MEASURING THE 3D PROPAGATION OF SOUND WAVES USING SCANNING LASER VIBROMETRY

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1 INTRODUCTION

In standard application **S**canning **L**aser **D**oppler **V**ibrometer (SLDV) are used determining structure-born noise surces by mapping the surface vibration velocity without touching. But in automobiles direct noise excitation sources contribute to the noise significantly. Here no vibrating object surface are the source of noise and so standard SLDV-measuring cannot give any information. A modification of the SLDV-arrangement provides new opportunities measuring sound fields and flow patterns in gases, fluids and (transparent) condensed matter. This new laser-optical method is already well established in the field of visualisation ultrasonic waves.

But the method is well applicable for the lower frequencies in the typical hearsound region. This is demonstrated investigating the noise generation and sound propagation from generator and intake of powerplants – two typical sources of airflow noise. In industrial R&D applications the Researchers like the high local resolution, th high dynamics and the possibility to trace the sound waves in detail. Combining these laser optical measurements with numeric tomography reconstruction true 3D informations for the sound field can be determined.

There are two proposals for the name of this new measuring method: Refracto-Vibrometry and Light Refractive Tomography.

2 BASICS OF LASER DOPPLER SOUND FIELD VISUALISATION

In the classical Laser Doppler Vibrometry the vibration velocity of a object surface is measured non-contacting in a scanning mode step by step. One dimensional 1D measurement for the perpendicular component (Out of Plane) as well 3D measurements are possible to determine the structure-born sound sources.

It is wellknown that the acoustic pressure wave $\Delta p\ (t, x,y,z)$ has an influence to the refractive index n of the air and so to the measuring signal. Refractive number fluctuations generate a virtual vibration velocity signal but whose value is 3 to 4 orders of magnitude smaller than the real mechanical surface vibration velocity [2, 3].

Nevertheless, this small virtual vibration signal can be sufficient for measuring and visualizing sound waves [2, 3]. Focussing the laser beam of the SLDV trough a sound field on an absolutely rigid reflector, the "virtual" optical path difference Δs_{opt} can be measured and can be used to visualize the sound field (fig. 1).

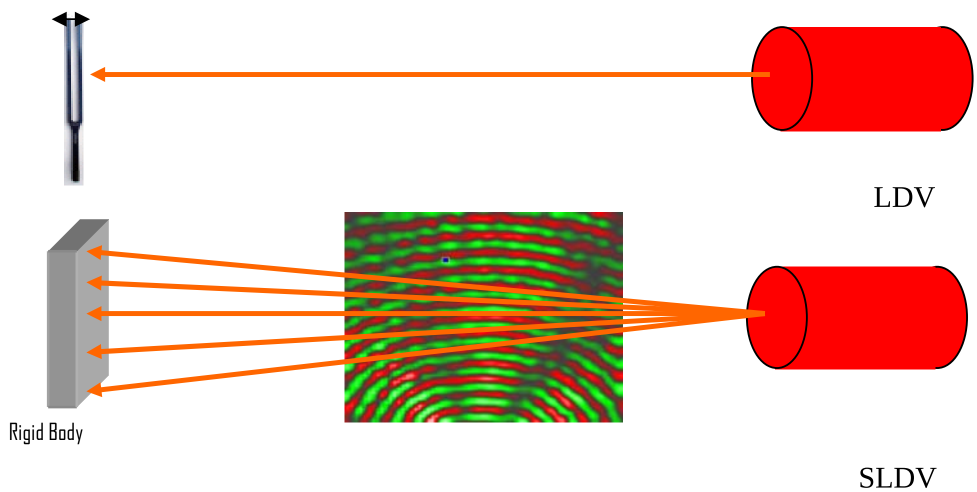


Fig. 1 Standard one point out-of-Plane measurement of the surface vibration – top
Measuring configuration for sound field visualizing using SLDV-system – down

The pressure induce virtual vibration displacement signal is

with: $$\Delta s_{opt} = s \cdot \Delta n = s \cdot (n_2 - n_1)$$ <1>

Δs_{opt} : optical path length difference (virtually)
s : geometrical path length difference
Δ : refractive index difference

The dependence of the refractive index on pressure p, temperature T and relative humidity RH is given by a modified Edlen formula /4/.

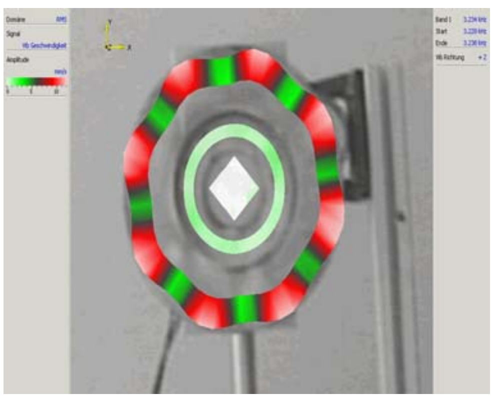
with:

$$n = 1 + 7.86 \cdot 10^{-4}\, p/(273 + T) - 1.5 \cdot 10^{-11} \cdot RH(T^2 + 160) \qquad \text{<2>}$$

p in kPa, T in °C, RH in %

$$\Delta n/\Delta p = 2.68 \cdot 10^{-6} \text{ per kPa} \qquad \text{<3>}$$

Fig. 2 show typical measuring results of scanning standard SLDV-measurement of a shaker excited brake disk.



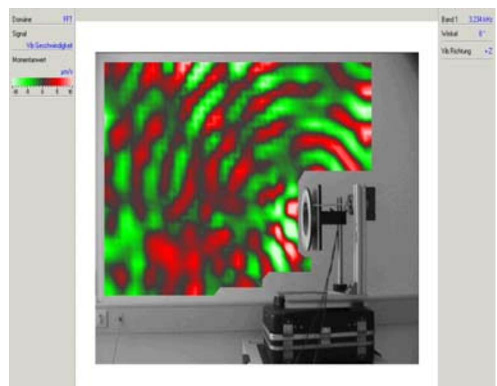


Fig.2 left – deflection shap of a shaker excited brake disk, 3234 Hz, out of plane vibration
right – visualizing the sound field in front of the brake disk

The amplitude of the sound field are about 3…4 orders of magnitude smaller than the real surface vibration velocity, which cause the sound field.

3 EXERMINATION OF AIR-BORNE NOISE IN VEHICLES

In modern automobiles the structure-born sound contributions of combustion process and mechanical components are reduced significantly. So sound sources with direct noise excitation becomes more and more dominant. Typical sources of air-born noise are cooling air fan, generator pulley and fan, belt drive systems and intake airflow. Especially for these noise sources the sound wave visualisation offers an ideal experimental tool to find the locations where the noise originates.

3.1 Example Generator Air-Borne Noise

Classical microphone measurements exhibit an enlarged sound level in the neighbourhood of generator. But the measurement structure-born vibration spectrum at the generator surface don't correlate to the sound pressure spectrum.
Therefore it is assumed that air-born noise mechanism are the origin of the enlarge generator noise. In a preliminary acoustic test the sound pressure level of the generator were measured both with build in fan impeller and without build in fan impeller. The spectra of both measurements are just differing as it is shown in Figure 3.

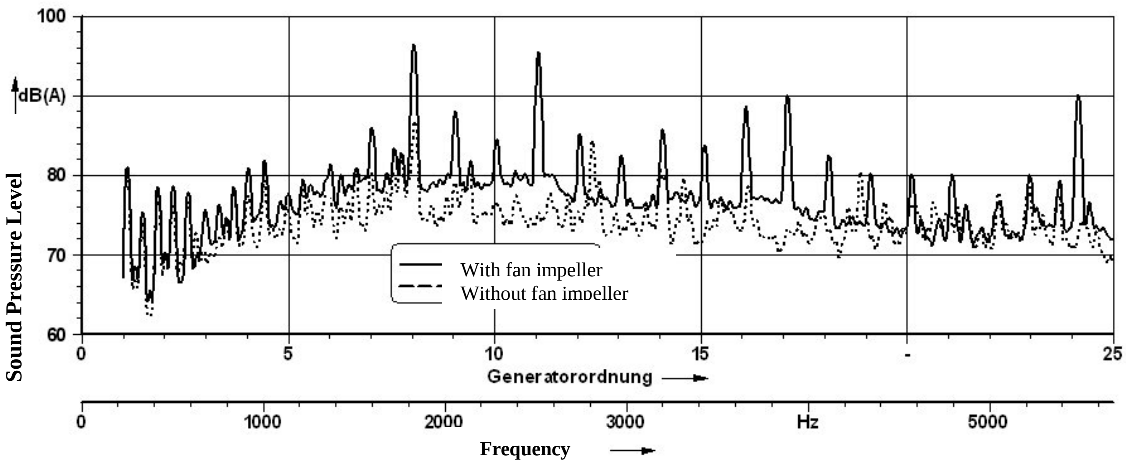


Fig. 3 Spectrum Generator Noise with and without fan impeller – Engine Speed 5000 RPM

This suggested that air-borne noise mechanism are the main source for the enlarge noise of this generator.
Figure 4 shows the 16-channel microphone array used in the acoustic Beamforming measurements and the result for the dominant noise frequency of 2730 Hz. It is well visible that the noise peak in the 2730 Hz band corresponds with the location of the generator. But the acoustic beamforming method is not able to resolve details.

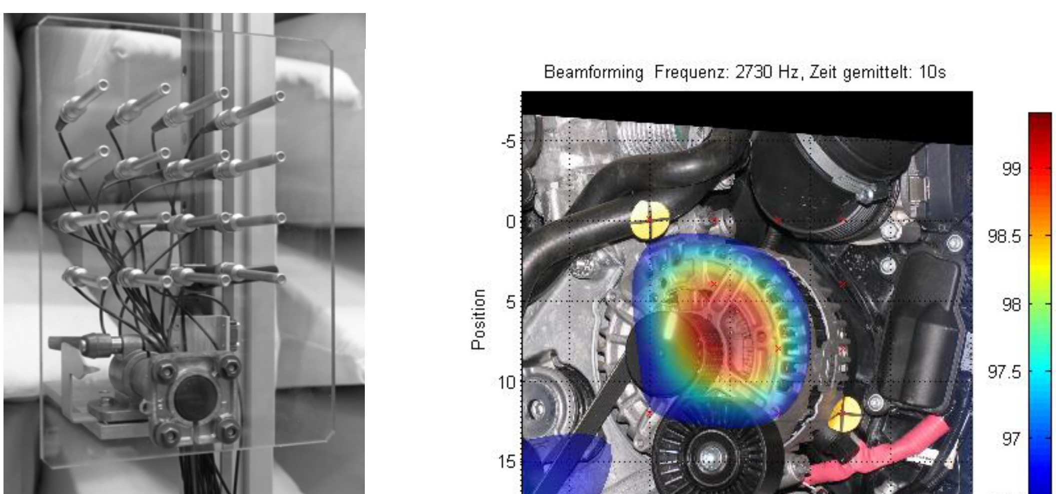


Fig. 4 left – 16-channel microphone array, pitch 14 cm used exterminating the generator noise
right – measured noise distribution nearby the generator – 2730 Hz band

The SLDV sound field measurement delivers a significant higher spatial and time resolution. This is shown in Fig. 5 for two different phase angle to the reference microphone.

Fig. 5 SLDV soundfield measurement – 2730 Hz band
left – phase angle 100°, right – phase angle 135°

In the result of the SLDV measurement the ventilation louvers of the generator housing are identifiable as the source of the airflow-born noise. The peak frequency of 2730 Hz corresponds to the cam speed of the generator 13550 RPM and the blade number 12 of the generator fan.

3.2 Example – Intake Noise

The intake noise is another dominant airflow born noise source in automotive combustion engines. Fig. 6 shows the arrangement of the 22-channel microphone array used for the comparable measurement. In the Beamforming picture the noise source nearly the end of the intake manifold is visible clearly.

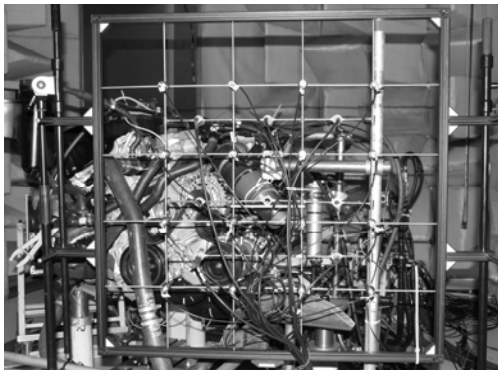
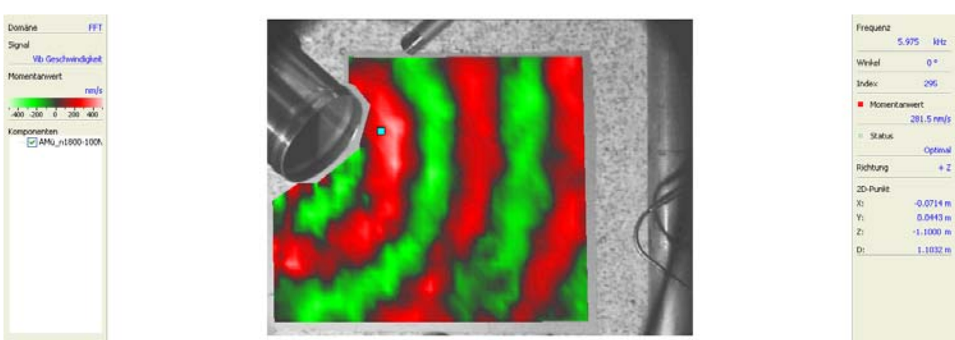


Fig. 6 Acoustic beamforming measurement to locate the source of intake noise
left – arrangement of the array, pitch 15 cm, stand of 50 cm
right – Beamforming result for 1900 Hz

Again the SLDV measurement delivers more details of the airflow born noise generation. In the background of Fig. 7 two main parts of the SLDV measurements are shown: the granite plate using as rigid reflector and the reference microphone using as fixed sensor for the phase information.



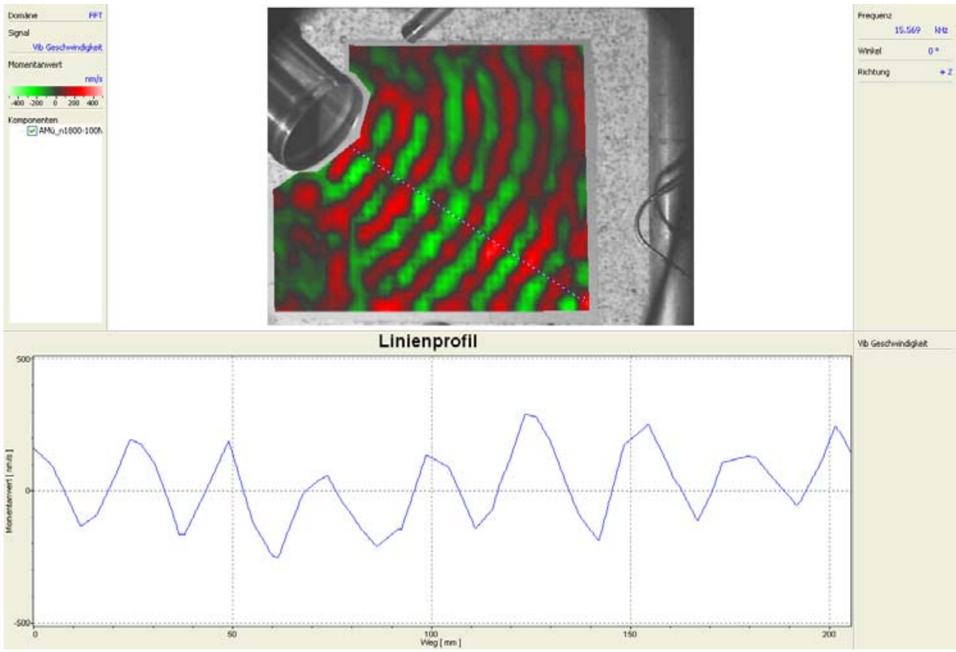


Fig. 7 Intake noise – sound wave propagation measured by SLDV
top – 5975 Hz, down – 15570 Hz

The measured length of the acoustic wavelength corresponds with the well known sound velocity of air.

4 CONCLUSION AND OUTLOOK

The method of the SLDV sound field visualisation becomes established not only in proper laboratory conditions but also in the harsh environments of industrial test blocks. The crossover from qualitative measurement to quantitative analysis is going on. Zipser etal [4] analyse fitting models for nearly plane waves. Getting real 3D informations Bahr and Lerch [6] as well Olsson [7] use tomographie methods for 3D alignment. Local (geometrical) resolution and dynamic range are higher comparable to acoustic Beamforming methods. On the other hand the SLDV method is not applicable for single shot transient processes.

For periodic transient processes the SLDV method is easy to apply. Many industrial applications are know. Researchers can zoom in on the locations where the noise originates and can trace the propagation of the sound waves in detail [8, 9].

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