Human middle-ear nonlinearity measurements using laser Doppler vibrometry

Reference:
Gladiné Kilian, Muyshondt Pieter, Dirckx Joris.- Human middle-ear nonlinearity measurements using laser Doppler vibrometry
Optics and lasers in engineering - ISSN 0143-8166 - 99(2017), p. 98-102
Full text (Publisher's DOI): https://doi.org/10.1016/J.OPTLASENG.2017.03.001
To cite this reference: https://hdl.handle.net/10067/1455280151162165141

Human middle-ear nonlinearity measurements using laser Doppler vibrometry

Gladiné Kilian[1, a)], Muyshondt Pieter G.G.[1, b)], Dirckx Joris J.J.[1, c)]

[1]University of Antwerp, Laboratory of Biophysics and Biomedical Physics, Groenenborgerlaan 171, 2020 Antwerp, Belgium

[a)] Corresponding author: Kilian.Gladine@uantwerpen.be
[b)] Pieter.Muyshondt@uantwerpen.be
[c)] Joris.Dirckx@uantwerpen.be

Abstract

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 [2], Nedzelnitsky [5] and Dalhoff et al. [3], 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. [10]). 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 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. [7]). 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 [6].

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.

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

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

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 [4].

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 $\mathrm{f_{res}}$ (i.e. $\mathrm{k_i} \in \mathrm{S_f}$ are odd) in the stimulation signal $\mathrm{s(t)}$, 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 $\mathrm{f_{res}}$. 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 to 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 spectrum at a stimulation level of 111 dB SPL and a zoomed view on the low intensity levels revealing the nonlinear responses above the noise.

3 Results

One of the seven ears showed erratic behavior and was excluded from the results. In two other ears one data point was an outlier, and was therefore removed to calculate averages. The remaining data was processed by first calculating the set of frequencies $\{f_{quadratic}, f_{cubic}\}$ at which the stimulation frequencies can produce quadratic $[(\alpha k_I + \beta k_{II}) \cdot f_{res} \in f_{quadratic}\ with\ \alpha, \beta \in \{-1,0,1,2\}\ \&|\alpha| + |\beta| = 2\ \&\ k_I, k_{II} \in S_f\ ]$ or cubic distortions $[(\alpha k_I + \beta k_{II} + \gamma k_{III}) \cdot f_{res} \in f_{cubic}\ with\ \alpha, \beta, \gamma \in \{-2,-1,0,1,2,3\}\ \&|\alpha| + |\beta| + |\gamma| = 3\ \&\ \mathrm{k_I}, \mathrm{k_{II}}, \mathrm{k_{III}} \in \mathrm{S_f}]$ within the range of stimulation frequencies. Only the frequencies of the set $\{f_{quadratic}, f_{cubic}\}$ within 5 Hz (i.e. f_{res}) or 10 Hz (i.e. $2f_{res}$) from a stimulation frequency were considered. For these frequencies the first-order correction to remove nonlinearities of the earphone speakers is the most accurate as it uses interpolated data from the frequency response function measured with those stimulation frequencies [1]. Secondly, for each stimulation level, only frequency components with vibration levels which exceed the noise were used. Finally, the sum of these nonlinear distortion levels was divided by the number of frequency components that satisfy this criterion.

Starting from a sound pressure level of about 99 dB, the measured nonlinearities exceeded the noise floor. As shown in Fig. 3, the level of the nonlinear distortions grows as a function of sound pressure level. The figure shows the mean amplitude of the nonlinear distortions as a function of sound pressure averaged over the six specimens. At 99 dB SPL the amplitude of the nonlinear vibration response is only 0.014 nm. At 120 dB SPL it has grown to 0.281 nm. The total vibration response (averaged over the available five data points and the number of stimulation frequencies) at this pressure level is 203.7 nm, or a factor of 725 larger than the nonlinear response.

In the response spectrum, the contribution of even and odd nonlinearities can also be measured separately. At all stimulation levels the odd nonlinearities were found to be slightly smaller than the even nonlinearities. The ratio of the amplitudes of even to odd nonlinearities has a nearly constant value of 1.56 over the entire stimulation range but the uncertainty bands are quite large. Fig. 4 shows the mean amplitude of even and odd nonlinearities as a function of stimulation level, again averaged over the six specimens. These amplitudes grow with a power of about 1.5 as a function of stimulus level.

It was not possible to observe the nonlinear behavior directly from the vibration response curves. As seen in Fig. 5, the response curve divided by the expected linear growth as function of stimulation level of each specimen deviates so little from a constant line that no nonlinear behavior can be quantified. The figure also shows that the vibration response can vary over about a factor of 10 between different specimens. This range of variability has also been observed in previous studies (e.g. Volandri [9]).

4 Discussion and conclusions

With the LDV technique it is possible to detect and to quantify the presence of nonlinearities in the vibration response of the human middle-ear. The level of nonlinear distortions is however very small: even at a sound pressure level of 120 dB, which is the pain threshold, the mean level of nonlinearity is still 57 dB below the mean linear vibration level. These extremely low levels are probably the reason why nonlinearity remained largely unobserved using other techniques as pointed out in the introduction. LDV makes it possible to detect the nonlinearities and to quantify their level.

It is demonstrated that the odd multisine stimulation allows for separate detection of even and odd degree nonlinearities. This is illustrated in Fig. 4. The level of the even degree nonlinearities seems to be a little higher than the odd degree nonlinearities. However, statistical testing showed that the difference is not significant, due to the large variability and the limited number of specimens. Further investigation on a larger data set will be needed to determine if the difference between the levels is a significant feature.

The results show that even and odd distortions grow with stimulus level at a power of about 1.5 which is less than expected a power of two for quadratic and power of three for cubic distortions. One possible reason is that we assumed that the nonlinear frequency components we examined were produced by only quadratic or cubic type of nonlinearities. Higher-order nonlinearities will also produce these very same frequency components and they might have a different phase. It might be the case that the higher-order distortions interfere with the lowerorder distortions. In this way the growth rate of these frequency components can be smaller than expected. If this is the case, there might even exist a sound pressure level at which some of the frequency components become zero and at even higher sound pressure levels start to grow again with the growth rate of a higher-order nonlinearity. Another contribution might be due to the fact that at high pressure levels, the frequency response of the system might change by small amounts. When the frequency response of the system changes, the nonlinear frequency response also changes and this might in decrease the growth rate of the nonlinearities. The paper by Rosowski et al. [10] also shows a decrease in growth rate of the nonlinearities: At first, the level of the third harmonic grows as a function of sound pressure level with a power of three, which is to be expected. For higher stimulation levels, the growth rate decreases significantly as pointed out by Rosowski et al. [10].

Fig. 5 suggests that only examining the total vibration response divided by expected linear growth as a function of sound pressure is an inadequate method to detect the nonlinear behavior of the ear. The vibration response will closely resemble a constant line, not revealing the extremely low level of the nonlinear component. One ear shows a small increase in growth rate for higher sound pressure levels. The opposite is often expected as a part of the energy is distributed over the distortion products. As mentioned before, the frequency response function of a system can change by small amounts at high pressure levels. Depending on the chosen stimulation frequencies, the total vibration level can exceed linear growth. This is possibly the case for sample 3. This case further supports the necessity to measure the level of nonlinear distortions themselves instead of the effects of nonlinearity on the expected linear growth at stimulation frequencies.

Due to ethical reasons, it is extremely difficult to obtain fresh human cadaveric material. Therefore, studies in hearing often need to be performed on specimens which have been harvested and frozen immediately after death on locations other than the lab where they are investigated. Elaborate studies have been performed to investigate the effect of freezing (Rosowski [6]), and it was found that the process does not influence vibration behavior significantly. It can however not be fully excluded that some changes in tissues occur, and that also the time post-mortem before freezing may have an effect. The LDV technique is minimally invasive since only a small reflective patch needs to be placed on the eardrum. Therefore, measurements can also be performed in vivo, but in this case the strongly nonlinear contribution of the inner ear will influence the results. Therefore, in-vitro studies seem the best choice to quantify the contribution of passive ear mechanics to the nonlinear response, but it should be noted that additional variability caused by time-dependent post-mortem artefacts cannot be fully excluded.

The driving sound signal also contains nonlinearities, especially at the higher sound pressure levels. These nonlinearities could erroneously be interpreted as nonlinearities generated by the ear. Aerts and Dirckx [1] have shown that this effect can be reduced by applying a first order correction in which the measured vibration response is being corrected for the actual sound input signal. The authors showed that for a sound generation system similar to the one used in the current experiments, no distortions were detected in the vibration of flat metal membranes which are indeed expected to have a near to perfect linear vibration response.

In conclusion, the LDV technique has made it possible to detect and quantify nonlinear response in the human eardrum. Nonlinearities can be detected at sound pressure levels starting from 99 dB and at 120 dB the mean level of the nonlinearities is more than 50 dB below the mean linear vibration response. It is possible to discriminate between even and odd degree nonlinearities, which can help to pinpoint the source of nonlinear behavior.

Acknowledgements

This work was supported by the Research Foundation Flanders (FWO), Grant no. G049414N.

References

[1] Aerts J, Dirckx J. A fast full frequency range measurement of nonlinear distortions in the vibration of acoustic transducers and acoustically driven membranes. Meas Sci Technol 2007;18:3344–50.

[2] Guinan J, Peake W. Middle-ear characteristics of anesthetized cats. J Acoust Soc Am 1967;41(5):1237–61.

[3] Dalhoff E, Turcanu D, Zenner HP, Gummer AW. Distortion product otoacoustic emissions measured as vibration on the eardrum of human subjects. PNAS 2007;104:1546–51.

[4] Pintelon R, Schoukens J. System Identification: A Frequency Domain Approach. 2nd ed Wiley-IEEE Press; 2001.

[5] Nedzelnitsky V. Sound pressures in the basal turn of the cat cochlea. J Acoust Soc Am 1980;68(6):1676–89.

[6] Rosowski JJ, Davis PJ, Merchant SN, Donahue KM, Coltrera MD. Cadaver middle ears as models for living ears: comparisons of middle-ear input immittance. Ann Otol Rhinol Laryngol 1990;99(5):403–12.

[7] Dong W, Olson ES. Detection of cochlear amplification and its activation. Biophys J 2013;105:1067–78.

[8] Abel C, Kössl M. Sensitive response to low-frequency cochlear distortion products in the auditory midbrain. J Neurophysiol 2009;101:1560–74.

[9] Volandri G, Di Puccio F, Forte P, Carmignani C. Biomechanics of the tympanic membrane. J Biomech 2001;44(7):1219–36.

[10] Rosowski JJ, Peake WT, Lynch III TJ. Acoustic input-admittance of the alligatorlizard ear: nonlinear features. Hear Res 1984;16:205–23.

Appendix

Example of a set of stimulation frequencies in Hz used during measurements (f_{res} is 5 Hz):

f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8
255	315	385	465	565	685	905	1095
f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}	f_{16}
1195	1555	1705	2035	2435	3185	3795	4145
f_{17}	f_{18}	f_{19}					
4935	5875	7645					

All frequencies are an odd multiple of f_{res} (as described in section 2.3). The range of frequencies is commonly used in vibration measurements in human middle ear research.

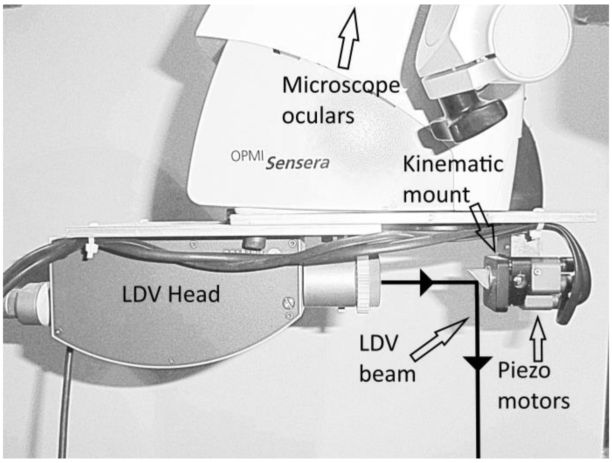
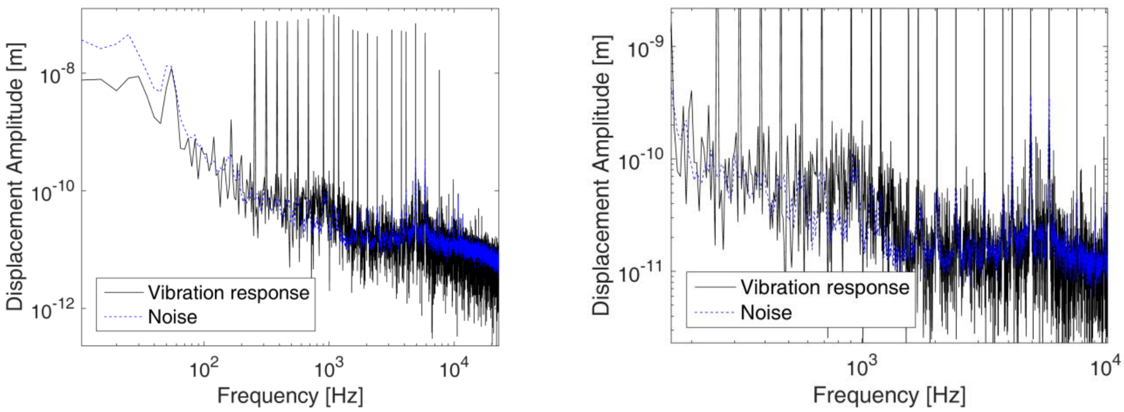


Figure 1. Experimental setup. The optical head of the LDV is attached to a stereo microscope. The kinematic mount driven by piezo motors allows for accurate positioning of the laser beam.



(a) (b)

Figure 2. (a): Vibration response spectrum of a single ear (ear 1) at 111 dB SPL, (b): a zoomed view illustrating the nonlinear components above the noise.

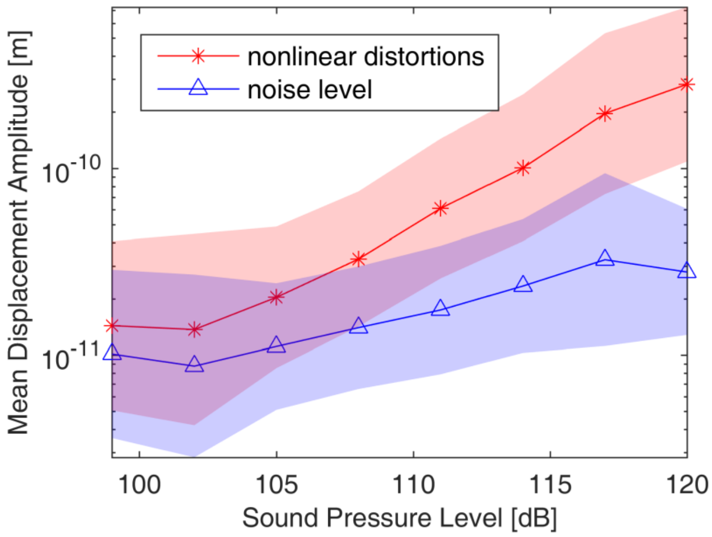


Figure 3. Mean amplitude of nonlinear distortions (★) and noise level (△) as a function of sound pressure level averaged over six specimens. The colored bands display the standard deviation. Nonlinear distortions are clearly detectable as of a stimulation level of 99 dB. Their level grows stronger as sound pressure level increases.

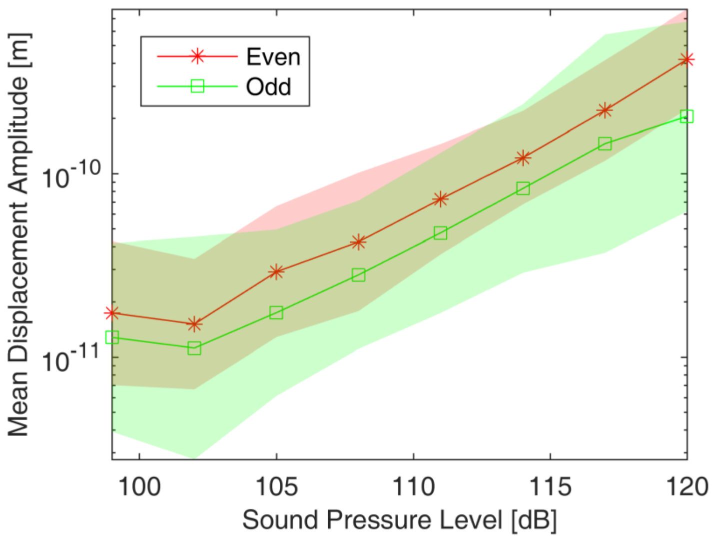


Figure 4. Mean amplitude of even (★) and odd (o) nonlinear distortions (e.g. quadratic and cubic distortion tones respectively) as a function of sound pressure level averaged over six specimens. The colored bands display the standard deviation. At all dB levels the level of the odd distortions is below the average level of the even distortions but within the limited number of specimens the difference is not significant.

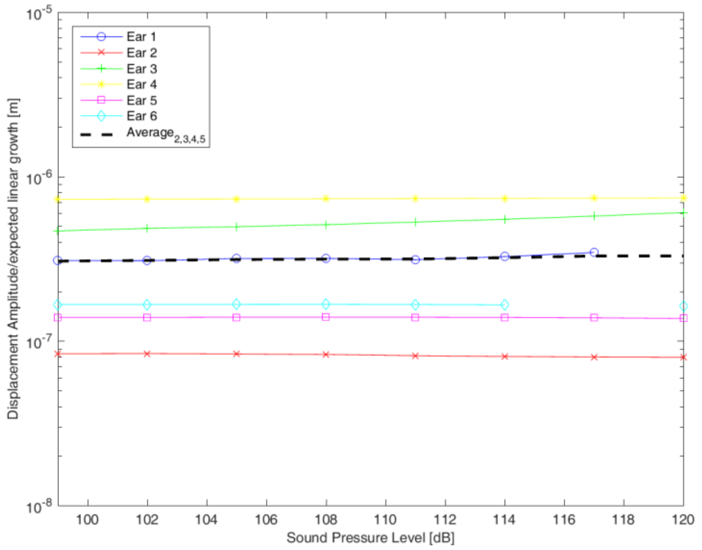


Figure 5. Vibration amplitude as a function of sound pressure level for all six samples individually divided by the expected linear growth. The curves closely resemble a constant line for each specimen. The average of ears 2-5 at each pressure level is indicated as a dashed line.