SCANNING LASER VIBROMETRY FOR DETECTION NOISE SOURCES WITH HIGH SPATIAL RESOLUTION

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ABSTRACT

Analog to the Acoustic Camera the Scanning Laser Vibrometers are used for determining the sources of noise.

A single point He:Ne Laser Doppler Vibrometer measure the vibration velocity by sensing the frequency shift of back scattered light from a moving surface. By integrating a Single Point Laser Vibrometer with a dual axis mirror system the Scanning Vibrometer samples a specimens vibration pattern.

In contrast to the beam forming systems the scanning mirror system samples the surface step by step. The maximum scan frequency is 100 surface points per second. The high precision scan unit offers an angular resolution < 0.002° = 35 µrad with an angular stability of < 0.01°/hr = 175 mrad/hr. With a laser spot of about 75 µm per meter stand-of distance a very high spatial resolution is achieved.

In this paper common an different properties of the beam forming an scanning vibrometer systems are discussed. The differences in the measuring the structure-borne and the air-borne noise are discussed.

Like the beam forming systems the laser doppler systems be able to measure the sound propagation pattern. This method uses the effect that the laser light is decelerated in different degrees by the density variation of the air within an sound field.

1 INTRODUCTION

Laser Doppler Vibrometry is a widely used technique to determine the vibration characteristics of an object. This technique becomes more and more important in the field of acoustics. Prediction of a sound field and Visualisation of sound fields based on vibration data shall be introduced in this paper with typical applications.

2 BASICS

2.1 Basis of Interferometric Velocity and Displacement Measurement

Optical interference can be observed when two coherent light beams are made to coincide. The resulting intensity e.g. on a photo detector varies with the phase difference Δφ between the two beams according to the equation[1].

$$I(\Delta\varphi) = \frac{I_{\max}}{2} \cdot (1 + \cos\Delta\varphi) \qquad (1)$$

The phase difference Δφ. is a function of the path difference Δs between the two beams according to

$$\Delta\varphi = 2\pi \cdot \frac{\Delta s}{\lambda} \qquad (2)$$

where λ is the laser wavelength.

If one of the two beams is scattered back from a moving object (the object beam), the path difference becomes a function of time Δs=Δs(t). The interference fringe pattern moves on the detector and the displacement of the object can be determined using directionally sensitive counting of the passing fringe pattern.

On scattering from the object the object beam is subjected to a small frequency shift which is called Doppler shift f_D and is a function of the velocity component in the direction of the object beam according to

$$f_D = 2 \cdot \frac{v}{\lambda} \qquad (3)$$

Superimposing object beam and internal reference beam i.e. two electromagnetic waves with slightly different frequencies generates a beatfrequency at the detector which is equal to the Doppler shift. Without further means, the sign of the Doppler shift cannot be determined. The direction of the velocity can be determined by introducing an additional fixed frequency shift f_B in the interferometer to which the Doppler shift is added with the correct sign. This frequency shift is realized by an acousto-optical modulator (AOM, Bragg-cell). Thus the resulting frequency at the detector f_{mod} is given by

$$f_{\text{mod}} = f_B + 2 \cdot \frac{v}{\lambda} \qquad (4)$$

Interferometers of this type which are directionally sensitive are described as heterodyne.

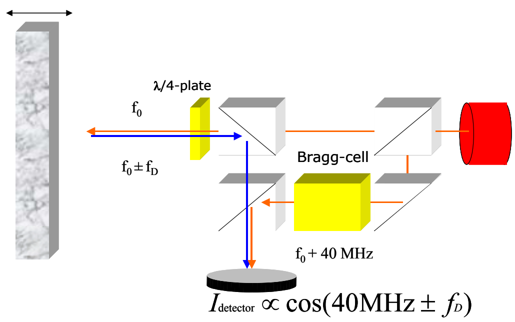


Figure 1: Heterodyne interferometer setup

2.2 Sound field visualisation

Highly precise interferometers for long term and static measurements have to take into account the refractivity of the medium. The refractivity in air is a function of the pressure and the temperature and can influence the measurement result. The influence of the humidity in air under lab condition is negligible. Edlen described that with the empiric formula[2].

$$n = 1 + 2.8793 \cdot 10^{-7} \cdot \frac{P}{1 + 0.003671 \cdot T} \qquad (5)$$

n: refractive index
T: ambient temperature
P : ambient pressure [hPa]

Sound originates when an object moves back and forth so that the air becomes compressed and expanded. The compression and expansion cause a pressure fluctuation in the air. As seen in Edlen´s formula a fluctuation of the pressure leads to a fluctuation of the refractivity.
When light goes through a sound field, the optical path length Δs_{opt} will be influenced as well as the refractive number.

$$\Delta s_{opt} = s \cdot \Delta n = s \cdot (n_2 - n_1) \qquad (6)$$

Δs_{opt}: optical path difference
s: direct path
Δn: refractive number difference

Using equation (5) in equation (6) results in

$$\Delta s_{opt} = s \cdot \frac{2.8793 \cdot 10^{-7}}{1 + 0.003671 \cdot T} \cdot (P_2 - P_1) \qquad (7)$$

This shows that a pressure difference in the air, as in a sound field, causes a refractive number difference and thus optical path difference.

Focussing the laser beam of an interferometer through a sound field on a rigid body, the Δs_{opt} can be measured directly and can be used to visualize the emitted sound field of a vibrating object.

3 MEASUREMENTS

A Laser Scanning Vibrometer is an excellent device to measure the time and position dependent Δs_{opt} in a sound field.
A Scanning Vibrometer (PSV-400) moves the laser beam automatically with the highest lateral resolution on a user defined scan grid through the sound field and measures Δs_{opt} for every scanpoint. An internal generator can be use to control the excitation of an vibrating object and to syncronize the phase between the measurement points.

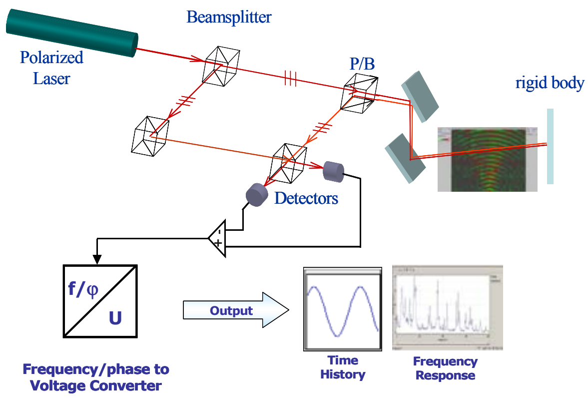


Figure 2: measurement setup with a Laser Scanning Vibrometer

While the laser beam moves through the soundfield over the surface of the rigid body like a wall, the data management system aquires the refractivity difference either as a virtual velocity or displacement on the rigid body.

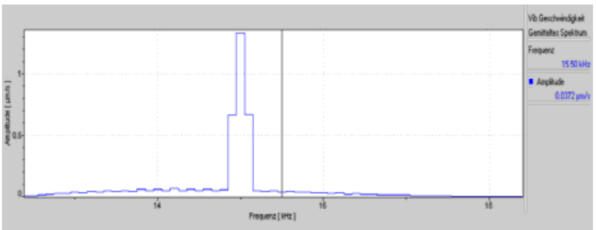


Figure 3: virtual velocity

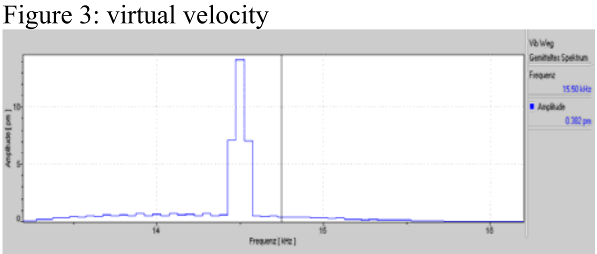


Figure 4: virtual displacement

Figure 3 shows the virtual velocity on a rigid body measured through a sound field of a loudpeaker. The excitation signal was a sine signal at 15kHz. Figure 4 shows the integrated velocity signal from figure 3 which gives a good impression of the resolution of the system. The noise floor is 0.38 pm at the cursor position after 20 averages.
With equation (7) one can calculate the minimum measurable pressure fluctuation in air. With s = 1m and Δs_{opt} = 0.38pm we get a minimum measurable pressure of 142µPa .

An interferometer integrates the refractivity along the laser beam through the sound field. This means when a soundwave occurs, which is not a plane wave, positive and negative refractive number fluctuation can cancel out each other.
That is the case when the vibration behavoir of a loudspeaker membran is measured directly. When a laser beam goes through the area A in figure 5, the sound wave has no influence at all on the vibration measurement. The positive and negative refractive number fluctuation cancel out each other. Not until the laser beam goes through the area B it has an influence, but this so small that it can be neglected.

Even when the refractive number fluctuation has no influence on vibration measurements, the virtual velocity of a soundfield is about 4 orders of magnitude smaller than the real surface vibration velocity, which cause the sound field..
On one hand the sound field can be measured and visualized and on the other the sound field does not influence a vibration measurement.

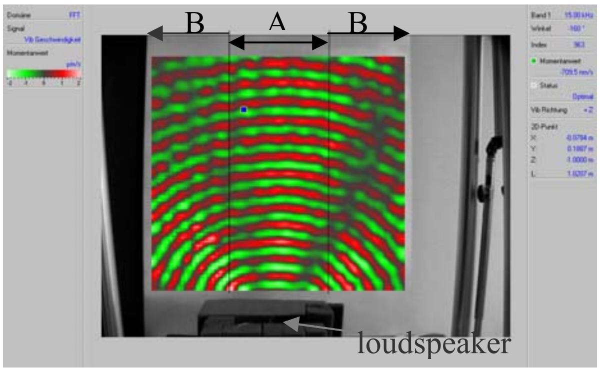


Figure 5: sound wave propagation of a loudspeaker, 4221 points have been measured

Figure 5 shows the sound field of a loudspeaker excited with a sine wave at 15kHz. The PSV-400 provides not only such a picture, but also a movie to get an impression of the soundwave propagation.
The wavelength of the sound wave can be easily measured by using the geometry modul of the PSV-400. The geometry modul measures for every point the geometry (x,y,z- coordinates). By using the point cursor it is easy to measure the distance between two maxima of the sound wave.

With time data analysis not only stationary, but also transient processes can be investigated as long as they are repeatable. As an example the sound field in front of a loudspeaker has been measured. The loudspeaker has been excited with a single pulse of a sine wave at 16 kHz.

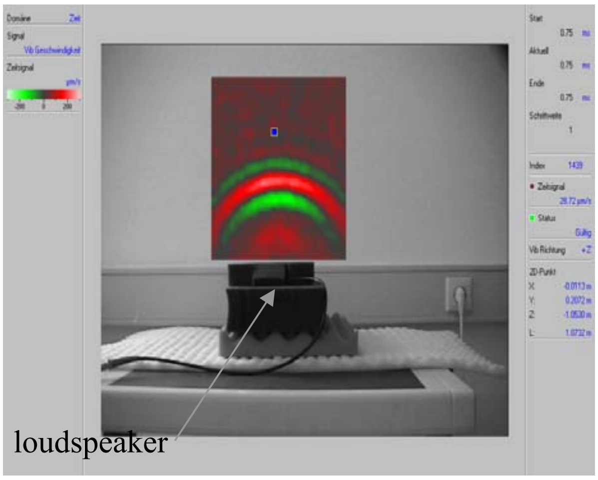


Figure 6: sound wave propagation of a single sine puls

Figure 6 shows the wave propagation 0.75ms after the pulse. The software can also display the whole propagation as an animation.

Another example for this measurement technique shows figure 8. 2419 points have been measured to display the soundfield of a jigsaw.

In figure 6 are the relevant resonances clearly visible. Each frequency can be selected for an animation as shown in figure 8

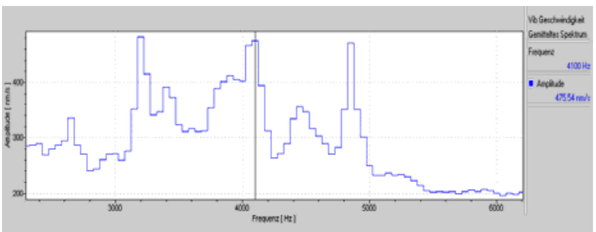


Figure 7: average spectrum of the jigsaw

In the following picture is the animation shown for the selected frequency of 4100Hz.

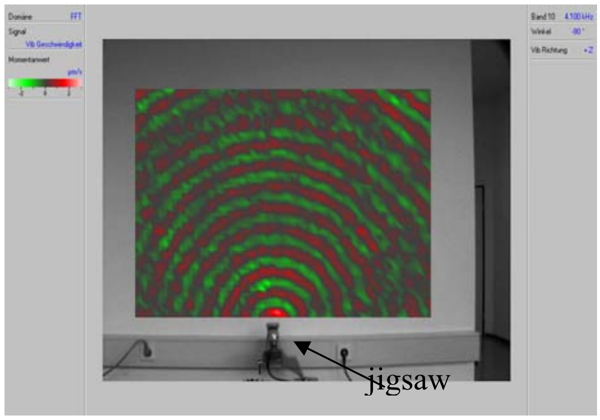


Figure 8: sound wave propagation of a jigsaw at 4100Hz

A second sensor was used for this measurement. As a phase reference a second single point laser vibrometer have been chosen, but also a microphone would have been possible. This is in difference to the loudspeaker measurement, where the internal generator has been used for the phase reference between the scanpoints.

4 SOUND FIELD SIMULATION BASED ON STRUCTURAL POLYTEC VIBROMETER DATA

Simulating the sound field requires the operational deflection shape (ODS) of the vibrating structure. The ODS can be obtained either by a finite element method (FEM) calculation or directly by a vibration measurement.
Sound field simulation based on the FEM requires in the first step a structural FE-model and an estimation of the mechanical properties (mass, stiffness) and the boundary conditions (excitation forces). The FEM calculates the vibration behavior of the vibrating structure based on these estimated parameters.
In a second step various methods like BEM, FEM, IFEM, HFA can be used to predict the sound radiation of the simulated vibrating structure.

The estimation of the mechanical properties and the boundary conditions is very difficult, needs a lot of experience and has big uncertainties, especially for high frequencies.
When in a later development process a test object (prototype) is available, the FE-model can be updated by using vibration data from a measurement. This makes the FE-modell and also the sound prediction of the vibrating object more accurate.

A different approach is to measure the ODS directly in order to predict the sound radiation by using above mentioned methods. This has the advantage that the structure is measured under real operating condition, and with this to avoid the uncertainties from the approximation mechanical properties and the boundary conditions.
In the following the procedure from measuring the vibration of the structure to simulating the sound field shall be shown.
The sound simulating software NADwork has been used, but all other software can be also used, who have directly access to the binary file of the Polytec data or who can import the universal file.

4.1 Measurement

4.1.1 Loudspeaker

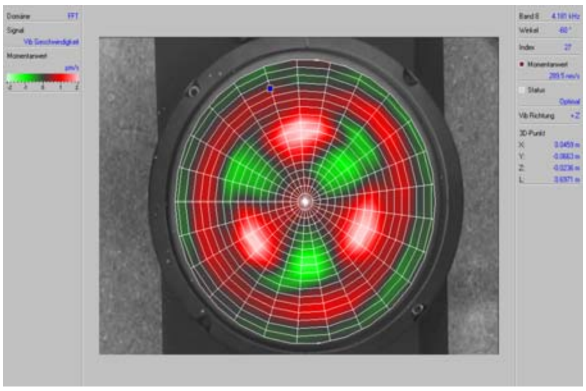


Figure 9: ODS of a loudspeaker membrane at 4181Hz

Figure 9 shows the Laser Scanning Vibrometer measurement on a loudspeaker membrane. 488 points have been defined. The excitation was a broadband exciation, a periodic chirp signal. Before the frequency spectrum has been measured for every scanpoint, the system measured the geometry coordinates. The geometry is important for the sound prediction, when the radiating surface is not flat. The grid with the geometry information can be directly imported to the simulation software.

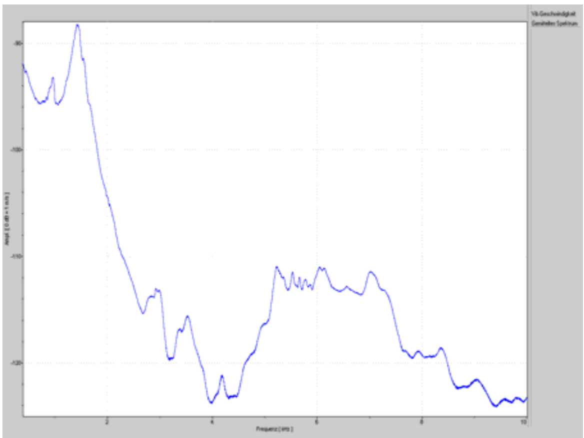


Figure 10: averaged frequency spectrum of all 488 points

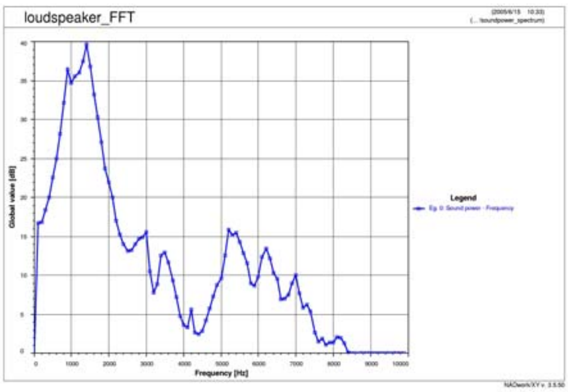


Figure 11: calculated soundpower power spectrum of the loudspeaker

Figure 10+11 show that the calculated sound soundpower spectrum and vibration velocity match quite good in the frequency.
A similar matching can also be shown between vibration measurements and sound intensity measurements.

The NADwork sound simulation software can now be used to simulate the soundfield in a plane, which has a certain distance from the object or in a hemisphere with a certain diameter[6].
Furthermore the sound intensity on the surface itself and be calculated and displayed as shown in the following figures.

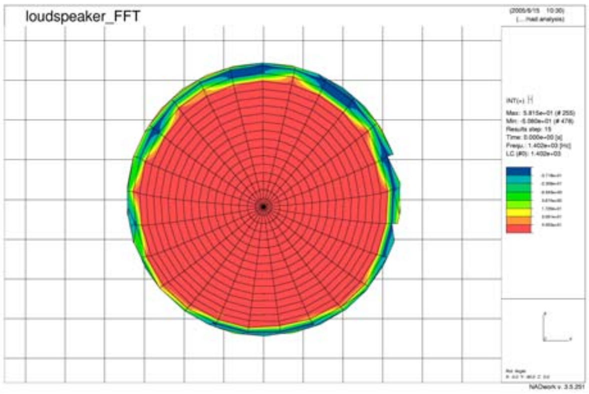


Figure 13: sound intensity on the loudspeaker membran at 1,4kHz

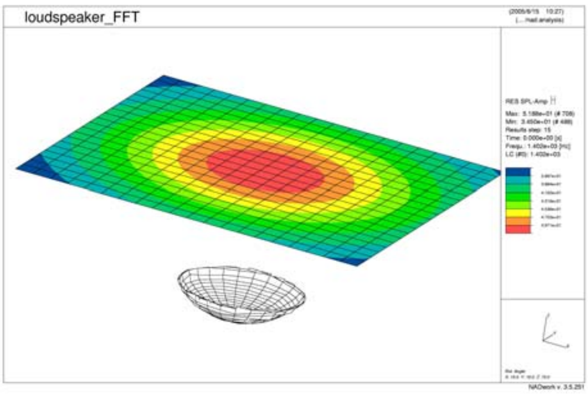


Figure 12: Sound pressure at 0.5m distance, 1.4kHz

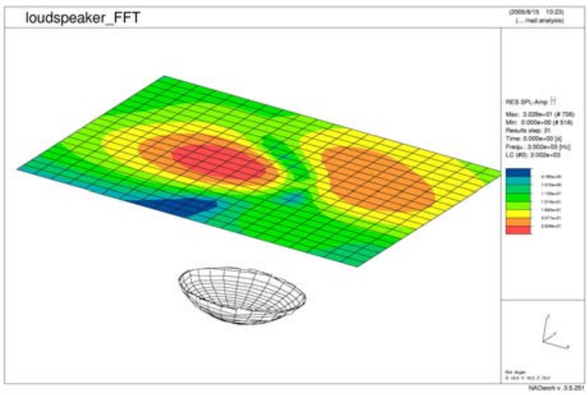


Figure 14: Sound pressure at 0.5m distance, 3kHz

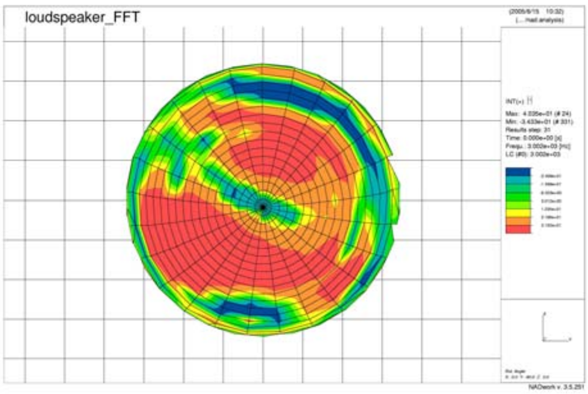
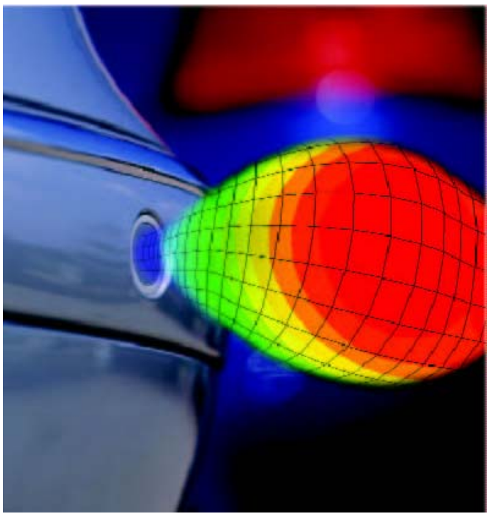


Figure 15: sound intensity on the loudspeaker membran at 3kHz

5 SUMMARY

The visualisation of sound fields using laser vibrometry has been already investigated a few years ago by Prof. Zipser from HTW Dresden and his colleagues[3;4;5]. Since that time this technique found more and more industrial application e.g. optimisation of ultrasound sensors as a parking aid in the automotive.



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It has been shown that stationary processes as well as transient processes can be investigated in the frequency and time domain.
In addition this technique can be used also for the visualisation of the airflow of e.g. valves as long as the flow is stationary over the measurement time or transients are repeatable[3;4].

A different approach is the sound field simulation based on vibration data. It is a great tool for sound engineers to make their daily work easier, faster and more accurate. The data can be used to improve the current prototypes and to build up experience of the next generation product.

[1] Polytec, "Manual Controller OFV-3001", Man-Vib-OFV3001-1202-05e

[2] B. Edlen, "The refractive idex of our", Metrologia 2, 71-80 (1966)

[3] L. Zipser, H. Franke, "Laser ScanningVibrometry for the investigation of sound generation and propagation", SPIE Vol.5503

[4] Patent, Zipser.L, Behrendt.R, Lindner.S, DE010057922C2, 2002

[5] L. Zipser, S. Lindner, R. Behrendt, Interferometrische Messung und Visualisierung von Schallwellen und Turbulenzen, Technisches Messen 6/2002, S. 275-281

[6] *NAD*work Polytec Connection, Software NAD GmbH, Wien

[7] Eugen Hecht, „Optik", 1974

[8] P.Castellini, M.Martareli, „Aeroacoustic Characterisation of Turbulent Free Jets using Scanning Laser Doppler Vibrometry", 6th international Conference on Vibration Measurements by Laser Techniques 2004

[9] Bosch Research Info, Issue 3/2003, Ultrasonic puls of automotive parking assistance – listening about 0.2 second