

Article

Fiber-Based Laser Doppler Vibrometer for Middle Ear Diagnostics

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Abstract: Laser Doppler vibrometry (LDV) is an essential tool in assessing by evaluating ossicle vibrations. It is used in fundamental research to understand hearing physiology better and develop new surgical techniques and implants. It is also helpful for the intraoperative hearing assessment and evaluation of postoperative treatment results. Traditional volumetric LDVs require access in a straight line to the test object, which is challenging due to the structure of the middle ear and the way the auditory ossicles are accessible. Here, we demonstrate the usage of a fiber-based laser Doppler vibrometer (FLDV) for middle ear diagnostics. Compared to classical vibrometers, the main advantages of this device are the ability to analyze several arbitrarily selected points simultaneously and the flexibility achieved by employing fiber optics to perform analysis in hard-to-reach locations, which are particularly important during endoscopic ear surgery. The device also allows for a simple change in measuring probes depending on the application. In this work, we demonstrate the properties of the designed probe and show that using it together with the FLDV enables recording vibrations of the auditory ossicles of the human ear. The obtained signals enable hearing analysis.

Keywords: laser Doppler vibrometer; middle ear diagnostics; coherent detection



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1. Introduction

Laser Doppler vibrometry (LDV) is currently the most accurate method for measuring displacement and vibration velocity. It has a broad range of applications in many different fields of study. In particular, it is commonly used in otology for basic research on middle ear mechanics [1–3], the nonlinearity of middle ear response to high-intensity sounds [4], evaluation of surgical procedures [5–9], e.g., those involving the implantation of middle ear devices and intraoperative assessment of hearing improvement resulting from surgical treatment [10–12]. Laser vibrometry is the only one that can measure the response of the ossicles of the ear in pulsed laser auditory evocation studies, as other methods are not sensitive enough [13]. LDV methods enable contactless measurements over a wide frequency range at a precisely selected point [14–16]. Therefore, they are the gold standard for cadaveric research. However, the scenario differs in in vivo testing, where despite numerous studies conducted, the utilization of LDVs remains relatively uncommon.

One of the main disadvantages of the LDV is the requirement for straight-line access to the measured point, due to the free-space laser beam propagation. This implies placing the LDV device at a certain distance from the patient (e.g., 0.5 m [17]), which makes it very difficult to use such a device in the operating room, where the space around the patient's head is filled with apparatus (including a microscope), a set of surgical instruments, and, above all, must allow free movement by the surgeon. Placing the LDV close to the patient's head is virtually impossible, thus representing a limitation of the

method's use in in vivo studies. Our previous article [18] details the impact of this limitation when measuring vibrations of the ossicles of the middle ear using classical surgical access (posterior tympanotomy). These limitations especially apply to measurements of the mobility of the stapes plate—the last element of the bone chain system of the middle ear. Measuring vibrations at this location is extremely important, as this element transmits vibrations directly to the inner ear.

Developments in endoscopic techniques for middle ear surgery provide insight into hard-to-reach areas, offering an alternative to extended microscopic access [19]. Instead of widening surgical access, endoscopic techniques use optics that can be viewed at different angles along with appropriately curved instruments. The development of a handheld vibration probe with a curved tip for vibration measurement would meet the expectations of such procedures. To our knowledge, there is no straightforward method of integrating classical LDVs with endoscopes that have been successfully used in middle ear surgery, as highlighted in [20].

This paper proposes using a fiber-based laser Doppler vibrometer (FLDV) with a handheld probe (HP) for middle ear diagnostics. This device combines the advantages of classic vibrometers with the flexibility of optical fibers. Our solution requires placing only a probe, about the size of a surgical scalpel, in the surgical field, connected via two optical fibers to the vibrometer's central unit, which can be placed even outside the operating room. The main focus of the study was on analyzing the properties of a middle ear diagnostic device consisting of a special handheld probe cooperating with a self-made four-channel fiber-based optoelectronics vibrometer [21,22]. It is shown that it is possible to perform this diagnosis effectively using the mentioned probe and one of the channels of this vibrometer. The article details the concept of making the probe and presents the results of its tests that are most relevant to its use in measuring vibrations of the middle ear ossicles. A comparison was made between the probe and the universal head with collimators, with which the vibrometer is equipped by default. This analysis provides a better understanding of the results of the vibration testing of the ossicles, which were presented in an earlier article [18], and, in particular, allows us to outline further plans for developing the device.

The proposed solution enables measurements to be taken in hard-to-reach areas, such as the stapes plate with classical access to the ear (posterior tympanotomy). The results obtained are promising and very relevant to the application of the device for both in vivo operation and integration with an endoscope.

2. Fiber-Based Laser Doppler Vibrometer

2.1. The Concept of FLDV

The concept of an FLDV involves the use of a wavelength at 1550 nm, which is eye-safe radiation, commonly used in telecommunications technologies. A schema of the FLDV is illustrated in Figure 1. The coherent light source is a laser diode pigtailed to a single-mode fiber. The laser beam is then split by coupler 1 into measuring and reference beams in the ratio of 99:1. The reference beam is shifted in frequency, typically by a few tens of megahertz, using an acousto-optic (AO) Bragg shifter. The analyzed object is illuminated pointwise using a collimator (measuring beam). If the object moves, the light scattered from its surface changes frequency due to the Doppler effect. The second collimator introduces part of this scattered radiation into the fiber. The polarization controller allows for improved interference efficiency.

Scattered light, which typically exhibits a power 5–6 orders of magnitude lower than the illuminating radiation, is combined with the reference beam in coupler 2. A coupling ratio was set to 10:90. An erbium-doped fiber amplifier (EDFA) is employed for additional signal amplification before photodetection. This represents a further advantage of using 1550 nm radiation. The interference of the measurement and reference beams on the photodetector results in a frequency-modulated signal with a carrier frequency equal to the frequency of the generator powering the AO shifter.

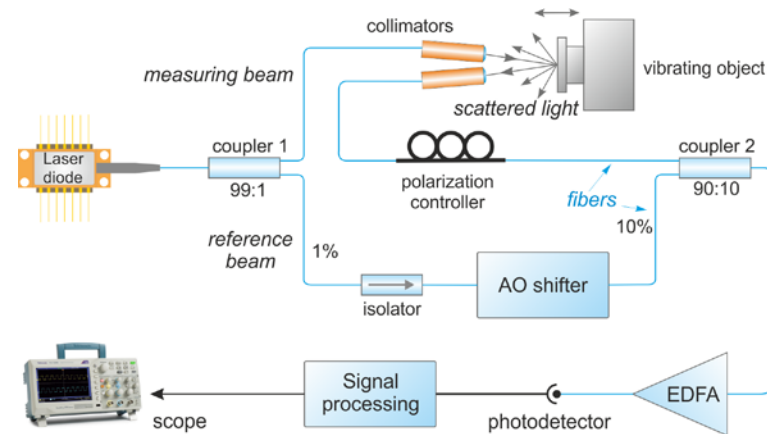


Figure 1. The concept of a fiber-based vibrometer (AO—acousto-optic, EDFA—Erbium Doped Fiber Amplifier, Fibers—standard single mode fibers).

When the target is in motion, displacement $s(t)$ results in a phase modulation $\varphi(t)$ that can be expressed as follows [23]:

$$\varphi(t) = \frac{4\pi}{\lambda} s(t), \quad (1)$$

where λ represents the wavelength of the laser.

As a consequence of the fundamental relationship for circular velocity $\omega(t) = d\varphi(t)/dt$ and for the linear velocity of the target $v(t) = ds(t)/dt$, we obtain the corresponding frequency shift $\Delta f(t)$ about the center frequency:

$$\Delta f(t) = \frac{2v(t)}{\lambda}. \quad (2)$$

The heterodyne signal from the photodetector is directed to the signal processing block, which contains the signal conditioner and demodulators (phase or frequency). Following phase or frequency demodulation, a signal with an amplitude proportional to the object's displacement or velocity is obtained, respectively.

2.2. Vibrometer Parameters

Based on the concept above and the WDM (Wavelength Division Multiplexing) technique, the Laser and Fiber Electronics Group (LFEG) at Wrocław University of Science and Technology (WUST) team devised and constructed a prototype of a four-channel, universal FLDV, which is detailed in [22,24,25]. Compared to the concept in Figure 1, the prototype uses coherence path equalizers and electrically variable optical attenuators (EVOAs) and replaces standard photodetectors with balanced photodetectors to achieve more efficient interference and lower noise. This device is capable of simultaneously measuring vibrations at four distinct measurement points.

Figure 2 depicts a photograph of the ready-to-use, four-channel FLDV. On the left is a set of four measuring heads mounted on a tripod. On the right side, the central unit of the vibrometer is located. Communication with the vibrometer is carried out through two applications developed in the LabView environment. In the first application, it is possible to control the operation of the vibrometer, primarily by turning the measurement channels on/off, selecting the type of demodulator (for each channel separately), changing the position of the receiving collimator in the measuring head, and reading the power level of the scattered signal.

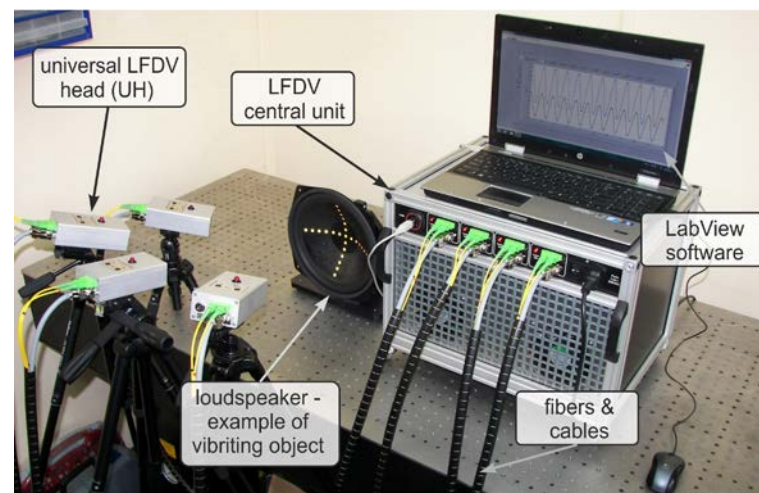


Figure 2. The four-channel FLDV that was made at WUST [18].

The second application is dedicated to data acquisition and processing. It allows setting the acquisition system parameters, calculating displacement from phase demodulator data, calibrating FM demodulators, digitally filtering, presenting results in graphs, and saving data to a file.

The basic parameters of the constructed vibrometer are summarized in Table 1.

Table 1. Main parameters of FLDV.

Parameter	Value
Number of channels	4
Operating wavelengths	1549.32, 1550.12, 1550.92, 1551.72
Number of demodulators	3 (one phase, two frequency)
Range of measured vibration velocity [m/s]	0–5
Frequency of measured vibration [Hz]	0.1–500 k
Dynamic range (displacement measurement) @ 1 kHz	70 pm–400 μ m
Measuring distance [m]	1 mm–2.5 m (depending on the probe)
Distance between the head and central unit of FLDV	up to 10 m—depending on fibers and coherence equalizers length
Auxiliary laser radiation (observation of the analysis points)	635 nm (red)

3. Fiber-Free Space Interface

3.1. Universal Head

In contrast to conventional volumetric laser vibrometers, the FLDV comprises two principal subsystems: the central unit and the set of heads that constitute the fiber-free space interface (Figure 2). This configuration allows for the heads to be interchangeable, depending on the intended application. The device is equipped by default with four universal heads (UHs), which facilitate the output and input of the light to the fiber via collimators with Gradient-Index lenses (Opto-link, WD—working distance 300 mm, $\phi = 3.2$ mm, IL—insertion losses of less than 0.6 dB). The transmitting collimator is positioned centrally, while the receiving collimator is mounted on a movable beam, whose position is adjusted by a stepper motor (Figure 3).

The measurement range of the presented head is 0.1–2 m. When the FLDV is used in conjunction with these heads, it is possible to search for the optimal position of the output collimator automatically. This is achieved by employing a specialized algorithm in LabView that searches for the maximum power of the scattered signal. Although the dimensions of the head ($70 \times 40 \times 130$ [mm]) are significantly smaller than those of volume vibrometers, they do not significantly enhance the comfort of middle ear examinations compared to

traditional LDVs. This is because the head remains an element that cannot be held by hand; it must be situated somewhere in the space above the patient.

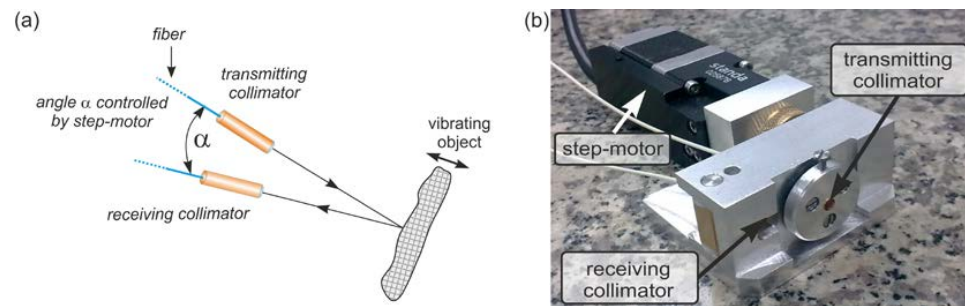


Figure 3. Default (universal) motorized FLDV head: (a) an idea; (b) a real photo.

3.2. Handheld Probe

After consultations with medical professionals, it was determined that the optimal configuration for the in vivo examination of auditory ossicles is a probe held by the surgeon in hand, approximately 5 mm from the examined object. Therefore, we developed a miniature handheld probe (HP) based on single-mode fibers.

The initial concept involved the insertion of two single-mode (SM) polymer-coated fibers, with a diameter of 250 μm each, into a metal injection needle and their fixation with an adhesive. Two significant challenges were identified: the axial misalignment of the fibers following insertion and contaminants on the fiber fronts associated with the glue, necessitating polishing. Consequently, it was decided to use a ceramic ferrule (CFX270-10, Thorlabs Inc., Newton, New Jersey, United States) with a length of 10 mm and three optical fibers. Three standard single-mode fibers with a cladding diameter of 125 μm were glued into the ferrule (Figure 4). During the ear measurement, only two fibers are used (for sending and receiving light).

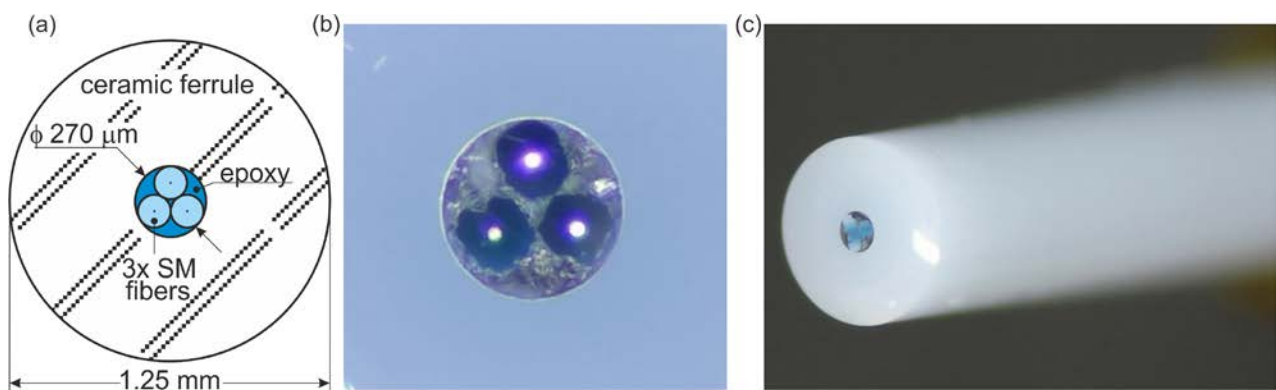


Figure 4. Ceramic hand probe tip: (a) the design; (b,c) photos.

The ferrule was secured within a brass tube with an outer diameter of 2.5 mm and a length of approximately 12 cm. The face of the ceramic ferrule was polished. Following consultation with the surgeons, the metal tube was bent at an angle of approximately 7 degrees with a radius of curvature of approximately 50 mm to provide more convenient access to the middle ear structures (Figure 5). The probe was initially evaluated by analyzing the beam profile in the far field (beam profiler: BP109-IR, Thorlabs Inc., Newton, NJ, USA) after introducing 1550 nm light.

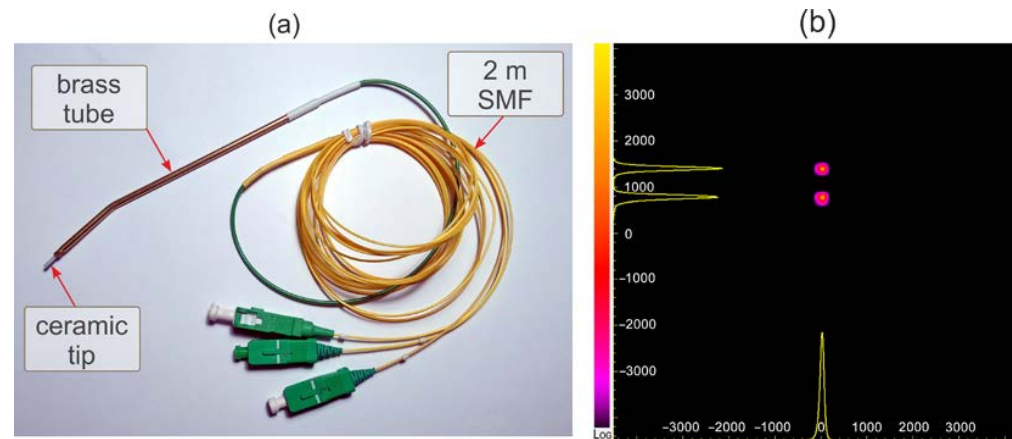


Figure 5. Handheld probe (HP): (a) photo; (b) far-field beam profiles (samples: 3760, target scan rate: 10 Hz, resolution $2.4\ \mu\text{m}$, 9.68 fps).

3.3. Collimators vs. Fibers

The profile of the light beam emitted from the collimator was compared with the profile of the beam emitted by a typical single-mode fiber with numerical aperture (NA) at level 0.11. The results of the measurements conducted using a beam profiler BP109-IR (Thorlabs Inc., Newton, NJ, USA) are shown in Figure 6. The range of the probe using fiber is limited due to the high divergence of the beam.

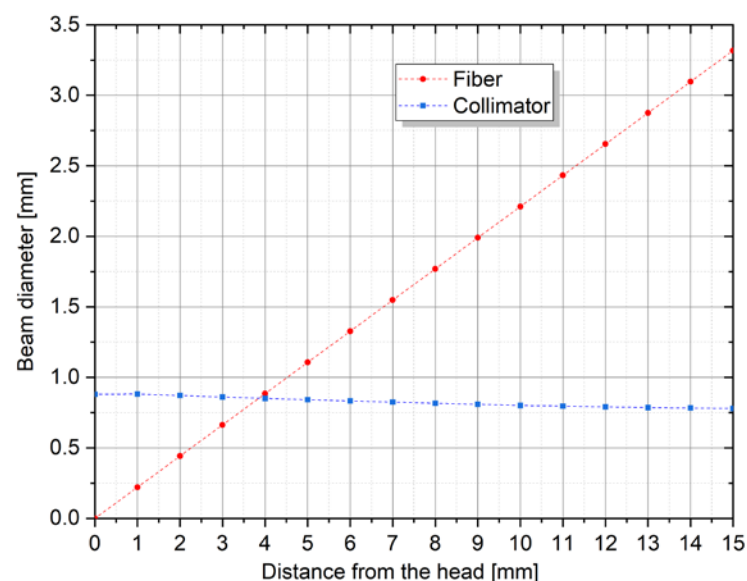


Figure 6. Comparison of the beam's diameter emitted from a fiber and a collimator.

The most important parameter of the vibrometer head is the amount of light collected from the sample. A comparison was made between the UH mounted on the FLDV (Figure 2) and the HP. The scattering surface (retroreflective 3 M sticker, Figure 7) was illuminated using a collimator (UH) or one of the fibers (HP). In both cases, the light source was a DFB laser diode @1550.12 nm with a power of 20 mW.

The signal scattered on the object was collected via the receiving collimator (UH) or the second fiber (HP), respectively. Given that the minimum distance from the test object for the UH is a few centimeters (due to the mutual position of the collimators in the head), the object was placed 10 cm from the head, and the collimators were initially aligned (Figure 8) and tuned to maximum power via the X and Y screws. Then, measurements were conducted with a step size of 0.5 mm along the Z-axis to quantify the scattered power

reaching the receiving collimator over a range of distances from the head: $10 \text{ cm} \pm 7.5 \text{ mm}$ ($\Delta z = 15 \text{ mm}$).

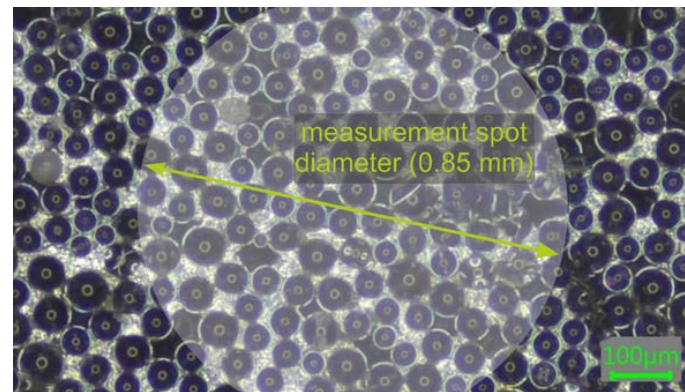


Figure 7. Retroreflective sticker with glass beads.

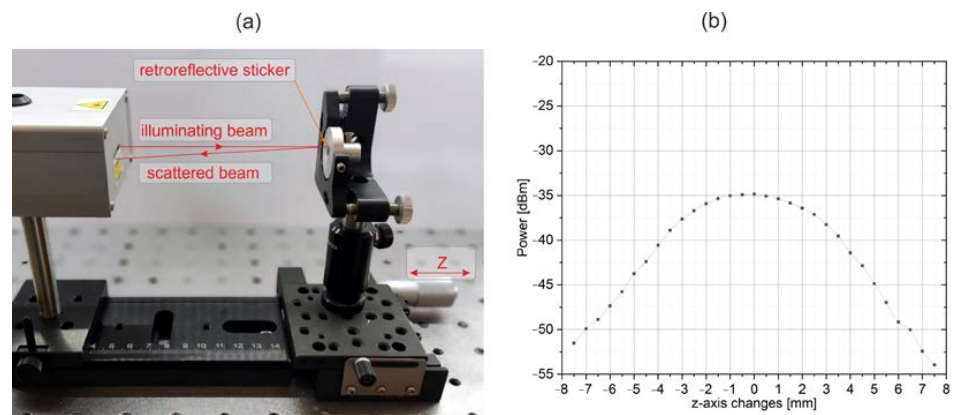


Figure 8. Measuring the power of scattered light returning to the system: (a) setup with universal head (UH); (b) results.

For HP, the measurements were performed similarly for the same variation interval of $\Delta z = 15 \text{ mm}$ (the distance from the ceramic ferrule was changed in the 0–15 mm). For this probe, an additional series of measurements was taken, in which the tuning to the maximum power was performed after each alteration of the distance rather than solely at the commencement of the measurements (Figure 9).

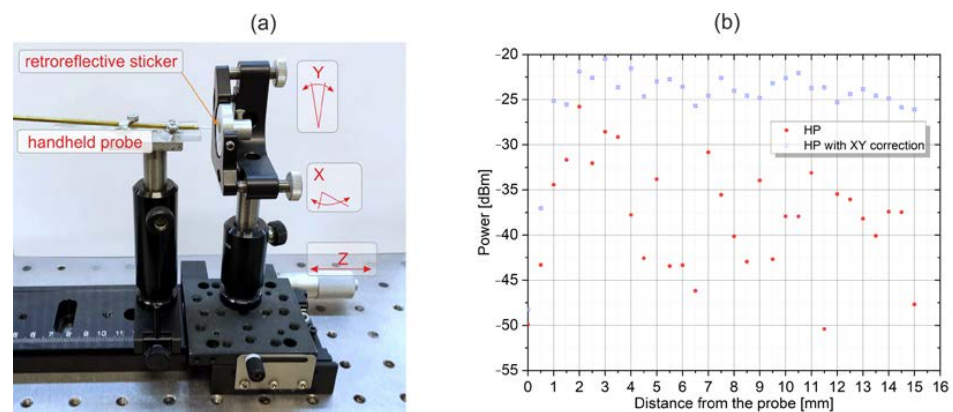


Figure 9. Measuring the power of scattered light returning to the system: (a) setup with handheld probe (HP); (b) results.

In the case of UH with collimators, a smooth curve was obtained. In this case, the changes in the power of the scattered signal result from alterations in the coverage of the transmit and receive beams with a change in the Z axis. In the case of the probe with fibers, large power fluctuations (approximately ~25 dB) were observed when changing the distance from the object. In each Z position, achieving a higher optical power was possible than in the case of UH, but the system had to be tuned along the X and Y axes. The sensitivity of the receiving system depends on the aperture of the observing system and the size of the speckles on its surface. Statistically, the average speckle size $\langle\sigma_0\rangle$ in the fully developed speckle pattern is given by [26–28]:

$$\langle\sigma_0\rangle = \frac{2\sqrt{2}\lambda z}{\pi D}, \quad (3)$$

where λ is the laser wavelength, z is a target surface to observe plane separation distance, and D is the Gaussian beam spot diameter. Table 2 summarizes the number of speckles observed by a standard single-mode fiber and a collimator (the collection area determined by the aperture was divided by the average speckle area).

Table 2. Handheld probe (HP) and universal head (UH) comparison.

Parameter	HP	UH
D —beam spot diameter [mm]	0.85	0.85
z [mm]	4	100
λ [nm]	1550	
$\langle\sigma_0\rangle$ [μm]	6.56	164.1
A —aperture [μm]	9	900
Number of speckles: $A^2 / \langle\sigma_0\rangle^2$	1.88	30.1

One of the main properties of specks is their high contrast [29]. Because of this, with a small number of specs observed by the receiving system (single-mode fiber), even minor alterations result in significant power fluctuations. In the case of the fiber terminated with a collimator, about 30 specs are observed, which makes the system considerably more resistant to power fluctuations due to changes in probe position.

4. Vibration Measurements of the Middle Ear Ossicles—Experimental Results

The classic surgical approach to the middle ear preserves the tympanic membrane via posterior tympanotomy. This entails accessing the middle ear structures via a narrow aperture situated a few centimeters deep into the mastoid process, as shown in Figure 10.

The dimensions of this opening preclude the possibility of inserting two collimators into the middle ear, specifically a transmitting collimator and a receiving collimator, each with a diameter of several millimeters, while maintaining an appropriate angle between them. For this reason, attempts have been made to design and manufacture a probe of the smallest possible size without collimators.

The obtained research results served as the basis for conducting vibration tests of the middle ear ossicular chain using FLDV and were presented in detail in our previous paper [18]. Instead of the UH, an HP was connected to one of the vibrometer channels. A calibrated ER-3A insert earphone (Etymotic Research, Elk Grove Village, IL, USA), powered by a programmable arbitrary waveform generator (DG1062Z, Rigol Technologies Inc., Portland, Oregon, United States), was used for ear stimulation. The stimulating signal consisted of four component frequencies: 0.5 kHz, 1 kHz, 2 kHz, and 4 kHz, with amplitudes determined based on the Interacoustic AD629 audiometer (Interacoustic, Middelfart, Denmark) calibrated following ISO 389-1:1998 standards [30]. The sound pressure level at the eardrum was determined based on the Real-Ear to Dial Difference (REDD) values [31].

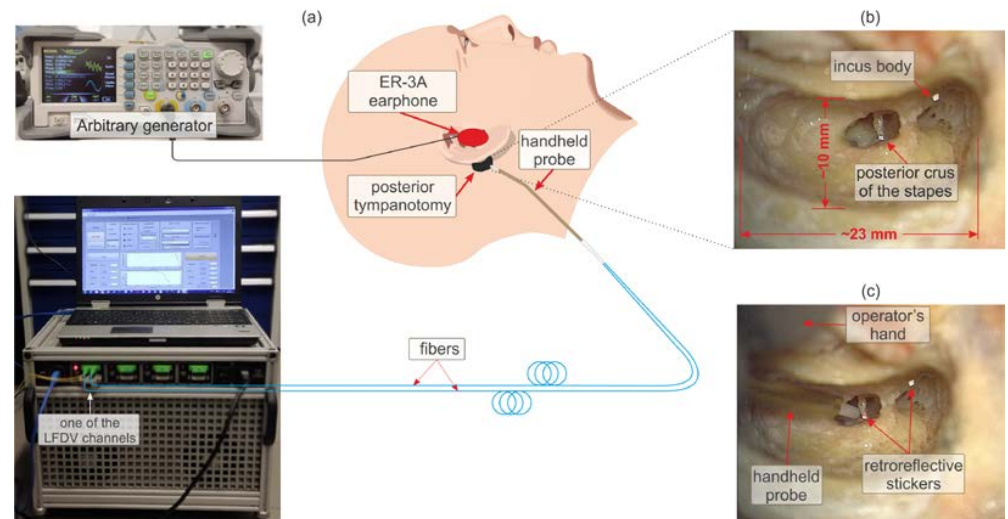


Figure 10. Typical access to the middle ear: (a) setup for measuring middle ear vibrations; (b) actual photo with visible ossicles and dimensions; (c) photo of the measurement on the posterior crus of stapes.

Tests were conducted on six ears in five donors. The cadavers were prepared in accordance with the established protocols for testing [18]. Vibration measurements were performed on the posterior crus of the stapes and the incus body. A retro-reflective sticker measuring approximately $1\text{ mm} \times 1\text{ mm}$ was placed on the analyzed area before illuminating it. The stimulating signal was connected to an earphone placed in the ear canal. The surgeon held an HP directed toward the object. If the signal level from the detector was appropriate ($> -40\text{ dBm}$), $N = 200\text{ k}$ samples were acquired at a sampling frequency of $f_s = 1\text{ MHz}$. The signal was applied to a digital bandpass filter (100 Hz–10 kHz, Bessel, 6th order, National Instruments, Austin, TX, USA) to reduce the influence of low-frequency vibrations, including operator hand vibrations, typically in the 8–12 Hz [32]. From this data set, a signal spectrum was calculated with a resolution of 5 Hz. The spectra were averaged, and the final vibration amplitudes were determined from at least 30 correctly (i.e., for the input signal) determined spectra. Figure 11 shows an example of an averaged spectrum for 60 dB HL stimulation measured on a superstructure of the stapes against a noise background (the noise signal was left unfiltered).

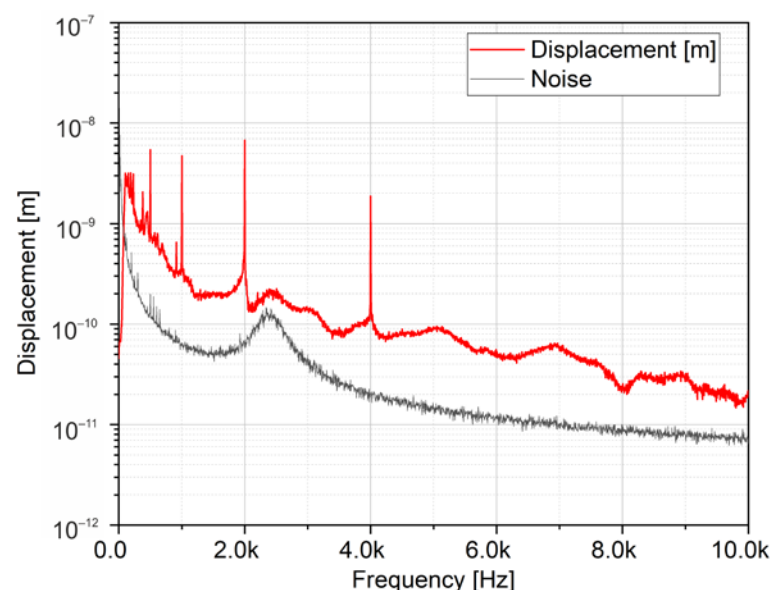


Figure 11. Averaged spectrum for 60 dB HL excitation over noise background [18].

Based on the measured spectra, multi-parametric data analysis was performed, the detailed results of which are presented in the [18]. We obtained a linear dependence of the logarithm of the amplitude of vibration of the auditory ossicles on the intensity of the sound signal. An example of such a characteristic for one of the test ears is shown in Figure 12. The middle ear transfer functions for the posterior crus of the stapes and the incus body were consistent with the results obtained by classical LDV vibrometer [1,8,33–35]. Additionally, no statistically significant differences were found between the measurements taken by surgeons and when the probe was mounted on a tripod [18].

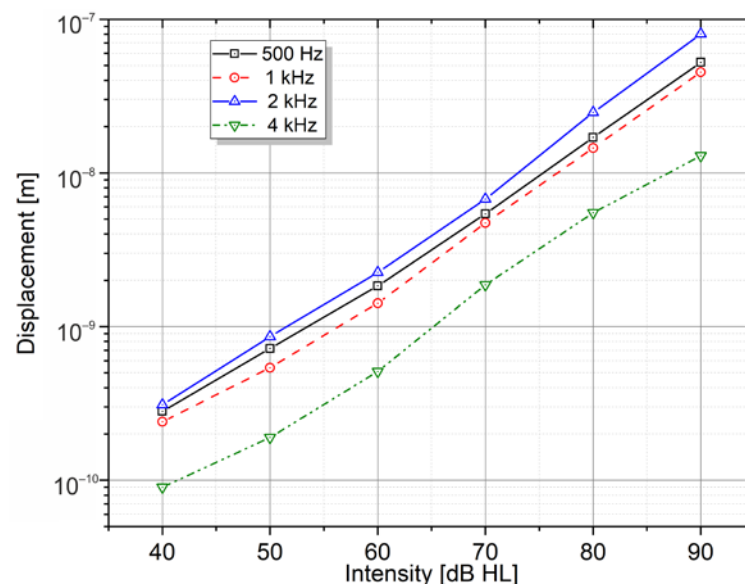


Figure 12. The amplitude of vibration of the superstructure of the stapes of an example ear as a function of stimulation intensity.

Due to FLDV noise, the intensity of 40 dB was the lowest for which stimulation could be measured for all frequencies.

5. Discussion

This paper presents a laser vibrometer developed using fiber-optic technology, the main advantage of which is the ability to make measurements in areas inaccessible in a straight line from the far field. Table 3 compares the properties of the developed vibrometer with those of the Polytec OFV-534, currently the most widely used vibrometry sensor head in research for measuring ossicular displacement [3,7,9,12,16,36–39]. The FLDV HP is much smaller, and lighter, and allows measurements from closer distances, but it has a larger spot size. Both solutions have similar sensitivity and allow the measurement of ossicular vibrations when stimulated by a sound at roughly 30 dB HL (Polytec OFV-534) and 40 dB HL (HP).

Table 3. Comparison of the fiber-based laser Doppler vibrometer (FLDV) handheld probe (HP) with the Polytec OFV-534 sensor head with a standard lens.

Parameter	FLDV HP	Polytec OFV-534
Operating wavelength	1550 nm	633 nm
Construction type	Fiber optics	Bulk optics
Minimum distance from the test object	1 mm	200 mm
Laser depth-of field	±1 mm	±1 mm
Spot diameter	850 µm (5 mm from the tip of the probe)	25 µm

Table 3. Cont.

Parameter	FLDV HP	Polytec OFV-534
Probe/Sensor head dimensions L—length, W—width, H—height, D—diameter	120 × 2.5 (L × D) mm	201 × 39 × 71 (L × W × H) mm
Probe/Sensor head weight	2 g	1000 g
Possibility of insertion into the middle ear	yes	no
Threshold intensity at audiometric frequencies for ossicle displacement measurement	~40 dB HL	~30 dB HL

The anatomical distances in the middle ear are relatively small. Although the measurement is made by a non-contact method, it is quite easy to inadvertently touch the structures of the middle ear with the face of the probe. The probe, which will eventually be used in the operating room, must therefore be aseptic, so sterilization requirements should be considered in its design.

Accidental contact of the probe with middle ear structures could also contaminate the probe face and reduce the power of the scattered signal reaching the system. However, this was not a cause for concern, as the power of the signal reaching the system was monitored continuously, and a simple wipe with a dust-free cotton cloth proved to be an effective solution.

The dissecting room where the measurements were made easily accommodated the entire system, consisting of a 46 × 36 × 38 cm laser vibrometer and a 23 × 11 × 29 cm sound generator. The fiber optic cable connecting the probe to the vibrometer remained suspended in the air. Before routine use of the system in the operating room, it is desirable to reduce the size of the system and provide mechanical protection for the optical fibers.

The measurement of ossicle displacements necessitated the collaborative efforts of the surgeon and the technical operator of the vibrometer. In the current iteration of the device, the surgeon was responsible for positioning the probe by observing the surgical field through the microscope, while the technician provided verbal feedback regarding the strength of the scattered signal. Verbal communication, however, introduced a delay in the measurements, as the surgeon had to inquire about the power of the scattered signal and the technician could not see the probe's movements. Therefore, the introduction of a new feature indicating the optimal power of the scattered signal by changing the color of the monitoring spot (e.g., from red to green) would facilitate measurements.

Surgeons can optimize prosthesis placement and parameters (e.g., length) based on knowledge of the vibration spectrum (for several frequencies of stimulating signals, e.g., 500 Hz, 1 kHz, 2 kHz, and 4 kHz) of selected middle ear structures. It is preferable to have access to the results in real time to provide the surgeon with the fastest feedback possible. The prototype (Figure 2) used an FFT algorithm, which provided an analysis time that was negligibly small compared to the acquisition time. In addition, it was easy to implement in the LabVIEW environment, which supports other FLDV components for control and signal acquisition (Picoscope 4824A, Pico Technology, St Neots, UK). At the same time, the FFT algorithm has its limitations. One of them is the stationarity of the signals. Fluctuations in the amplitude of the photodetector signal, mainly caused by the speckle effect, were compensated in the prototype by using an automatic gain control (AGC) circuit. However, the AGC not only amplifies the useful signal but also the noise. The possibility of using other signal analysis methods, such as empirical mode decomposition (EMD) or variational mode decomposition (VMD), which are more robust to noise than the aforementioned FFT algorithm, is currently under consideration.

The HP proposed in this article lacks a collimator, resulting in a low coupling efficiency. Nevertheless, this proved sufficient for short distances. In the future, we intend to utilize

a solution analogous to the UH, which employs Gradient-Index lenses. Modifying the fiber fronts by fabricating micro lenses will improve this coupling ratio and thus reduce noise. We also plan to improve the signal-to-noise ratio (SNR) by using more advanced signal analysis methods, such as activation function dynamic averaging (AFDA). Ideally, we would like to achieve such efficiency that there is no need for retroreflective stickers.

During the design of the fiber-based vibrometer, the replacement of single-mode (SM) fibers with polarization-maintaining (PM) fibers was considered as a potential means of increasing the SNR. This was based on the observation that the FLDV system is sensitive to fiber vibrations. The fiber immobilization increased the stability of performance and the repeatability of results. In accordance with the concept illustrated in Figure 1, a system with optical fibers and PM elements was constructed. A comparison of these two configurations showed no substantial improvement in SNR for the PM system. The underlying cause of this finding is the random polarization of light scattered on the test object. For less rough objects, where reflection begins to dominate more, it was possible to obtain better SNR with the PM system (after tuning the polarization state with the controller). In contrast, the results were less favorable for rougher objects. Given the versatility of the device, it was decided to retain the use of SM fibers. Immobilizing the SM fibers and then tuning the polarization state with a controller proved to be a more optimal approach. In the FLDV prototype (Figure 2), easy access to the polarity controllers was provided, but in practice, an adjustment of the polarization state is rarely necessary.

6. Conclusions

The presented results of experiments carried out with the FLDV in conjunction with a fiber HP confirmed the suitability of this device for measuring vibrations of the middle ear ossicles. The technical aspects that allow for the use of the HP in locations that are difficult to access, particularly those that are not accessible in a direct line from the far field, were presented.

The development of the FLDV for middle ear diagnosis is significant in the current times when endoscopic techniques are rapidly developing in medicine. Using the FLDV with an HP during endoscopic ear surgery is straightforward, unlike classical vibrometers.

At present, efforts are being made to enhance both the probe and the FLDV parameters. The work related to the probe concerns the possibility of reducing its sensitivity to specular images by using structures produced directly on the fiber. We also intend to use a third of the fiber in the HP to transmit information to the operator, such as introducing a green light that will be visible when the power of the scattered signal is optimal.

The findings of this research are also relevant to optimizing the FLDV itself. Primarily, the objective is to reduce the noise level so that measurements can be made without retroreflective stickers. We also intend to reduce the device's size, facilitating its use in the operating room.

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