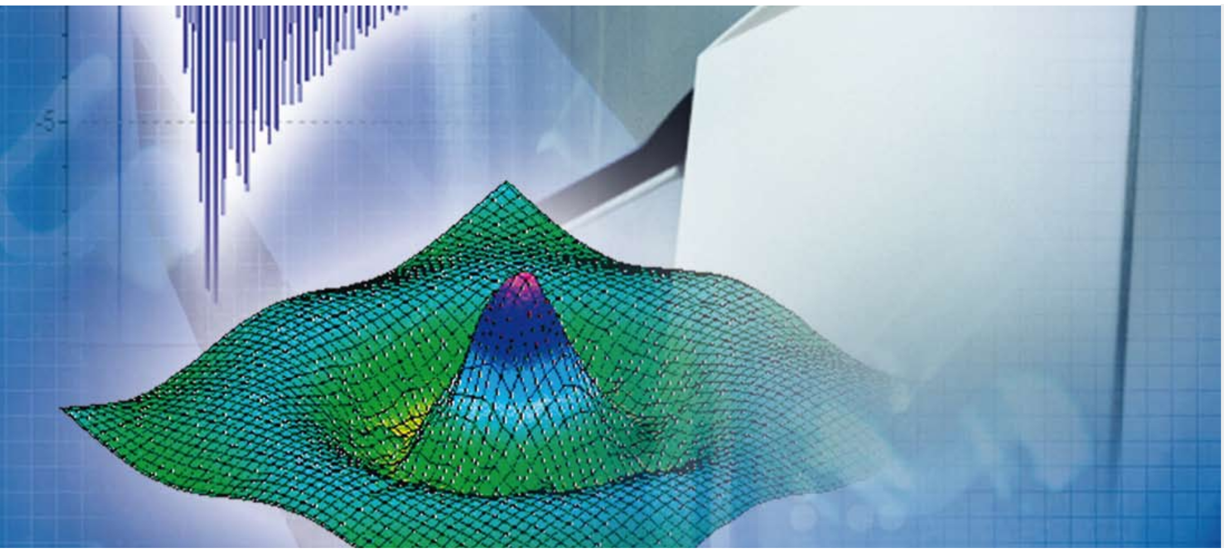
Refracto-Vibrometry



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Refracto-Vibrometry: Making Sound and Ultrasound Visible

Scanning laser vibrometers have been used successfully for years now in ultrasonic technology, allowing surface vibrations with tiny amplitudes and high frequencies to be made visible. Apart from harmonic vibrations, the new generation of instruments can also acquire periodically repeating time sequences. It is still a relatively unknown fact that scanning laser vibrometers can also be used to make sound and ultrasonic waves visible in 2-D. In this contribution several applications will be discussed.

The Classic Laser Vibrometry Application: Visualization of Surface Waves

In ultrasonic technology, resonance vibrations of solids (i.e. harmonic vibrations) are typically excited with frequencies above the auditory threshold of 20 kHz. In this frequency range, only minimal deflection amplitudes can be generated (typically 20 to 50 µm and in extreme cases >100 µm), which is why they are not visible to the human eye. To measure these vibrations, special measurement technology is required. Laser vibrometry is an ideal measurement process for visualizing surface waves in ultrasonic technology (see Fig. 1). It measures without making contact, allows quick 2D acquisition of harmonic vibrations and, as it measures velocity directly, it has absolutely no problem with the extreme conditions in ultrasonic technology.

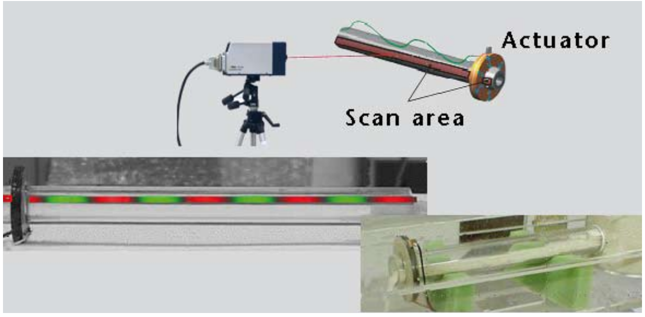

Fig. 1: Scanning laser measurements of an ultrasonic powder metering system showing a deflection shape.

Refracto-vibrometry for Visualizing Sound Distribution

In many ultrasonic technology applications, piezoelectric ultrasonic generators are used to radiate ultrasonic waves in fluid media (air or water). Known applications with sound radiation in water are ultrasonic cleaning technology, ultrasonic flow measurement technology, sonars and echo sounding as well as sonographic applications in medical technology (e.g. pregnancy diagnostics).

An important application using ultrasonic radiation in air is distance sensor technology or range finding. Commercial applications of this technology cover hand-held measuring devices for hobby and trade to professional solutions for industrial automation, including distance sensors used in automotive parking and backup warning sensors.

For all these applications, the targeted ultrasonic distribution in space (the so-called sound cone or radiation pattern) is of great importance for ensuring that the systems work reliably. Laser vibrometers offer the option of measuring this distribution by making non-contact measurements of the sound pressure waves in air.

This process is called refracto-vibrometry and makes use of the fact that a pressure change based on a sound wave always results in a change in density in gases and therefore leads to a slight change in the optical refractive index. For a laser beam sent through the medium, this means a change in the transit time of the lightwave from which the local pressure can be deduced.

Correspondingly, the name "Refracto-vibrometry" can be explained as a symbiosis of the terms "refraction" (approximately: bending light) and "vibrometry". Basic effects on refraction of light by ultrasonic waves (e.g., Debye-Sears and Doppler effects) are explained in Kuttruff [1]. Zipser et al. [2], [3], [4] and Matar et al. [5] explained how to measure pressure distributions contactless using scanning vibrometers and then visualize them as an animation with time. For this purpose, it is practical to use an assembly in which the laser beam transmits through a propagating ultrasonic wave and is reflected back from behind the sound field by a stationary reflector (Fig. 2).

Applications of this technique are presented in [6] and [7]. Post-processing of the Scanning Vibrometer data after the measurement shows a virtual velocity distribution which an untrained user might incorrectly interpret as the surface movement of the reflector. However, it is a qualitative representation of the distribution of the acoustic pressure in the area of interest, as is shown in the example of the sound pressure distribution under an ultrasound-based levitation oscillator according to Lierke [10] as shown in Fig. 3.

A certain degree of caution needs to be exercised when interpreting the measurement result precisely, as every measurement point is an integration of the sound distribution along the path which the laser beam traveled on its way from the measuring instrument to the reflector and back again. Mathematically this can be expressed by a line integral along the beam path [8], [9].

For plane waves as shown in Fig. 2, the virtual velocity value shown by the vibrometer is directly proportional to the sound pressure at the respective location (assuming a sufficiently large measurement distance between the vibrometer and the object). For non-planar sound pressure distributions, the precise values of the sound pressure can be determined with a reasonable amount of care. For example, the standing sound wave formed under the positioner shown in Fig. 3 is a rotationally symmetrical sound distribution appearing uniform only because of the 2-D representation. When properly examined, a sound pressure level of approx. 166 dB was ascertained for the points of maximum sound intensity in the standing wave. The process for calculating the sound pressure level from the measured virtual velocity is described in greater detail for the example shown in [8].

For complicated sound pressure distributions, refracto-vibrometry quickly provides a good qualitative overview of the real sound distribution which might otherwise require much greater effort and time. This is extremely helpful when

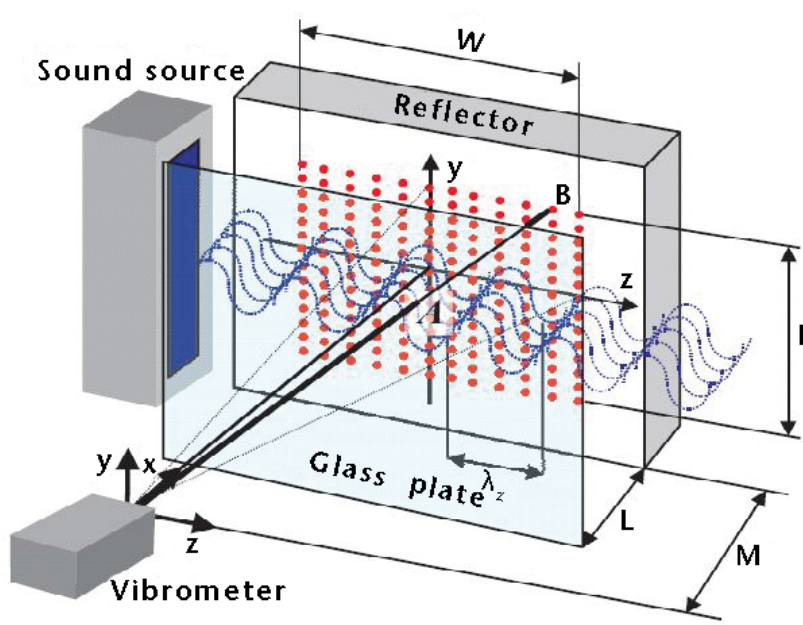

Fig. 2: The arrangement of a Scanning Laser Vibrometer and corresponding reflector to provide Refracto-vibrometry measurements on a propagating sound or ultrasonic plane wave in air (according to Zipser et al. [9]).

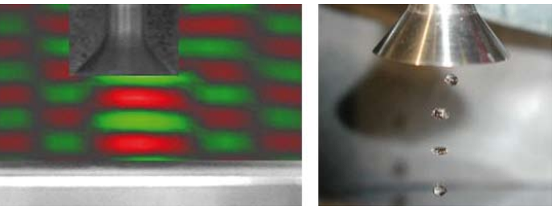

Fig. 3: Sound pressure distribution under an ultrasonic transducer that generates a standing wave in the air (effectively a standing wave positioner according to Lierke [10]). The image on the right shows water droplets which are kept suspended by the standing wave in the sound pressure nodes. The measurements were made jointly with colleagues from the Mechatronics and Dynamics group at the University of Paderborn.

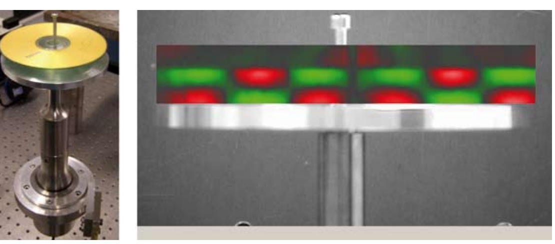

Fig. 4: Ultrasonic vibration of a circular bending plate causes a compact disc to levitate [11]. By means of refracto-vibrometry, an impression of the sound pressure distribution in the resonance sound field can be easily obtained.

there is no precise a priori knowledge of the sound pressure conditions. An example is given by the sound pressure distribution for the ultrasonic air cushion shown levitating a compact disc in Fig. 4, [11]. In the figure, the pressure distribution in the resonance sound field created underneath the CD is shown. The levitated CD, itself, acts as a sound reflector.

Because the laser beam passes through several circular zones here with high and low sound pressure, the quantitative calculation of the sound pressure is very complicated and would require special tomographic reconstruction procedures. At the 9th Polytec vibrometer seminar, a tomographic procedure was presented which can be used to quantitatively reconstruct the sound pressure distribution of an ultrasonic emitter suspended in water using a refracto-vibrometric measurement [12].

The technique is particularly impressive when refractometric measurements are made with scanning vibrometers on periodic signal sequences of arbitrary shape rather than of sinusoidal shape. At ATHENA Technologie Beratung GmbH, the sound wave of a manual device for measuring distances working using the pulse-echo method was analyzed. In Fig. 5, an instantaneous image of the pressure wave packet "Impulse" is shown while traveling at c = 344 m/s (speed of sound) from the converter to the reflector. The ultrasound frequency, f = 40 kHz, results in a separation of pressure maxima corresponding to the wavelength, $\lambda = c/f = 344\ (m/s)/40\ kHz = 8.6\ mm$.

The ultrasonic range finder determines the distance from the reflector automatically on the basis of the transit time measurement of the wave packet which travels from the transducer to the reflector and back. Immediately after the piezoelectrically generated ultrasonic burst at the transducer's radiating surface decays, the transducer switches over to receiver mode and the time is measured until the sound echo wave causes the piezoelectric transducer to vibrate again. Since the wave velocity, c, in air is known, the distance, s, between transmitter and reflector can be calculated from the transit time of the wave packet according to $s = c\ t/2$. With this particular refracto-vibrometricmeasurement, the "Time measurement" option of the scanning vibrometer was used. A similar example is described in [13] for a wave propagating in water rather than in air.

Summary

Scanning vibrometers are not only suitable for measuring surface vibrations but can be configured to provide an animated display of sound pressure distributions. While it is relatively easy to generate qualitative results, precise numerical values for the sound pressure can only be obtained in special cases without excessive signal processing. With complicated, three-dimensional sound pressure distributions, complex tomographic procedures must be applied to determine the local sound pressure from the "virtual" velocity measured by the vibrometer. Usually a hypothesis on the qualitative sound pressure distribution is used at some point in the reconstruction process to speed up the calculations. Therefore, it is not possible to define an automatic "sound pressure evaluation option" for the scanning vibrometer.

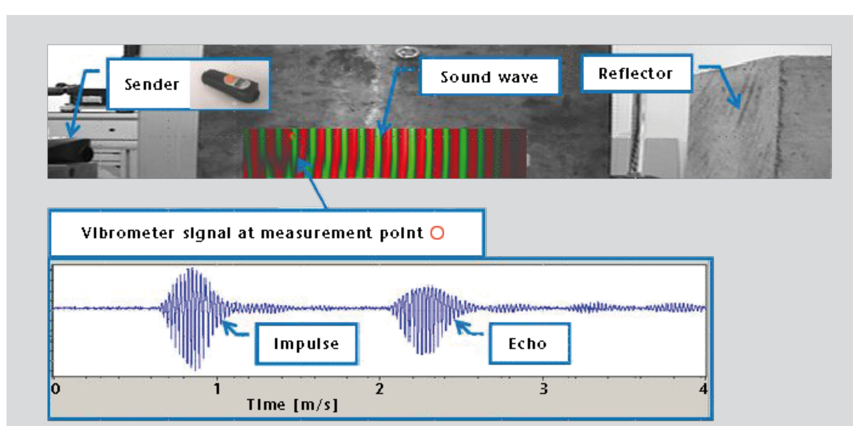

Fig. 5: Refracto-vibrometric measurement of the propagating sound pressure packet of an instrument measuring pulse-echo distance.

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