Refracto-vibrometry - a novel method for visualizing sound waves in transparent media

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For the development of acoustic devices, the optimization of new sonic techniques or the understanding of complex sonic phenomena it is often desirable to visualize the generation and distribution of the invisible sound waves. A novel method for measuring and visualizing the sound waves in transparent media was developed and tested by the authors. This non-contact method is based on a scanning laser-Doppler vibrometer. It can be used for measuring and visualizing sound fields in gases, fluids and even pellucid solid objects. The variation of the optical refractive index n of transparent media, caused by the sound waves, is used as measuring effect. This justifies the denomination "refracto-vibrometry". The paper describes the theoretical fundamentals and the technical equipment required for the novel method. As examples, the generation and radiation of sound in air, water and transparent solid objects are presented. The reproduction of the results as videos is impressive and instructive. In education and systems design, refracto-vibrometry has a large potential to make acoustics clearer and more feasible for application.

1 Introduction

Refracto-vibrometry is a novel interferometric, non-contact method for measuring and visualizing of actually invisible phenomena in transparent media [1]. The variation of the optical refractive index n, caused by periodic disturbances in the measuring area of a Scanning Laser-Doppler Vibrometer (SLDV), is used as measuring effect. This justifies the denomination refracto-vibrometry. The method is qualified for investigating and illustratively presenting numerous acoustic, fluidic and stress phenomena. The paper describes theoretical fundamentals and the required equipment of this method. As examples, the generation of sound by vibrating objects or vortexes, the propagation of sound in air or water and the generation of dynamic stress in Perspex are presented. In the field of education and acoustics design, refracto-vibrometry has a large potential to make acoustics clearer and more feasible for application.

2 Classical Laser Vibrometry

For non-contact measurement of the velocity $v(t)$ of vibrating objects Laser-Doppler vibrometers (LDV) are used. These types of vibrometers are based on a Mach-Zehnder-Doppler interferometer (Fig. 1). The beam splitter BS1 splits a laser beam into measuring and reference beams. The reference beam reaches BS3 via a prism. The measuring beam hits the reflecting object at the end of the measuring area, is reflected there and then guided by BS2 towards BS3.

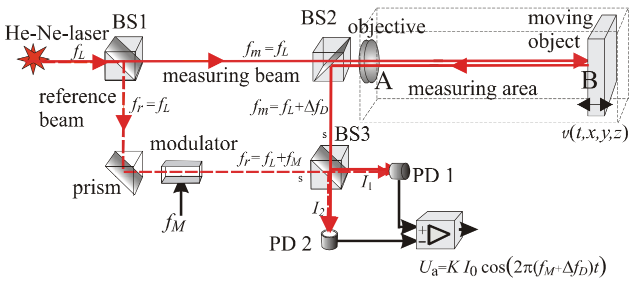

Fig. 1 Scheme of a Mach-Zehnder-Doppler interferometer

Behind BS3 measuring and reference beams interfere and result in a light signal with fluctuating intensities $I_1$and I_2 .

If the object is moving along a geometrical distance $\Delta L_g(t)$ with a velocity $v_g(t)$, then, because of the Doppler effect, the frequency f_m of the reflected measuring beam changes about the Doppler-shift

$$\Delta f_{Dg}(t,x,y,z) = \pm \frac{2v_g(t,x,y,z)}{\lambda_m} \quad (1)$$

with reference to the primary frequency $f_L = f_r$ of the laser. For identifying the actual direction of the velocity $v_g(t)$, the reference beam with the frequency f_r is sent through a modulator. There, a shift frequency f_M is superposed. Behind the BS3 both laser beams reach photo detectors and are electronically summarized to an output signal

$$U_a(t) = K I_0 \cdot \cos(2\pi(f_M \pm \Delta f_{Dg})t)\,, \quad (2)$$

which depends on Δf_{Dg} and therewith on the velocity $v_g(t)$. It is for this reason, that vibrometry is also called velocimetry.

However, it is not regarded in equation (2) that mechanical disturbances can occur in the measuring area between LDV and the moving object. Such disturbances, e.g. pressure variations Δp caused by sound or turbulences, can change the optical path length L_n along the measuring beam about

$$\Delta L_n(t) = 2\int_A^B \Delta n(t,x,y,z)dl \quad (3)$$

because pressure fluctuations cause variations of the optical refractive index [3]

$$\Delta n(t,x,y,z) = \left(\frac{\partial n}{\partial p}\right)_S \Delta p(t,x,y,z)\cdot \quad (4)$$

The differential in (3) is the piezo-optical coefficient [4]. Considering optically effective disturbances, additionally to the geometrical velocity $v_g(t,x,y,z)$ a dynamic variation of the optical path length is to be regarded. Consequently, the total Doppler shift results from the superposition of the geometrical and the refractive shares

$$\Delta f_{D\Sigma}(t) = \frac{2}{\lambda_m}\left(v_g(t,x,y,z) + \left(\frac{\partial n}{\partial p}\right)_S \int_A^B \frac{d}{dt}(\Delta p(t,x,y,z))dl \right) \quad (5)$$

In most LDV measurements is $\Delta f_{Dg}(t) >> \Delta f_{Dn}(t)$, i.e. the efractive share of the Doppler shift can be neglected. The reason for this is that the sound from the vibrating object or air turbulences in the measuring area causes only small variations $\Delta n(t,x,y,z)$ of the refractive index. Additionally, these variations are mostly connected with alternating magnitudes along the measuring beam. According to (3) the effect of pressure disturbances can be compensated along the measuring beam.

3 Refracto-Vibrometry

Nevertheless, the small refractive share of the Doppler shift is sufficient for measuring and visualizing sound and turbulences in fluids or dynamic stress in transparent condensed matter. For this purpose a set-up according to Fig. 2 can be used. Thereby it is advantageous to use a modern SLDV. To eliminate the geometrical share of the Doppler shift $\Delta f_{Dg}(t,x,y,z)$, an absolutely rigid reflector is required. Moreover, the source of sound must be arranged laterally with respect to the reflector. In this case, the sound wave crosses at right angles with the measuring beam. Sometimes it is helpful to limit the measuring space by placing a glass plate in a short distance L_n in front of the reflector. Then the resulting narrow measuring area acts as a wave guide and the compensation of positive and negative fluctuations of the refractive index $\Delta n(t,x,y,z)$ along the beam between points A and B and back will be reduced significantly according to (3).

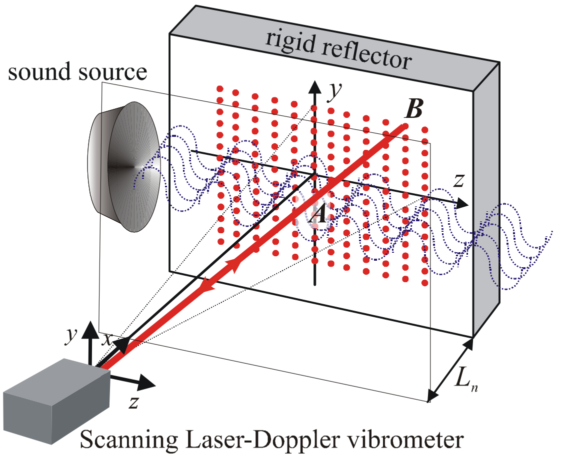

Fig. 2. Principle of refracto-vibrometry

Pressure variations $\Delta p(t,x,y,z)$ from sound or vortexes as well as from dynamic stress in transparent condensed matter cause fluctuations of the refractive index $\Delta n(t,x,y,z)$ and therewith variations of the optical path length $L_n(t,x,y,z)$. Even though the reflector is absolutely rigid, it seems to move, from the point of view of the SLDV, with the velocity

$$
\begin{aligned}
v_n(t,x,y,z) &= \frac{d\left(2\Delta L_n(t,x,y,z)\right)}{dt} \\
&= 2\left(\frac{\partial n}{\partial p}\right)_S \int_A^B \frac{d}{dt}(\Delta p(t,x,y,z))dl.
\end{aligned}
\quad (6)
$$

This virtual velocity represents the first derivative of the mean sound pressure fluctuations $\Delta p(t,x,y,z)$ in the measuring area between points A and B along the measuring beam or respective stress fluctuations $\Delta\sigma(t,x,y,z)$ in a transparent solid object, which is screened by the measuring beam. The signal-to-noise ratio of the measurements is the better, the higher the frequency of the fluctuations of pressure $\Delta p(t,x,y,z)$ or stress $\Delta\sigma(t,x,y,z)$, respectively, is. Measurement errors, which are caused by integration according to (3) are discussed in [1].

4 Measurements

In the following we present a number of characteristic examples of measurements with a set-up according to Fig. 2 using an SLDV from POLYTEC, type PSV 100/200.

Fig. 3 shows the reflection of a bundled ultrasound lobe, coming out of a transducer, at a 45°- plate. The regions of the undisturbed free field, the reflected field and the interference between them can clearly be distinguished.

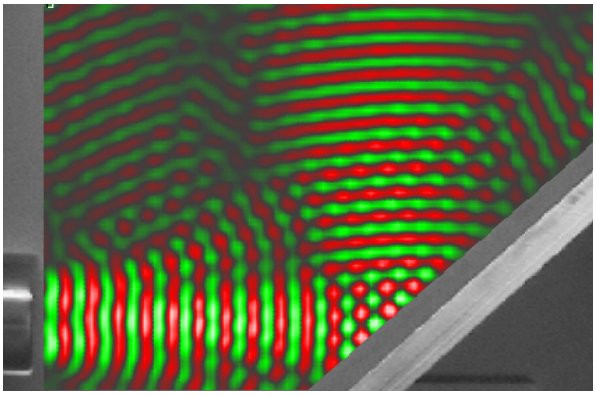

Fig. 3 Bundled ultrasound field reflected on a plate

In Fig. 4 an ultrasound wave is reflected on the inner surface of a shell made of a halved tube. A complicated interference pattern with a virtual focus near the tube wall is recognizable. The irregularities in the pattern result from the non-plane wave from the transducer.

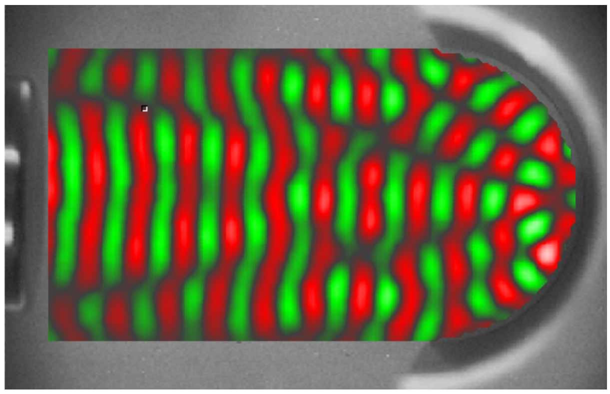

Fig. 4 Ultrasound field reflected on a semicircular shell

In opposite to Fig. 4, in Fig. 5 an ultrasound field radiated out of a paraboloid is presented. A paraboloid is also arranged in axial direction as an obstacle. We can see the symmetrically reflected waves, which interfere with the primary wave.

For measuring the ultrasound fields in Figs. 3 to 5, frequencies about f = 40 kHz are chosen. In this frequency range high pressure fluctuations $\Delta p(t,x,y,z)$ arise and with them an excellent signal-to-noise ratio. Furthermore, the short wave length λ of the ultrasound permits the presentation of intensely structured sound fields in a relatively small area. But also at lower frequencies in the audio range satisfying measurements of sound fields can be realized.

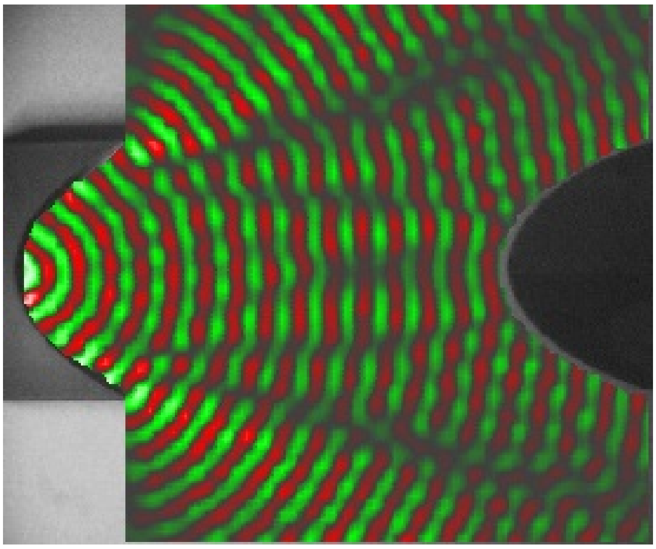

Fig. 5 Ultrasound field out of a paraboloid reflected by a paraboloidic obstacle

An interesting example shows Fig. 6. There, a pulsed air flow with a frequency f = 2,2 kHz is generated, which sluices out of a small tube with a diameter D = 4 mm. For the first time we can here actually visualize the transformation of air pulses into sound waves. As expected the propagation speed of the sound waves is much faster than the flow velocity of the air pulses. The line below represents the pressure distribution $\Delta p(t,x,y,z)$ of both: the long-wave sound and the short air pulses in axial direction.

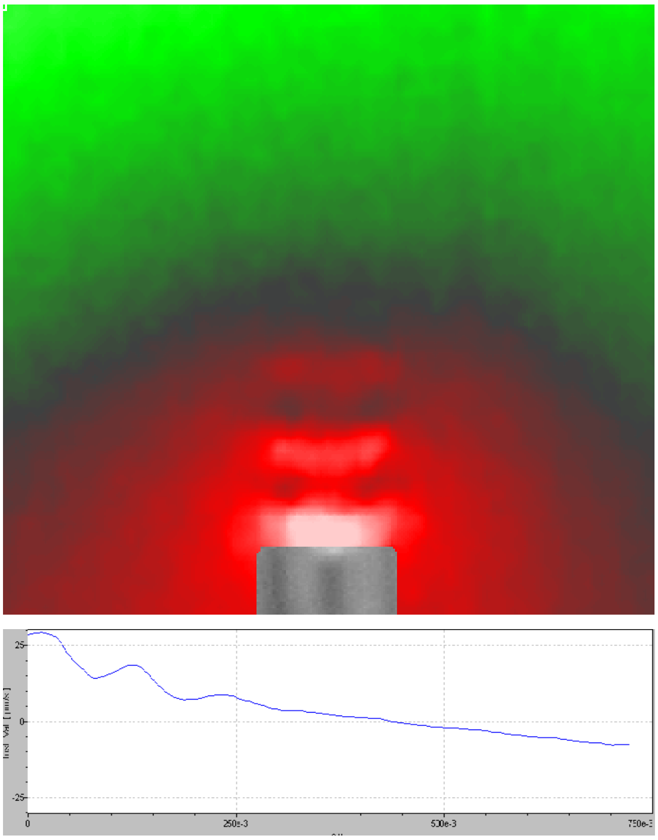

Fig. 6 Acoustic sound and periodical vortexes out of a small tube (above). Pressure distribution $\Delta p(t,x,y,z)$ in axial direction (below).

Even recurrent air pulses of low frequency f = 360 Hz generate pressure distributions $\Delta p(t,x,y,z)$, which are fast enough for satisfying refracto-vibrometrical measurements. Fig. 7 shows a pseudo 3D-presentation of such a pulse run.

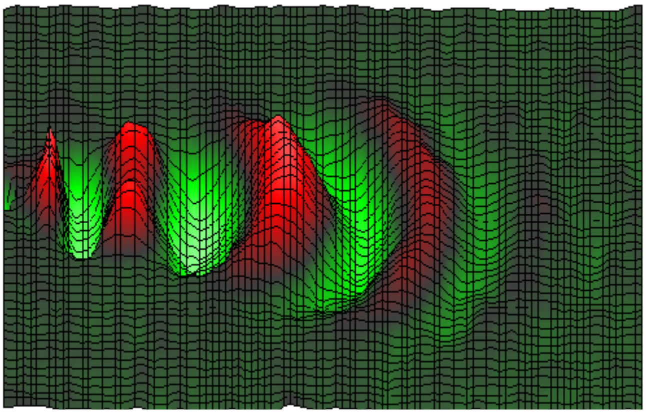

Fig. 7 Pseudo 3D-presentation of periodical air pulses out of a small tube at f = 360 Hz

The transformation of periodical air vortexes into sound waves can be excellently visualized in organ pipes or in fluidic-acoustic oscillators. Such an activated oscillator is presented in Fig. 8. The planar oscillator has a thickness of only 1,5 mm, i.e. the measuring area is extremely small. Nevertheless, the vortexes near the edge and the resulting $\lambda/2$-wave in the resonating cavities are clearly visible.

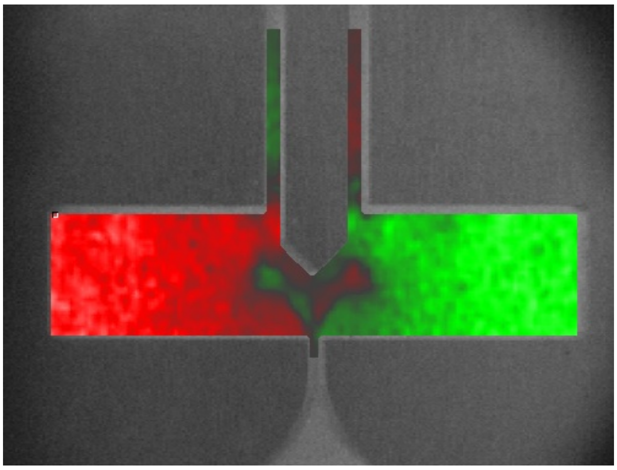

Fig. 8 Vortexes and the resulting $\lambda/2$-wave in a planar fluidic-acoustic oscillator.

Refracto-vibrometical measurements can be carried out not only in gases but also in transparent liquids and condensed matter.

For example, Fig.9 shows a standing sonic wave in a water- filled aquarium (200 x 200 x 300) mm. The wave is excited by an US-transducer at 37 kHz. The transducer is just touching the water surface. Its active area has a diameter of D = 36 mm, i.e. it is much smaller than the surface of the water. Nevertheless, a nearly linear standing wave is generated. The reason for this is the abrupt change of the acoustic impedance at the plane interfaces of the water where the sonic wave is totally reflected.

In Fig.10 the surprising possibilities of the refracto-vibrometry for analysing the dynamic stress distribution in transparent bodies are demonstrated. The two horizontally excited Plexiglass samples of different shapes show extremely different stress distributions. The left example shows a stress distribution as it is expected.

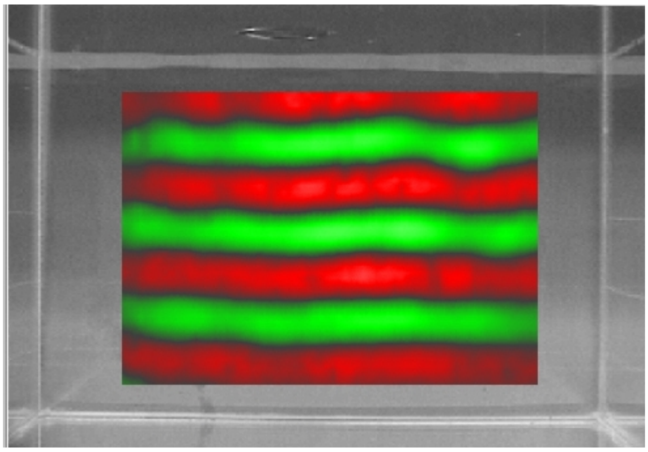

Fig. 9 Standing linear acoustic wave in water, excited by a centrally arranged transducer.

Surprisingly in the right example two stress-free regions evolve adjacent to the exciting axis. Reference measurements with classical laser vibrometry confirm this result. The stress-free region exhibits no motion at this point of the sample surface.

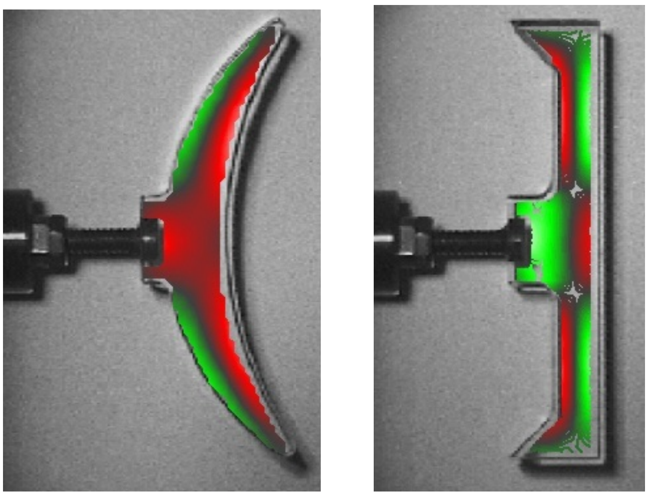

Fig.10 Inner dynamic stress distributions in horizontally excited Plexiglass samples

5 Conclusion

Based on a scanning laser-Doppler vibrometer, a novel method for the non-contact measurement and visualization of sonic waves is presented. With this method, impressive results in transparent gases, liquids and condensed matter can be achieved in both the ultrasound and audio ranges. Refracto-vibrometry is adequate for the investigation and visualization of numerous harmonic or non-harmonic periodic acoustic, fluidic and mechanic phenomena. Scientific and engineering tasks being tangent to these phenomena can be solved effectively and in a short time. In the field of education, the method has a large potential to make acoustics clearer and readier for application.

References

[1] L. Zipser, F. Wächter and H. Franke, “ Refracto-vibrometry for the Visualization of Sound Radiation from Vibrating Objects”, *Intern. Conference on Noise and Vibration,* Leuven, Belgium, 2006; Proc. ISMA 2006, ISBN 90-73802-83-0, pp. 3193-3200