Mapping of fluid pressure fluctuations using a scanning Laser-Doppler interferometer

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Introduction

Mapping sound fields can extend the understanding of sound creation and radiation. For an experimental recording of sound fields, pressure, velocity or intensity values have to be collected at many measurement positions with great effort. However, the presence of conventional sensors like microphones or anemometers may significantly influence the sound field. When investigating aero-acoustic noise sources the sensors may also disturb the flow and additional noise might be produced. These disturbances can be avoided by using Laser-Doppler interferometers. The method described here has been introduced e.g. by Lindner & Zipser. [1]-[4]

Basics

Functional principle

The method is based on the dependency of the refractive index on the local fluid pressure. A laser beam passes through the sound field and is back-scattered by a fixed reflector (see Figure 1). The optical path length along the laser beam varying with time according to the pressure variations can be detected by the Laser-Doppler interferometer. As a reference signal for the phase of the local pressure fluctuations e.g. a microphone outside the measurement field or the driving voltage of the sound source can be used.

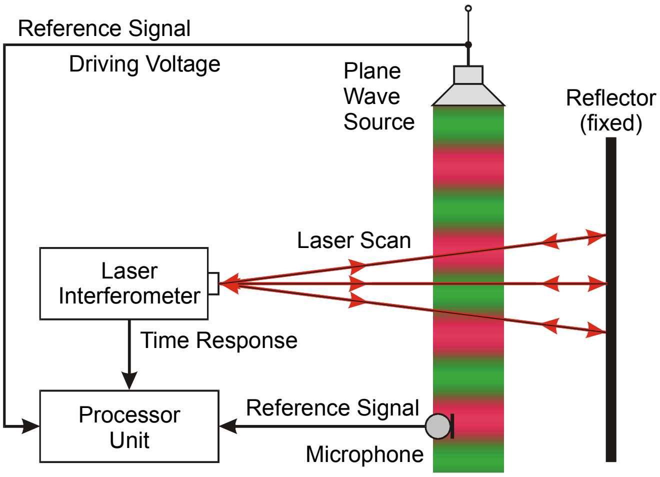

Figure 1: Functional principle

Relation between pressure, refractive index and virtual displacement

The pressure of the fluid will be considered having a static and a fluctuating component [3]

$$p_1(t) = p_0 + \Delta p(t) \ . \tag{1}$$

The same notation will be used for the refractive index

$$n_1(t) = n_0 + \Delta n(t) \ . \tag{2}$$

The relationship between the fluid density ρ and the refractive index n can be given with the Gladstone-Dale constant K: [5]

$$K \rho = n - 1 \ . \tag{3}$$

The adiabatic pressure-density relation with the adiabatic exponent κ is:

$$\frac{p_0}{p_1} = \left(\frac{\rho_0}{\rho_1}\right)^{\kappa} \ . \tag{4}$$

With (3) and (4) a dependency between pressure and refractive index can be established:

$$\frac{p_0}{p_1} = \left(\frac{\frac{n_0 - 1}{K}}{\frac{n_1 - 1}{K}}\right)^{\kappa} \ . \tag{5}$$

Some rearrangements and use of the notation of eq. (1) and (2) give

$$\Delta n(t) = (n_0 - 1)\left[\left(1 + \frac{\Delta p(t)}{p_0}\right)^{\frac{1}{\kappa}} - 1\right] \ . \tag{6}$$

Considering $p_0 >> \Delta p(t)$ the change of pressure is proportional to the change of the refractive index:

$$\Delta n(t) \cong \frac{n_0 - 1}{\kappa \, p_0} \Delta p(t) \ . \tag{7}$$

Virtual displacement at the interferometer

When the refractive index

$$n_{\text{fluid}} = \frac{c_{\text{vacuum}}}{c_{\text{fluid}}} \tag{8}$$

is changed, the optical length changes and the laser interferometer with the fixed reflector will display a virtual displacement $\Delta l(t)$. In order to determine the virtual displacement, the pressure fluctuations have to be integrated along the path of the laser (length L, see eq. (7)):

$$\Delta l(y,z,t) \cong \frac{n_0 - 1}{\kappa \, p_0} \int_0^L \Delta p(x,y,z,t) \, \mathrm{d}x \ . \tag{9}$$

Benefits and limitations

The laser interferometer is a widely used tool for mapping vibration amplitudes. The application of this method to sound pressure fields is easy. The main advantage compared to conventional techniques is the fact that no sensor influences the sound field. The visualization is possible in time domain and with a very high spatial resolution in two dimensions.

The integration of the pressure fluctuations along the laser beam causes an averaging over zones of low and high pressure. If the pressure is constant over the entire laser beam path (e.g. perpendicular to one-dimensional sound propagation) the value of pressure can be calculated.

Applications

Ultrasonic field

Our first example is the pressure field of an ultrasonic transducer emitting a continuous sine wave at 50 kHz. Various obstacles are placed in front of the transducer – see Figure 2. The picture shows areas of standing waves, deflection and reflection. This example demonstrates the capability of the method to visualize sound fields.

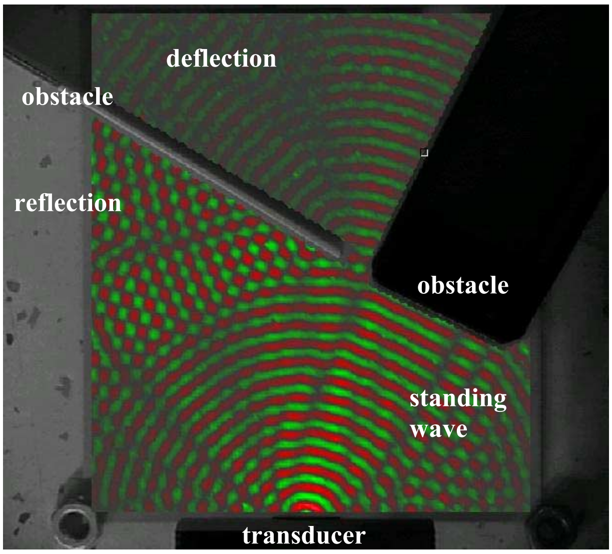

Figure 2: Sound field of an ultrasonic transducer with obstacles

Back-scattering of ultrasonic field

The next example demonstrates the ultrasonic field of a car parking aid. The radiation and propagation of the ultrasound and its back-scattering at a car bumper are investigated. For details see Figure 4 and [6].

Aero-acoustic noise generation

As an example of aero-acoustic noise generation a free jet on a plate with a small cylinder is shown in Figure 3. [7] The method shows both kinds of pressure fluctuations: turbulence and sound pressure. A differentiation between both types is possible considering the dimensions of the pressure fluctuations.

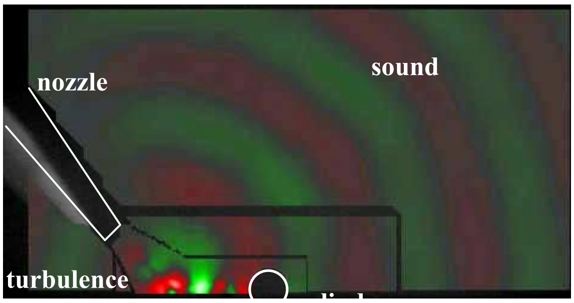

Figure 3: Aero-acoustic noise generation from a free jet on a plate with cylinder (air nozzle and cylinder white outlined)

Conclusion

Laser-Doppler interferometry provides an easy, ready to use tool for sound field mapping. No sensor influences the sound field. It is capable of visualizing varying pressure fields in time domain with a very high spatial resolution. Due to the averaging along the laser beam the method allows a quantitative and unique analysis for certain sound field situations only.

References

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[4] Woisetschläger, J. ; Lang, H. ; Hampel, B. ; Göttlich, E. ; Heitmeir, F.: *Laser-optical investigation of turbine wake flow*. Experiments in Fluids, Vol. 34 (2003) No. 3, 371-378

[5] Gladstone; Dale (1863), Phil. Trans, 153, 317

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[7] Thanks to Martin Fischer, Robert Bosch GmbH, Department FV/FLP for providing the example.

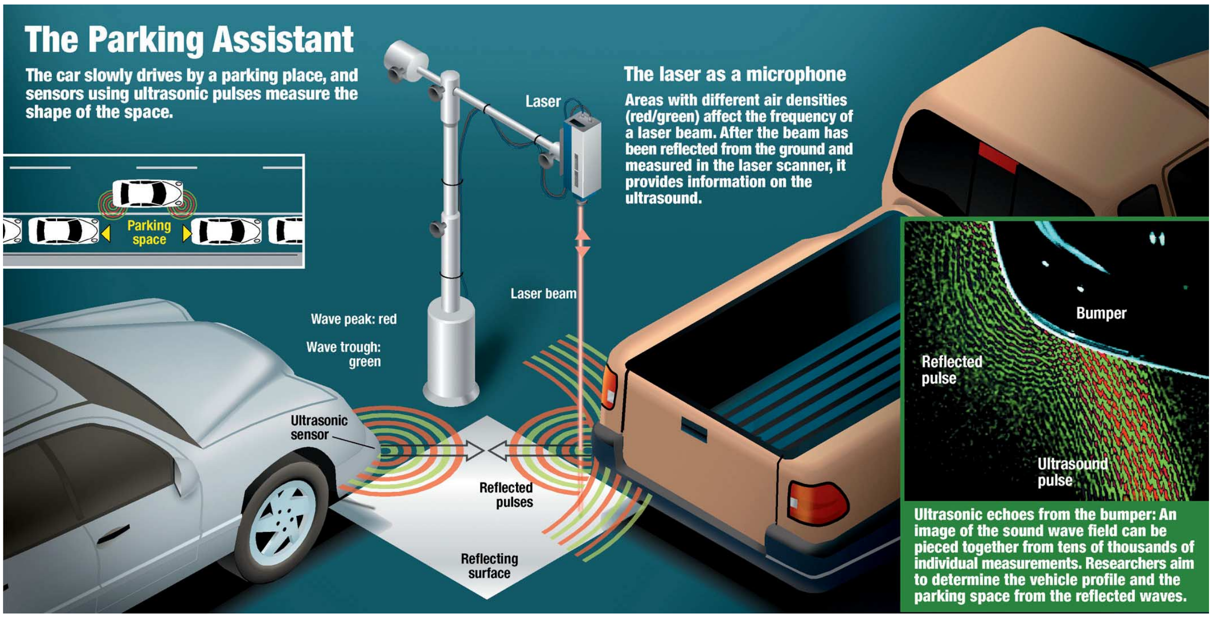

Figure 4: Mapping of an ultrasonic field of a car parking aid