (6 × 6 cm cross-section and 7 cm height), the device provides precise, real-time detection of vibration, making it suitable for a wide range of applications in remote 3D vibration sensing.

II. CONCLUSION

In the present work, we proposed and demonstrated a refined approach for remote 3D vibration registration of an object, emphasizing the necessity of identifying and compensating for undesired parasitic vibrations that affect the emitter-receiver components of the system. The developed 3D measurement scheme, based on interference wedges aligned along the three orthogonal axes, enables precise spatial tracking of translational object vibrations. However, in real-world environments, the influence of parasitic vibrations - particularly at the location of the system's emitting and receiving elements - can distort the acquired data and compromise the accuracy of the registered signals.

To address this challenge, we introduced and validated a highly sensitive method for detecting such parasitic effects using a compact water mirror configuration. The water mirror was realized as a rectangular container partially filled with water and topped with a transparent glass plate, forming a surface capable of reflecting incident laser beams. As part of the study, the dimensions and construction of the container were optimized through a series of comparative experiments involving containers of different sizes and geometries. The selected configuration provided maximal sensitivity to low-amplitude mechanical vibrations. Additional comparisons with a rigidly mounted solid reflector - a glass plate - demonstrated the superior responsiveness of the water mirror, particularly in its ability to capture the onset and termination of vibrational motion with minimal inertia.

The system's adaptability to varying environmental conditions was further confirmed through successful testing with alternative liquid media, supporting the broader applicability of the liquid mirror approach.

These features enable accurate extraction of the object's intrinsic vibration signal by separating it from the parasitic background, either via digital or analogue subtraction. The developed remote 3D vibration registration system, together with the proposed improvements, is particularly applicable to the registration of vibrations in objects associated with transport-related infrastructure - including railway bridges, segments of railway tracks, adjacent rock formations, and nearby buildings subject to vibrations caused by rail activity.

The experimental results validate the water mirror's potential for high-fidelity vibration sensing and confirm the feasibility of its integration as a reliable auxiliary element in precision vibration diagnostics. The findings suggest that this approach may find broader application in systems requiring accurate remote sensing of small mechanical displacements, especially in environments affected by structural or ambient mechanical noise.

Building upon the presented results, future research will focus on optimizing the geometric and material parameters of the water mirror element to further enhance sensitivity and stability. Additionally, the integration of automated signal processing modules for real-time subtraction and compensation of parasitic vibration signals is envisioned. The proposed method also opens possibilities for adaptation in compact portable diagnostic systems and in the monitoring of delicate or structurally sensitive objects, where conventional sensors may be insufficient or intrusive.

Future work will also focus on further miniaturization of the water mirror module and its integration into compact 3D sensing units suitable for in-field deployment. Additionally, expanded testing under real-world conditions - such as long-term monitoring of railway infrastructure and surrounding structures - will help validate the system's robustness, reliability, and applicability in practical engineering environments.

ACKNOWLEDGMENT

The authors would like to thank the Competence Center "Intelligent mechatronic, eco- and energy-saving systems and technologies" IMEESST, Lab. C8-4 "Optical and laser technologies in the automotive industry" and Sci. Lab. “Quantum and Optoelectronics” for the opportunities to perform the experiments of the article, as well as the Research and Development Sector at the Technical University of Sofia for the financial support.

This research was funded by the European Regional Development Fund within the OP “ Research, Innovation and Digitalization Programme for Intelligent Transformation 2021-2027 ”, Project CoC “Smart Mechatronics, Eco- and Energy Saving Systems and Technologies”, No. BG16RFPR002-1.014-0005.

REFERENCES

[1] M. Born and E. Wolf, *Principles of Optics*, 7th ed. Cambridge, UK.: Cambridge Univ. Press, April 2013. [Online]. Available: https://doi.org/10.1017/CBO9781139644181

[2] T. T. Kajava, H. M. Lauranto, and R. R. E. Salomaa, “Fizeau interferometer in spectral measurements,” *J. Opt. Soc. Am. B*, vol. 10, no. 11, pp. 1980–1989, 1993. [Online]. Available: https://doi.org/10.1364/JOSAB.10.001980

[3] P. Langenbeck, “Fizeau Interferometer – fringe sharpening,” *Appl. Opt.*, vol. 9, no. 9, pp. 2053–2058, 1970. [Online]. Available: https://doi.org/10.1364/AO.9.002053

[4] M. Deneva, E. Stoykova, and M. Nenchev, “A novel technique for a narrow line selection and wideband tuning of Ti:Al_2O_3 and dye lasers,” *Rev. Sci. Instrum.*, vol. 67, no. 5, pp. 1705-1713, May 1996.

[5] M. Nenchev, E. Stoykova, and M. Deneva, “Composite wavelength tunable wedged interference structures with increased free spectral range,” *Opt. Quant. Electron.*, vol. 50, no. 12, art. No 433, 2018. [Online]. Available: https://doi.org/10.1007/s11082-018-1668-9

[6] M. N. Nenchev and M. A. Deneva, “Interference wedged structure for remote and purely optical intensity control of a powerful laser beam with a low-intensity light,” in Proc. 31st Int. Sci. Confer. Electronics (ET 2022), IEEE, pp. 1-5, 2022, doi: 10.1109/ET55967.2022.9920277

[7] M. Deneva and M. Nenchev, “Laser system for remote 3D registration and measurement of vibration and translational movements of objects” *J. Phys.: Conf. Ser.*, vol. 2994, art. No 012011, 2025. [Online]. Available: https://doi.org/10.1088/1742-6596/2994/1/012011

[8] W. Demtröder, *Laser Spectroscopy*, Vol.1: Basic Principles, 4th ed., Springer Berlin, Heidelberg, 2008. [Online]. Available: http://doi.org/10.1007/978-3-540-73418-5

[9] T. A. Hall, “Fizeau interferometer profiles at finite acceptance angles,” J. Phys. E: Sci. Instrum., vol. 2, no. 10, p. 837, 1969.

[10] R. Roberts and P. Langenback, “Homogeneity Evaluation of Very Large Disks,” *Appl. Opt.*, vol. 8, no. 11, pp. 2311–2314, 1969. [Online]. Available: https://doi.org/10.1364/AO.8.002311