ADVANCES AND APPLICATIONS OF VIBRATION MEASUREMENTS BY LASER TECHNIQUES
Validation of Near-Field Holography Results by Laser Doppler Vibrometry

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Near-field acoustic holography (NAH) has been shown to be a powerful tool for the study of sound radiation from vibrating structures, as it provides the reconstruction of the normal surface velocity from pressure measurements made near the vibrating structure. However, predictions of the vibration properties may sometimes be inaccurate, due, for example, to the presence of several uncorrelated sources.

In order to analyze the degree of accuracy of NAH results in terms of surface velocity, measurements taken by a laser Doppler vibrometer were used for comparison, in the case of an automotive muffler. This study was conducted within the Growth Project “ACES” (Optimal Acoustic Equivalent Source Descriptors for Automotive Noise Problems) No.96.3632.

INTRODUCTION

The Near-field Acoustic Holography (NAH) technique [1] allows the determination of the acoustic field in the 3-D space surrounding a vibrating object, starting from simultaneous microphone measurements performed on a plane array. Also the particle velocity in correspondence of the structure surface can be computed, which may be of great help in the localization of the “hot spots” of the source, i.e. the parts of the structure subjected to higher vibration. However, the accuracy in the determination of this velocity component may decrease in particular cases, e.g. when dealing with objects with complicated shape or with several non-correlated sources. Because of that, the possibility of measuring the vibration velocity with high accuracy using an independent mean can be of great interest for the validation of the NAH technique.

After a detailed analysis of existing techniques, Scanning Laser Doppler Vibrometry (SLDV) [2] was identified to be the most suitable one to overcome some of the limitations of the traditional single-point approaches for vibration measurement. In this paper, a demonstration case study (an automotive muffler) was experimentally approached and results were processed and analyzed.

EXPERIMENTAL CASE STUDY

The set-up used for vibration measurement consisted of the muffler positioned horizontally over two supports, coated with elastic material. Mechanical excitation was given by fixing a shaker to the structure, and a white noise signal was used as driving input. An accelerometer fixed to the muffler shell provided the phase information.

Subsequently, acoustic measurements were conducted in semi-anechoic room, in the same conditions of the vibration measurement (see Figure 1). A set of four reference transducers was positioned around the muffler and the signal from an accelerometer fixed near the shaker served as the fourth reference.

FIGURE 1. Set-up for NAH measurements.

ANALYSIS OF RESULTS

The SLDV can be usefully employed for NAH validation, as it allows to scan very quickly all over the vibrating surface of interest. Furthermore, the SLDV can be set in such a way as to have the velocity component along the optical axis of the instrument re-
computed (starting from the measured component) by using the scanning angles utilized to move the mirrors (see Figure 2). This feature has been employed to perform a comparison with the results achievable by microphone array measurements. In fact, it is sufficient to pose the SLDV optical axis orthogonal to the microphone array.

In the investigated case (Figure 2), the microphone array is positioned parallel to the plane tangential to object, where the velocity distribution is successively determined. The difference between the two resulting distributions is related to the fact that the laser measures the velocity on the surface (point $Z'$ of Figure 2), while the acoustic approach is able to supply the velocity on the point of the tangential plane (point $Z$ of Figure 2). This geometrical error seems to be negligible in the case of the muffler, but may increase significantly if the object shape is more complicated and very different from a plane.

**FIGURE 2.** Scheme of the layout utilized with the scanning laser Doppler vibrometer.

At the end of the tests, the two velocity distributions are available for comparison and validation.

In Figures 3 some of the results are shown. The velocity distributions achieved by microphone-array measurements are computed in frequency bands with a width of 50 Hz each, while the maps from the vibrometer are obtained by applying a peak-peaking analysis on each central frequency of the bands utilized in the acoustic approach (the frequency resolution in the vibration velocity spectra is of 2.5 Hz).

**FIGURE 3.** Comparison between velocity distributions measured (above) and calculated (below) in the 1000 Hz band (left) and 1750 Hz band (right).

From the analysis of the results it is clear that the correlation is satisfactory. The “hot spots” with higher vibration and noise emission are well identified and the mode shapes seem to be well described. Although the spatial resolution of SLDV is higher, the acoustic approach is capable of determining the velocity distributions with reduced uncertainty. Besides the lower spatial resolution, the slight differences observed are due also to the geometrical problem previously described.

In conclusion, it is possible to state that an experimental procedure for near-field holography results validation has been established, which is based on Scanning Laser Doppler Vibrometry (SLDV).

**ACKNOWLEDGMENTS**

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**REFERENCES**


Laser Interferometry Providing Traceable Vibration and Shock Acceleration Measurements

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During the past five years, ISO Technical Committee 108 "Mechanical vibration and shock" has specified upgraded and new standard methods for the vibration and shock calibration of transducers for the different levels of a traceability chain. In compliance with these standards, laser interferometry - which is the primary vibration calibration method preferred in this field at the level of National Metrology Institutes (NMI) - has been further developed at PTB in recent years as a uniform methodology and technique for the primary measurement of translational motion quantities (e.g. linear acceleration) and rotational quantities (e.g. angular acceleration). A traceability chain has been defined and developed which realizes and disseminates the units of the respective physical quantities at those time dependencies which reproduce as closely as possible, during calibration of any transducer, the conditions of use after calibration. Heterodyne laser techniques with digital signal demodulation are applicable to both, national standards and commercial calibration equipment used in calibration laboratories. Different applications of methods and equipment developed at PTB are presented.

INTRODUCTION

International traceability to the SI is increasingly demanded for vibration and shock acceleration measurements specified in international standards, recommendations and regulations to ensure product quality, health and safety. A conventional traceability system had been based on primary vibration calibration by laser interferometry (ISO 5347-1:1993) of reference standard accelerometers at the level of the National Metrology Institutes (NMI), the accelerometers being afterwards used for secondary vibration or shock calibrations by the comparison method (ISO 5347-3:1993 or ISO 5347-4:1993) at the level of accredited calibration laboratories. Also at the lower level of industrial (non-accredited) calibration laboratories the comparison method has been preferably used.

To meet the increased demands for traceability in the field of vibration and shock acceleration measurements, the PTB has initiated, and contributed to, the international standardization of improved and new interferometric methods ensuring
- Primary vibration calibration in extended frequency ranges, including absolute phase calibration (ISO 16063-1:1998; ISO 16063-11:1999),
- Primary shock calibration (ISO 16063-13:2000),
- Primary vibration calibration of angular transducers (to become ISO 16063-15).

In compliance with this progress achieved in international standardization, a more efficient traceability system has been established in Germany and is being used in different countries [1].

GENERALIZED APPROACH TO ENSURING TRACEABILITY

The terms "vibration" and "shock" are defined as special variations with time of the magnitude of a quantity which describes the motion or position of a mechanical system. Traceability for "vibration" and "shock" measurements can be ensured by generating at NMI level the three translational and three rotational motion quantities described in Table 1, with sinusoidal, shock-shaped and other, user-defined time histories and by measuring them by laser interferometry.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Quantity</th>
<th>Relationship</th>
</tr>
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<tbody>
<tr>
<td>Translational (i.e. linear)</td>
<td>Displacement $s$</td>
<td>$s(t)$</td>
</tr>
<tr>
<td></td>
<td>Velocity $v$</td>
<td>$v(t) = \frac{ds}{dt}$</td>
</tr>
<tr>
<td></td>
<td>Acceleration $a$</td>
<td>$a(t) = \frac{d^2s}{dt^2}$</td>
</tr>
<tr>
<td>Rotational (i.e. angular)</td>
<td>Rotation angle $\Phi$</td>
<td>$\Phi(t)$</td>
</tr>
<tr>
<td></td>
<td>Angular velocity $\Omega$</td>
<td>$\Omega(t) = \frac{d\Phi}{dt}$</td>
</tr>
<tr>
<td></td>
<td>Angular acceleration $\alpha$</td>
<td>$\alpha(t) = \frac{d^2\Phi}{dt^2}$</td>
</tr>
</tbody>
</table>

To lower levels of the traceability chain, the comparison method remains indispensable; current standardization projects, i.e. ISO 16063-21 for secondary vibration calibration, ISO 16063-22 for secondary shock calibration and ISO 16063-23 for angular vibration calibration have responded to the increased demand. The generalized traceability system allows, however, the comparison method to be replaced by absolute calibration provided the reference standard laser vibrometer traceable to a relevant national standard is used.

Figure 1 is to demonstrate the universal concept and technique developed and applied by PTB at the top level of the traceability chain. Special exciters have been developed which ensure uniaxial rectilinear or circular motion with sinusoidal or shock-shaped time dependencies [2]. For the measurement of rotational motion, a diffraction grating interferometer has been invented which makes use of a sine-phase grating (grating constant: 0,4192 µm) on the lateral surface of a disc.
The disc forms the air-borne measurement table of the angular acceleration exciter [3]. A Mach-Zehnder heterodyne interferometer with frequency conversion and digital data processing as shown in Figure 1 has proved to be most advantageous [2].

CALIBRATION AND MEASUREMENT CAPABILITIES (CMCs)

Six different national standard devices have been developed at PTB [2] to provide highly accurate primary calibrations of transducers, measuring instruments and calibrators for the six motion quantities listed in Table 1. The CMCs described in [2] and in the BIPM Database [4] are characterized by examples (e.g. sinusoidal excitation available from 0.1 Hz to 20 kHz, amplitudes of 1 nm to 0.5 m).

FIGURE 2. Linearity test of an accelerometer in the nanometer range (frequency: 5 kHz)

Figure 2 demonstrates that laser interferometry is used to measure displacement amplitudes down to 1 nm with a measurement uncertainty of 0.1% (i.e. 1 pm at 1 nm). A piezoelectric (quartz) accelerometer was found to behave linearly in the range of the calibrations.

Using the special arrangements shown in Figure 3, commercial translational and rotational laser vibrometers were investigated and calibrated. A specially developed reference standard vibrometer [5] deviated from the PTB reference value by maximally 0.6% in the range from 20 Hz to 20 kHz (by less than 0.1% up to 5 kHz).

CONCLUSIONS

The latest developments in laser interferometry have made it possible to establish a uniform methodology for primary measurement, covering the variety of motion quantities, sinusoidal and shock shaped time dependencies and wide parameter ranges. The potential high accuracy of measurement can be achieved only in conjunction with high-performance standard exciters, by special vibration isolation and by data acquisition at a high sampling rate, with high resolution and large memory. The national standards briefly described are mainly used for the primary calibration of reference or transfer standards which are later used in accredited calibration laboratories in Germany and other countries [1]. Moreover, a multicomponent motion exciter combined with multiaxial laser interferometry has been developed [6].

REFERENCES

Fiber Optic Polarimetric Sensors for the Dynamic Measurements

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The present paper compares three different fibers used for the Fiber Optic Polarimetric Sensor (FOPS) system for the dynamic measurements. In this sensor design the dynamic response of the FOPS due to the birefringence variation and consequently the polarization fading of the light beam along one of the principle axes of the fiber has been analysed. Two applications are used to evaluate the capabilities of the individual fibers.

INTRODUCTION

Fiber optic sensors have become an essential part of the smart structures for the global health monitoring as well as for sensing external stimuli to the structures [1-6]. There is an enormous potential for this sensing technique over the conventional sensors in a variety of applications including the structural health monitoring of aerospace and civil structures, smart bridges etc. Fiber optic sensors have numerous fascinating merits that make them suitable to those above-mentioned applications. They are very small in size, having lightweight and moreover offer chemical and electromagnetic insensitivity. Thus fiber optic sensors have made a break through by incorporating intelligence into the engineering materials and structures.

Among the various fiber optic sensor designs that are currently available, fiber optic polarimetric sensors (FOPS) have their own unique advantages. Compared to point sensors, FOPS is sensitive to perturbations over its entire length. These sensors can be surface mounted or embedded into the structures with minimum effect on the structures and hence enable them for the on-line monitoring of global structural integrity. The fibers used for this can vary from normal single mode, to the polarization maintaining Hi-birefringence fibers to the newer specially designed low birefringence fibers.

In the present paper we evaluate these three sensors as part of the Fiber Optic Polarimetric Sensor (FOPS) system for the dynamic applications. Primary application of the present FOPS system is for real time detection of defects in composite specimens under dynamic and impact loading conditions. Also the application of the sensor for the vehicle weighing in motion, through dynamic load sensing is used for a comparative study of the three types of fibers.

EXPERIMENTAL SET-UP

The schematic of the experimental set-up for the dynamic testing of composite materials is shown in fig. 1. Light from a linearly diode laser is polarized and launched into the input end of the fiber through a half wave plate and lens. The half wave plate is used to rotate the plane of polarization of the input beam into the fiber to excite both orthogonal eigenaxes equally. Light from the output end of the fiber is passes through an analyzer and is detected by a photo detector whose output is fed to a digital oscilloscope. The loading is by means of an impact hammer at the center of a simply supported beam. The resulting output is stored in the digital oscilloscope and its Fourier transform analyzed.

For damage detection studies, ten layers of glass fiber reinforced (GFRP) specimens with dimension 300 mm x 100mm x 1.25 mm were prepared for the present investigation. The optical fiber is embedded between two consecutive layers and defects were programmed via release film (Teflon film) at predetermined location between the adjacent plies during lamination process.
For the test involving weighing vehicles in motion on roads without any traffic interruption the response of the three different fibers were evaluated using the fiber layout shown in figure 2. The illumination and the detection configurations are the same as described in the previous section. The optical fibers were sandwiched between two rubber mats as shown in fig. 2. The fibers were protected using protective sleeves to avoid damage during use.

RESULTS AND DISCUSSION

The presence of the defects in the composite beam manifests itself as changes in the flexural stiffness of the specimen. The response from the three specimens is quite similar with each of them giving the same fundamental frequency and higher harmonics. However there are some small differences. The signal amplitude from the single mode fiber is low and damps quite rapidly. The Hi-Bi fiber shows a slightly better response but once again the signal dies of rapidly. The Lo-Bi fiber however has a large signal contrast and maintains the signal for a longer period. This affects the Fourier Transform and is most noticeable at the higher frequencies (above 200 Hz.)

For damage studies, the basic theory that relates the change in flexural stiffness to the change in the dynamic characteristic of the beam is discussed in ref. [7]. Thus the change in flexural stiffness will be reflected in the overall dynamic behaviour of the structure and is picked up by the embedded fiber optic polarimetric sensor as a change in the birefringence along the length of the fiber.

For the vehicle in motion weight measurement system the response of the three fibers are quite different. As soon as the vehicle tire contacts the fiber there is an instantaneous response due to the change in birefringence at the region of contact. The car was travelling at a speed of 10 kmph. The Hi-Bi fiber gives a periodic response with increasing/decreasing load For the single mode fiber the response shows a continuous increase as the load is increased followed by a similar decrease. Thus one cycle has the entire loading curve. For the Lo-Bi fiber, however the results are quite erratic.

CONCLUSION

The concept of fiber optic polarimetric sensors (FOPS) can be implemented successfully for evaluating the structural health under dynamic conditions. For the application like online vehicle weigh measurements FOPS system is a suitable method, that offers high sensitivity and reliability.

ACKNOWLEDGEMENT

The support of NTU and the Ministry of Education through grant MLC 1/97 is appreciated.

REFERENCES

1. Selvarajan, A and Asundi, A Photonics, Fiber optics sensors and their applications in smart structures Non destructive evaluation, 1995, 15/2 pp41-56
Application of Laser Doppler Vibrometry to the Vibro-acoustic Analysis in the Industrial Field

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Due to its large capabilities of investigation in experimental vibration testing, Laser Doppler Vibrometry (LDV) [1] is being applied with increasing interest in many research and industrial fields [2]. Indeed, LDV has proven to offer relevant advantages over traditional transducers in a wide range of applications, from modal analysis and damage identification to quality control and dynamic testing, etc. 

In this paper, after a short description of the basic working principles of LDV, the use of this technique in the area of the structural acoustic analysis is addressed and the related key advantages are here presented and described.

PRINCIPLES OF LASER DOPPLER VIBROMETRY

A laser Doppler vibrometer is an extremely valuable and flexible instrument for measuring structural vibration response. There are various differences in the design but, basically, a coherent laser beam is directed at the point whose motion is to be measured and the back-scattered light is compared with the incident light in an interferometer [1]. The Doppler shifted wavelength is then measured and processed to give the surface velocity in the direction of the incident laser beam.

Typical performances are a bandwidth up to 1 MHz, a velocity range of ±10 m/s, a resolution of about 8 nm in displacement and 0.5 mm/s in velocity. The calibration accuracy is about ±1.5% of RMS reading.

Deflecting mirrors can be provided to direct the laser beam at the desired point on the surface under test, providing a scanning capability. This Scanning Laser Doppler Vibrometer (SLDV) can quickly and precisely perform the scanning of the laser beam on the structure under test, allowing the analysis of large surface with high spatial resolution and short testing time.

This particular capability, together with the non-contact nature, makes the SLDV technology suited for situations where the use of accelerometers is not possible, that is in the case of hot, light and rotating surfaces. Besides, if a high number of measurements have to be taken over different points, it would be necessary to arrange an array of these transducers, that is time consuming and costly. The SLDV also provides both spatial information and time dependence of the vibration, on the contrary other optical techniques, including Electronic Speckle Pattern Interferometry (ESPI) and double-pulse laser holography, provide only spatial information and not any means to control the time dependence.

The outstanding capabilities outlined are certainly important to extend limits of experimental vibration and acoustical testing. In fact, the possibility of performing accurate vibration measurements provides a reliable database to be used in a large number of applications in vibro-acoustic analysis, as it will be pointed out in the following.

APPLICATION CASES: OVERVIEW

In recent years, the vibro-acoustic analysis has been gaining growing importance in the control and reduction of the noise levels in various fields of the engineering application. In the automotive industry, for example, a lot of effort has been made in reducing noise from engines, tyres, covers... either to optimize vehicle cabin acoustics or to meet the more and more stringent governmental regulations aimed at limiting the growing noise pollution. Moreover, short production times and low costs are critical issues in the industrial field and efficient vibro-acoustic analysis and design would help to reduce the time to market and the costs due to the realisation of a high number of prototypes.

In the development of accurate structural acoustic modeling and design, the use of experimental data proves to be of great importance since it is generally more suitable in the analysis of vibro-acoustic problems than that of pure numerical data. In fact, especially in the case of complex structures or excitation conditions, numerical models are less
reliable and experimental vibration data can play an important role for the accuracy of the acoustic analysis.

In this context, the scanning laser Doppler vibrometry can offer important advantages, for its non-contact nature, high resolution and sensitivity, optimal dynamic response. Furthermore, it has shown to be preferable to traditional accelerometers for the possibility of collecting vibration data from up to thousands of individual points in a short time and for the absence of mass loading and mounting problems. The latter problems are present in the case of light and thin structures, which are often investigated for noise problems, since they can easily be subjected to strong undesired vibration. An example consists in covers often present in internal combustion engines for the protection of valves and belts, or for the lubricant oil. Due to their light weight and low stiffness, they experiment large amplitude vibration in operative conditions, thus producing noise and sometimes amplifying the noise produced by the engine. Another application case is represented by the loudspeaker membranes, which can hardly be experimentally analysed using conventional transducers. In Figure 1 an example of result on a vibrating loudspeaker membrane is shown: the vibration velocity pattern obtained by LDV at a given frequency is displayed.

**FIGURE 1.** Vibration pattern of a loudspeaker membrane, measured by LDV.

Also in the case of hot or rotating structure the laser vibrometer can offer the best performances, due to its non-contact nature. For example, in the case of power transmission belts, it would not be possible to use contact sensors for measuring during operating conditions, neither punctual non-contact sensors due the low amount of information obtained. Moreover, thank to recent developments, novel systems have been realised which are able to track a point on a structure moving with a circular, linear or arbitrary trajectory. These techniques enhance the potential of laser Doppler systems, allowing to analyse also transient phenomena and to avoid the influence of material non-homogeneity for example.

Laser Doppler vibrometry can also be successfully employed for supporting the development and validation of numerical or hybrid acoustic prediction techniques. Indeed an effective acoustic and structural acoustic modelling should be based on refined numerical prediction techniques as integral parts of the CAD/CAM/CAE process. With this respect, numerical codes can be valuable tools to analyse the effect produced by design modifications on the noise radiation, the importance of different co-existing noise sources and, in general, the noise generation and propagation mechanisms. A key issue of acoustic radiation prediction is the definition of accurate velocity boundary conditions. Indeed it has been proven in many occasions that the accuracy of the acoustic prediction depends on the accuracy of the structural vibrations used as boundary conditions. On the other hand, results from finite element structural analysis constitute a reliable source of information but their accuracy is limited by uncertainty on the material properties, the actual boundary conditions... Anyway, if experimental values are more accurate they are seldom (almost never), available in every node. In fact, by employing traditional transducers it is not feasible to collect vibration data from a high number of points, especially when the test structure is big. Laser Doppler vibrometry can override this problem, since, especially in the case of planar structures, it makes it feasible to collect as much information as the number of the nodes of interest in the acoustic analysis.

For the mentioned reasons, laser Doppler vibrometry can offer invaluable help in the analysis of acoustic problems, when structural vibrations can be identified as the major cause of noise radiation.

REFERENCES

2D Laser Doppler Velocimetry Measurement in a Loudspeaker port

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This paper deals with 2D measurements inside a glass port built outside the loudspeaker box, in order to facilitate the use of optical measurements. Quantitative estimates of the magnitude and phase of the sound, the mean flow caused by the sound, and the RMS value of the acoustically induced turbulence, have been achieved using a synchronous demodulation of the randomly spaced LDV data.

INTRODUCTION

The loudspeaker port is used to enhance the level of low frequencies, especially in compact audio systems. Over the past ten years, manufacturers have been designing ports with smooth discontinuities, in order to avoid non-linearity effects, such as vortex generation outside the port and turbulence noise, generated by the low frequency velocity fluctuations inside the port. Although these phenomena have been described in the literature [1], pressure measurements have testified the presence of such unwanted noise, few measurement have actually been performed inside the port, where the turbulence is generated. In a first part, the setup and preliminary measurements are described. In a second part, quantitative values of the acoustically induced turbulence are presented.

EXPERIMENTAL SETUP

The experimental setup is shown in Figure 1. The resonator's frequency is about 25 Hz and permits a significant enlargement of the frequency band. All measurements were performed for an excitation frequency of 25 Hz. Preliminary measurements have been performed using Particle Imagery Velocimetry, where velocity vectors are extracted using correlation techniques. The measuring plane (10x10cm²) included 2/3 of the entrance of the port and 1/3 of the outside. The images have been taken synchronously with the acoustic wave where 16 points were taken for each period. Averages have been performed for each value of phase. Figure 2 only shows two results: in a) when the flow maximally exits the port and in b) when the flow enters the port. Vortex shedding clearly appears outside (fig. 2-a) of the port as measured and described in literature [2] some years ago. Conversely, during the inflow of air into the port, there exists a region close to the edge in the vena-contracta zone where averaging causes measurement of zero velocity probably due to the random nature of turbulence.

2-D LDV MEASUREMENTS

Because of the poor time resolution of the PIV, a 2-D LDV system has been used first to understand how the turbulence instabilities are convected inside the port.
close to the edge and the wall and secondly to extract its RMS values. The investigations have been performed in the vena-contracta where the major nonlinearities are located. Two components of the velocity are measured: the longitudinal component displayed in Figure 3 a) resulting from the acoustic waves, plus the turbulence resulting from the high velocity which appears at a certain phase of the signal. Furthermore, the turbulent velocity measured through the second component of LDV clearly appears on Figure 3 b) at the same time on the transverse axis. This temporal coincidence serves to emphasize the multidimensional aspect of the turbulence. In order to quantify exactly the RMS value of the induced turbulence, an estimation of the magnitude and phase of the acoustic wave is achieved using data processing described in paper [3]. The acoustic velocity component is subtracted and the RMS value of the difference between the measured data and the estimated acoustic velocity is computed. The RMS value is shown in Figure 3 b). The curve obtained is flat until the half period after which it is more agitated. A smoothing RMS value of the transverse component is shown in Figure 4-b and the increase is coincident with the increase shown in Figure 3-b.

**RESULT AND COMMENT**

If x is the longitudinal axis and y the transversal axis, the measurements have been performed along the wall at x=5mm every 2.5mm from y=5mm. The superimposed curves displayed in Figure 4 show the convection of the turbulent structure inside the port and its decay. Table 1 presents the RMS value of the mean acoustic velocity taken inside the port, the level of turbulence estimated at the maximum value obtained for each measurement and finally an estimation of the convection velocity of the turbulent structure.

![Figure 3](image1.png)

**FIGURE 3.** a) longitudinal velocity component measurement b) RMS value in relation to the phase of the difference between measurements and estimated acoustical wave.

![Figure 4](image2.png)

**FIGURE 4.** a) Transverse velocity component b) RMS values in relation of phase

![Figure 5](image3.png)

**FIGURE 5.** Measurement at y=5mm and x=5mm in steps of 2.5mm along the longitudinal axis (signal processing equivalent to those displayed in Figure 3-b)

<table>
<thead>
<tr>
<th>x</th>
<th>Uac RMS (m/s)</th>
<th>U_turb/Uac</th>
<th>Convection Velocity (m/s)</th>
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<td>0.15</td>
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<td>0.13</td>
<td>1.7</td>
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**REFERENCES**

Method and application of an optical measuring and calibration technique for microphones.

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Condenser microphones are the most effective and accurate transducers in audio acoustics. They cover the whole range of human hearing regarding frequency and dynamic range. The electroacoustic transfer function of a typical condenser measurement microphone is nearly perfect since it has a frequency-constant magnitude of sensitivity and almost linear phase. Due to these advantages, condenser microphones are widely used for recording sound, for measuring sound and for representation of the physical „sound unit“, the Pascal. The latter application is important for absolute measurement standards. In legal metrology, the acoustical unit is represented by a precision calibration method based on the laboratory standard microphone. Precision calibration of condenser microphones is, however, a very complicated and time consuming procedure, if primary methods are applied.

In this article a new technique for measuring the characteristics of transducers and a direct reciprocal primary method for calibration of condenser microphones is described. Due to the novelty of the approach, the method and the results are introduced and first results with different transducers are discussed.

RECIPROCAL MEASUREMENT TECHNIQUE

Reciprocity is one of the most important features of electro-acoustic transducers, in this case the transducer can be driven from the acoustical and from the electrical side.

\[
\begin{align*}
I & \rightarrow \frac{Q}{p} \\
U & \rightarrow \text{two-port}
\end{align*}
\]

Fig. 1: Two-port representation of an electro-acoustical transducer

And the complex sensitivity factors \(M_0\) are identical:

\[
\frac{U_{p=0}}{p} = \frac{Q_{p=0}}{I} = M_0
\]

(1)

with \(U_{p=0}\) denoting the open-circuit receiver voltage, \(p\) the driving sound pressure, \(Q_{p=0}\) the source volume velocity and \(I\) the driving current (Fig. 1). All quantities are complex frequency functions.

Due to the fact that direct primary calibration involves an absolute measurement of the open-circuit voltage, \(U_{p=0}\), and the sound pressure, \(p\), it is clear that we run into a circular problem because \(p\) can only be accurately measured by means of a calibrated microphone. If the reciprocal equation for determination of \(M_0\) is used directly, the microphone driving current, \(I\), and the resulting volume velocity, \(Q_{p=0}\), must be measured directly as absolute values.

Measurement arrangement

Fig. 2 shows the experimental arrangement for the simultaneous measurement of current and velocity.

The laser instrument which was used in this project consists of a scanner interface, a laser head with interferometer and the vibrometer. The scanner interface is used for the laser beam positioning on the microphone membrane, which was oriented perpendicular to the beam. The mode for velocities of up to 100 mm/s with a bandwidth of 250 kHz was used here. Sweeps were used for excitation providing the possibility of coherent averaging and distortion extraction, which is a great advantage compared to MLS-signals [1]. 256 averages were made to obtain a measuring signal with sufficient S/N ratio. Fig 3 shows typical frequency spectra of the quotient \(v/I\) for different points on the membrane (the index \(i\) denotes the number of the actual point on the membrane).
Absolute measurement of the microphone sensitivity

The overall microphone sensitivity can be composed by calculating the ratio between the membrane velocity and the driving current. At first, the microphone is considered small compared with all acoustic wavelengths. Then we can achieve a first impression of a sensitivity curve, and the effective volume velocity can be taken as the single-number superposition of the locally measured point-velocities multiplied with the surface area belonging to it:

\[ Q = \sum_{n=1}^{N} v_n \cdot S_n \] (2)

The result is shown in Fig. 4. For frequencies where the microphone can be considered small compared to the wavelength this is identical to the sensitivity \( U/p \).

This monopole condition is applicable at low frequencies (in particular at the pistonphone frequency 250 Hz) where the measured sensitivity must agree with the open circuit sensitivity given by the manufacturer. This is true for the measurements shown here within 0.3 dB deviation. However, the reason for this error has to be investigated and solved to make the method applicable for the laboratory.

Directivity considerations

At higher frequencies the above discussed monopole sensitivity is changing for frontal sound incidence due to the piston size of the membrane and diffraction effects that have not been taken into considerations. To achieve the correct frequency response for this range further numerical processing of the measured data is required. The far field directivity can be calculated with BEM (Boundary Element Method) for the microphone as a source and hence the radiation impedance causes the frequency curve to increase with additional 6 dB / octave. If the monopole frequency response (Fig. 4) is corrected by an additional slope of 6 dB / octave and the result is subtracted from the BEM-result the increase due to directivity effects is obtained. This is shown in Fig. 5 but with a correction by –6 dB / octave for easier display.

Conclusion

The proposed calibration method for microphones proves to be an advantageous tool for high precision measurements and primary calibration purpose. The expense for this method seems to be large (laser vibrometer, software for BEM, etc.) but, however, classical reciprocal calibration also needs high-end measuring techniques and the sensitivity against errors seems to be even greater. Moreover, with this method it is possible to derive additional information, like vibration pattern, or idealized directivity plots, without any influence of the ambient sound field. Some measurements on \( \frac{1}{2} \) inch microphones have been carried out and the results are very encouraging.

REFERENCES