Optical Measurements of Nonlinearity in the Middle Ear

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Abstract. In the acoustic frequency range, the mammalian middle ear is known to behave as a fairly linear system. However, strong nonlinearity has been demonstrated in response to quasi-static pressure loads, and in previous work our research group was able to detect small nonlinear distortions at sound pressure levels of 96 dB SPL in the vibrations of the gerbil's tympanic membrane. The tympanic membrane is the input to the middle ear; similar measurements were not performed at the output to the middle ear, the stapes footplate. Thus it is unclear how these nonlinear distortions change as the signal passes through the middle ear bones.

To answer this question we made use of a measurement and analysis method, based on multisine excitation signals, to measure the nonlinearity in the rabbit ear.

Introduction

The middle ear is a small but complex system consisting of the tympanic membrane (or eardrum), three bones, two muscles and a number of ligaments. The primary purpose of this system is to bridge the acoustic impedance gap between sound travelling in air, and sound travelling in cochlear fluid.

Until fairly recently this system was believed to behave linearly in response to acoustic frequencies up to sound pressure levels of around 130 dB SPL. However, given that strong nonlinearity was detected in response to quasi static pressure changes [1], it was expected that small nonlinear distortions would be present at lower sound pressure levels, if only a more sensitive measurement method were used. Such a sensitive method was developed based on multisine excitation signals, and used to measure the nonlinearity in the vibrations of the gerbil tympanic membrane. This was able to detect small nonlinear distortions rising above the noise floor at around 96 dB SPL and then increasing linearly at higher sound pressure levels [2].

These measurements were only performed in one species, and at one location in the middle ear. Thus the measurements leave open the question of whether or not this behaviour is common to all mammals, or what happens to the nonlinear distortions as the signal is passed along the ossicular chain.

We conducted some further measurements aimed at answering these questions. We measured the vibrations response and nonlinearities in the tympanic membrane and stapes footplate in rabbits using a sensitive analysis method based on the use of multisine excitation signals specially designed for the detection of nonlinearities [3].

Materials and Methods

The setup consists of a test object that is stimulated acoustically by an earphone speaker (Sennheiser). A probe microphone (Brüel & Kjær 4182) is used to measure the sound level stimulating the object, and the vibration of the object is measured with a laser vibrometer (Polytec model OFV-534) coupled to a surgical microscope. The signals to the speaker were designed in custom built software using Matlab. An A/D - D/A conversion board (RME HDSP 9632) with 24-bit resolution and a sampling rate of up to 192 kHz, was used to generate and record the input and output signals.

For our measurements the test object was a rabbit ear. The rabbit ear was chosen over other animals such as the gerbil due to its larger size which meant the complex preparation procedures had more chance of success. The bullae were removed post mortem from five adult male rabbits and the middle ear cavity was drilled open to expose the tympanic membrane. Next, the cochlea was drilled open so as to allow free visual access to the footplate. Care was taken in this step to ensure that the bone surrounding the footplate and the ligament that holds it in place remained intact.

$$s(t) = \frac{1}{\sqrt{N}} \sum_{k=1}^{N} A_k \sin(2\pi k f_{res} t + \varphi_k) \tag{1}$$

The input signal (s) is described mathematically in equation 1. The signal is a multisine consisting of N harmonically related sines with user defined amplitudes (A_k) and random phases (φ_k). All frequencies are multiples of f_{res} and the period of the signal is f_{res}^{-1}. Our multisine signal consisted of frequencies between 125 and 16000 Hz, The frequencies are spaced quasi-logarithmically, i.e. the harmonics are logarithmically spaced but chosen to coincide with the frequency grid determined by the frequency resolution f_{res}.

If we take such a multisine signal and use it as the input to a system, we will record a multisine at the system's output. If the system is linear, the output multisine will consist of the same harmonics used in the input signal, but with the amplitudes having been modified by the system's frequency response. The only signal we will record at the unexcited harmonics will be due to noise. If, on the other hand, the system is nonlinear, we will also see some signal above the noise floor in the excited harmonics. By measuring the size of these nonlinear distortions at the unexcited harmonics we can, by linear interpolation, determine the nonlinear contribution at the excited harmonics.

In our signal, only the odd harmonics are excited. The unexcited even harmonics are used to detect even degree distortions. In order to detect odd degree distortions we split our odd harmonics into groups of 3 and randomly eliminate one in every group.

In order to distinguish the nonlinear distortions from the noise, a method is needed to estimate the noise level. In our measurements we made use of the periodic difference method described by Aerts et al. [4] Thus in one single measurement we are able to determine the frequency response, nonlinear distortions, and noise level of our system. We used this to measure in rabbit temporal bones at sound pressure levels from 90 dB to 120 dB.

Results

The noise and nonlinear distortions were calculated for each measured ear (n=5) and an rms average was taken. The result is shown in Fig. 1.

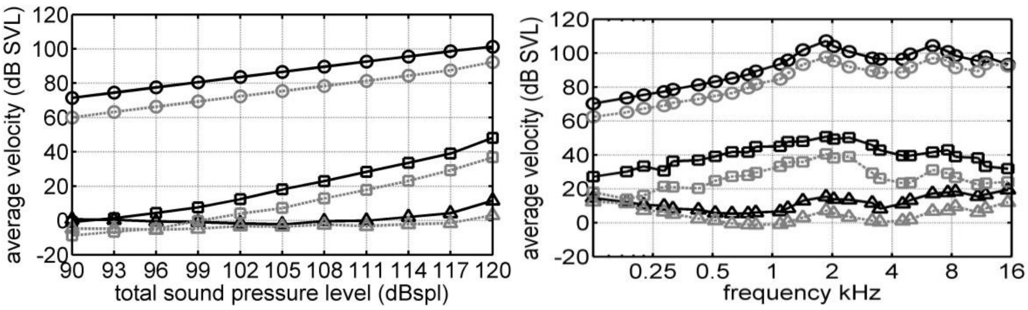

Fig. 1. The mean output response (○), noise level (∆), and nonlinear distortions (□) of the umbo (black) and footplate (grey) from five rabbit ears. The graph on the left shows data in the 1 – 2 kHz octave as a function of pressure, while the graph on the right shows data at 120 dB SPL as a function of frequency.

From these graphs we can see that the response and nonlinearities appear to show exactly the same behaviour as they do at the umbo, only they are around 10 dB lower. Overall neither the vibration response nor the nonlinearities show a different pattern when going from Umbo to footplate. With this technique we are able to detect small nonlinear distortions rise above the noise floor at 93 dB at the umbo and at 99 dB for the footplate. As we continue to increase the sound pressure level the vibration response and nonlinear distortions increase fairly linearly, except that the nonlinear distortions increase around twice as fast as the vibration response.

Conclusions

With the measurement and analysis method described, we are able to detect small nonlinear distortions in the vibrations of the tympanic membrane and the footplate in rabbits. The method has proven to be very sensitive and easy to perform.

These measurements in rabbits show similar behaviour to previous measurements in gerbils, indicating that the same behaviour can likely be found in most other mammals. The measurements also showed that the transfer of sound vibrations from the umbo to the footplate did not introduce any significant nonlinear distortions, meaning that measurements on the umbo are likely sufficient to understand the nonlinear behaviour of the middle ear.

References

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