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Human middle-ear nonlinearity measurements using laser Doppler vibrometry

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A B S T R A C T

It has long been supposed that the middle-ear has near to perfect linear characteristics, and several attempts have been made to investigate this hypothesis. In conclusion, the middle-ear was regarded as a linear system at least up till sound pressure levels of 120 dB. Because of the linear relationship between Doppler shift of light and the vibration velocity of the object on which the light is reflected, laser Doppler vibrometry (LDV) is an intrinsically highly linear measurement technique. Therefore it allows straightforward detection of very small nonlinearities in a vibration response. In this paper, laser Doppler vibrometry and multisine stimulation are used to detect nonlinear distortions in the vibration response at the umbo of the tympanic membrane of seven human cadaver temporal bones. Nonlinear distortions were detected starting from sound pressure levels of 99 dB and measurements were performed up to 120 dB. These distortions can be subdivided into even degree (e.g. quadratic distortion tones) and odd degree nonlinear distortions (e.g. cubic distortion tones). We illustrate that with odd multisine stimulation the level of even and odd degree nonlinear distortions can be investigated separately. In conclusion, laser Doppler vibrometry is an adequate tool to detect nonlinear distortions in the middle-ear system and to quantify the level of such distortions even at 57 dB below the vibration response. The possibility to analyze even degree and odd degree nonlinear distortion levels separately can help in future work to pinpoint the source of the nonlinearity.

1. Introduction

In the ear, sound waves propagating in air are transformed to sound waves propagating in the fluid-filled cochlea, where eventually the sound energy is transformed into electrical impulses going to the brain. Because the acoustic impedance between air and water differs with about a factor 1000, most of the sound energy would normally be reflected at the interface between air and fluid. In the mammalian ear, sound impinges on the eardrum where it is transferred to a minuscule mechanical system consisting of a chain of three ossicles. The first ossicle (malleus) is connected to the eardrum and the third ossicle (stapes) vibrates in an opening into the inner ear, generating sound pressure waves in the fluid. The shape of the eardrum and the joints, and also the complex relative motion of the ossicles, function as a mechanical impedance transformer that converts relatively large motions with little force (of sound waves in air) into smaller motions with higher force (of sound waves in fluid). Previous measurements have led to the assumption that the mammalian middle-ear is functionally linear, where middle-ear output has been observed to grow approximately linearly with stimulus levels of near the hearing threshold to about 120 dB SPL. This statement is supported by the work of Guinan and Peake [4], Nedzelnitsky [7] and Dalhoff et al. [5], who measured middle-ear input-output functions at varied stimulus levels. That linearity is generally a good approximation has been pointed out by others (e.g. Rosowski et al. [13]). In conclusion, the middle-ear was regarded as a mainly linear system at least up till sound pressure levels of 120 dB, though small nonlinearities exist but could not be quantified.

Because of the perfectly linear relationship between the Doppler shift of light and the velocity of the object on which the light is reflected, laser Doppler vibrometry (LDV) is an intrinsically highly linear measurement technique. Only the electronic demodulation of the frequency modulated (FM) carrier signal can be a source of nonlinearity, but in current commercial systems using digital processing the FM demodulation is performed with near perfect linearity. This makes LDV an ideal technique to detect small nonlinearities in vibrating systems. Many other detection methods such as Mössbauer probes, homodyne interferometry and electromagnetic measurement methods are all intrinsically nonlinear to some degree and need displacement dependent calibration which makes detection of nonlinearities in the vibrating system more difficult. Measurements on vibrating membranes with

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known linear response have shown that the LDV technique does not generate artifact nonlinearities down to a detection level of 70 dB below the measured vibration response [1] and that nonlinearities due to distortions in the sound generating system can be adequately removed.

In the living ear, the main source of distortions is the inner ear in which active hair cells produce acoustic energy to enhance hearing thresholds and frequency discrimination (e.g. [5,11]). It has been shown that this source of distortion disappears shortly after death (e.g. [10]). In the current work we used in-vitro specimens in which the active nonlinear role of the inner ear has ceased to exist, so we can investigate the (much smaller) nonlinear contribution of the passive middle-ear mechanics. We will demonstrate how LDV makes it possible to detect and quantify extremely low levels of nonlinear distortion in the sound induced vibration response of the human eardrum which have not been detected before. Data on the level and nature of these nonlinearities will deepen the understanding of the middle-ear function.

2. Materials and methods

2.1. Materials

Seven cadaver temporal bones were used. The bones were removed from the skull within 24 h after death, and were immediately frozen. Prior to the measurements, the bones were left to thaw for 24 h at 4 °C, and one hour before measurement they were left to accommodate to room temperature. It has been shown that the freezing process does not have a significant influence on the vibration response of the middle-ear system [8].

2.2. LDV setup

Because the middle-ear is a small structure, and the eardrum is hidden deep in the outer ear canal, an operation microscope is needed to position the LDV laser beam at the desired location on the eardrum. Fig. 1 shows a picture of the experimental setup. The optical head of a one-dimensional single-point vibrometer (Polytec, OFV-534, Waldbronn, Germany) is attached to the head of a stereo operation microscope (OPMI Sensera/S7, Carl Zeiss, Jena, Germany). The focusing ring of the vibrometer head is equipped with a small driving motor so that the laser beam can be focused without touching the microscope. This is necessary, because even small manipulations of the microscope head make the laser beam move in the field of view. A right angled reflection prism is positioned between the two viewing pupils of the microscope and reflects the LDV laser beam down to the object, nearly coaxial with the viewing direction. In this way, shadow problems are avoided when looking through the narrow ear canal. The reflector is mounted on a kinematic mount driven by two miniature piezo motors (NewFocus 8885-UHV). Custom built electronics allow control of the motors using a joy stick. In this way the laser beam can be positioned anywhere within the field of view of the microscope again without touching the microscope head.

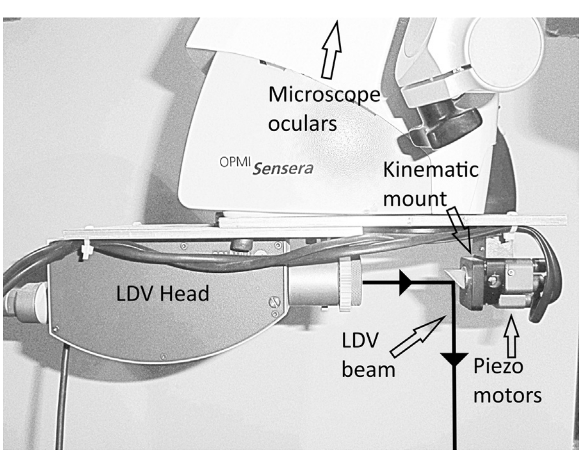

Fig. 1. Experimental setup. The optical head of the LDV is attached to a stereo microscope. The kinematic mount driven by piezo motors allows for accurate positioning of the laser beam.

To perform a measurement a small patch of reflective tape (standard reflective material provided by Polytec) is placed on the umbo, the central and deepest point of the eardrum. Using the motor-controlled prism, the beam is positioned on the patch and the focus is adjusted until a maximal vibrometer signal is obtained.

The ear canal was reduced in length to obtain good visible access to the tympanic membrane. A small cavity (about 1 ml volume) was placed over the ear canal and was acoustically sealed to the temporal bone using silicone paste. The cavity had an anti-reflection coated window at one side to allow access by the laser beam. Two earphone speakers (Senheiser type MX170) were glued in holes at both sides of the cavity. Sound pressures were measured using a probe microphone (Bruel & Kjaer 4182) of which the needle was inserted in the sound generating cavity through a tightly fitting hole.

2.3. Nonlinearity detection using multisines

In order to measure small nonlinearities, multisine stimulation was used. This type of stimulation permits an excitation of the specimen with a broad frequency range in a short time frame. In addition, the number of frequencies at which the nonlinear distortions can occur is much higher compared to using single sine stimulation. The multisine stimulation signal $s(t)$ can be described as

$$s(t) = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} A_{k_i} \sin(2\pi k_i f_{res} t + \phi_{k_i}) \; with \; k_i \in S_f$$

which consists of a sum of N harmonically related sine functions because the frequencies of these sine functions are all an integer multiple k_i of the fundamental frequency f_{res}. The choice of these integers k_i belonging to the set S_f is described below. The fundamental frequency f_{res} determines the period of the signal $s(t)$ and subsequently the minimal duration of the measurement to avoid spectral splatter. Since multisine stimulation can be used to excite the specimen in a broad range of frequencies, it is convenient to use a quasi-logarithmically spaced frequency grid as opposed to a linear one. The amplitudes A_{k_i} are often chosen equal. To realize this, a correction is needed for the frequency-dependence of the speaker. The phases ϕ_{k_i} are chosen randomly as described in Pintelon, Schoukens [6].

If the input presented to a linear system is a multisine signal, the output will be a multisine signal with the same frequency content as the input, but with different amplitudes and phases depending on the frequency response function of the system. In contrary, a nonlinear system will also generate signals at unexcited frequencies. By including only odd multiples of f_{res} (i.e. $k_i \in S_f$ are odd) in the stimulation signal s(t), a distinction can be made between even (quadratic, …) and odd (cubic, …) nonlinearities in the output. The contribution of even (resp. odd) nonlinearities to the output will be only visible at even (resp. odd) multiples of f_{res}. In order to detect not only even but also odd degree nonlinearities in the output, only a limited number of odd multiples ($k_i \in S_f$) of f_{res} are included in $s(t)$. Unwanted nonlinear distortions produced by the speaker in the experimental setup were eliminated using a first order correction [1].

Vibration responses were measured for a frequency range of 255–7645 Hz, using approximately 4 stimulation lines per octave and f_{res} was chosen to be 5 Hz. This gives a total number of 19 stimulation frequencies (see Appendix). The amplitudes A_{k_i} were chosen to be equal. Measurements were done at sound pressure levels between 99 and 120 dB, in steps of 3 dB. Fig. 2 shows a typical measured vibration