Sound field simulation and visualisation based on Laser Doppler Vibrometer measurements

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Optimisation of acoustical and vibrational properties of components has a very high priority already in the early development process. Both can either be measured directly or simulated. Simulation is in the first instance a good approximation, but have to be validated with measurements during the development process. Laser Doppler Vibrometry is already an accepted and widely used technique to measure very accurately and with highest point density the structure borne sound without touching the object surface. The contactless measured data of the Polytec Scanning Laser Vibrometer cannot only be used to measure the operational deflection shapes or to determine the modal parameters of a dynamic system, but also to calculate the sound field of a vibrating structure and to visualize a sound field. The working principle will be introduced and different examples are shown in the Polytec paper.

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 Theory 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].

\[ I(Δφ) = \frac{I_{\text{max}}}{2} \cdot (1 + \cos Δφ) \]  \hspace{1cm} (1)

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

\[ Δφ = 2π \cdot \frac{Δs}{λ} \]  \hspace{1cm} (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

\[ f_D = 2 \cdot \frac{v}{λ} \]  \hspace{1cm} (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 $f_{\text{mod}}$ is given by

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

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

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 $\Delta s_{\text{opt}}$ will be influenced as well as the refractive number.

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

$\Delta s_{\text{opt}}$: optical path difference
$s$: direct path
$\Delta n$: refractive number difference

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

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

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 $\Delta s_{\text{opt}}$ can be measured directly and can be used to visualize the emitted sound field of a vibrating object.

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].

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

Figure 1: Heterodyne interferometer setup

3 Measurements

A Laser Scanning Vibrometer is an excellent device to measure the time and position dependent $\Delta s_{\text{opt}}$ 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 $\Delta s_{\text{opt}}$ for
every scanpoint. An internal generator can be use to control the excitation of an vibrating object and to synchronize 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 loudspeaker. 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 $\Delta s_{opt} = 0.38pm$ we get a minimum measurable pressure of $142\mu Pa$.

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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. 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 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.

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

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

A second sensor was used for this measurement. As a phase reference a second single point laser vibrom eter 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.

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.
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 excitation, 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 10+11 show that the calculated sound power 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[4]. Furthermore the sound intensity on the surface itself and be calculated and displayed as shown in the following figures.

Figure 11: calculated soundpower power spectrum of the loudspeaker

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

Figure 13: sound intensity on the loudspeaker membran at 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]. Since that time this technique found more and more industrial application e.g. optimisation of ultrasound sensors as a parking aid in the automotive.

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.