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Research Paper

Average middle ear frequency response curves with preservation of curve morphology characteristics

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ABSTRACT

For the validation of modelling results or the comparison of middle ear interventions, such as prostheses placement, average responses of middle ear vibrations are needed. One such response is the amplitude and phase of the vibration of the stapes footplate as a function of frequency. Average responses and their standard deviation are commonly obtained by calculating the mean of a number of measured responses at each frequency. A typical middle ear magnitude response curve shows a number of distinct peaks, and the location of these peaks varies between ears. By simply taking an average along the magnitude or phase response axis, the typical fine structure of the response curve is flattened out, delivering an average curve which no longer has the typical morphology of an individual response curve. This paper introduces methods to avoid this problem by first aligning the typical curve features along the frequency axis prior to calculating the average along the magnitude or phase axis, resulting in average magnitude and phase curves which maintain the typical morphology of the curve obtained for an individual ear. In the method, landmark points on the response magnitude curves are defined and the frequencies at which these points occur are averaged. Next, these average frequencies are used to align the landmark points between curves, prior to averaging values along the magnitude or phase axes. Methods for semi-automatic and manual assignment of landmark points and curve alignment are presented. After alignment, the correspondence between the original landmark frequencies and aligned frequencies is obtained together with the warping function which maps each original magnitude curve to its aligned version. The phase curves are aligned using the warping functions determined from the corresponding magnitude curves. Finally, a method is proposed to compare the data set of an individual measurement or model result to an aligned average curve in terms of magnitude and frequency by applying the alignment procedure to the individual curve.

1. Introduction

Frequency response curves of ossicular vibrations provide important data for validation of middle ear modelling results. As many models are built using average material parameters and shapes, it is common to compare model outcome to average response curves (De Greef et al., 2017). The most common way to obtain such a response curve is to average magnitude and phase values for each measured (or interpolated) frequency. Such averages give a good representation of the general frequency response of the middle ear (e.g. Rosowski et al., 2007).

Each individual response curve has a specific morphology, with local maxima that can be attributed to some extent to specific physiologic parameters or characteristic properties of the system, such as the resonance frequency of the ear canal (Keefe et al., 1993; Stinson, 1990) or the first ossicular mode (Homma et al., 2009). As shapes, masses and other parameters of middle ear structures vary from one individual to the next, both the height and frequency location of local maxima differ. By averaging along the magnitude axis (or along the phase axis), the sharpness of these local maxima diminishes because for each individual specimen the frequency location of the maximum is slightly different. As a result, the average response curve taken over many specimens shows a much less detailed structure than an individual response curve, and the typically peaked morphology of the curve tends to flatten out

Abreviations: MLA, Manual landmark assignment; SLA, Semi-automatic landmark assignment

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towards a broadly spread maximum at a center frequency. These less-pronounced peaks/troughs could easily be misinterpreted by modelers to mean that the middle-ear is more damped than it really is.

Therefore, it would be useful to generate average response curves which preserve the typical morphology of the individual response curve. In this paper we present a procedure to first align the typical morphologic features of response curves along the frequency axis prior to taking the cross sectional average along the magnitude or phase axis.

2. Materials and methods

2.1. Input data

To demonstrate the new processing method, we used stapes vibration data obtained from human temporal bones in previous work (Niklasson, 2017). In these experiments, the stapes footplate velocity was measured from the medial side at the center of the footplate after removal of the inner ear, and sound stimulation was presented through the intact ear canal. The response curves therefore show the transfer function of the middle ear system without cochlear loading. Measurements were taken at 16 frequencies per octave in a frequency range of 0.125–8 kHz. As the processing of the data benefits from using more densely sampled curves, the curves were resampled using smoothed spline approximation to obtain a set of 500 logarithmically spaced data points.

2.2. Assigning landmarks

The alignment algorithm makes use of landmark points which are to be defined on individual curves (Kneip and Gasser, 1992). In this section, we describe two ways to assign such landmark points. These landmark points will be used to align the vibration magnitude and phase curves.

2.2.1. Manual landmark assignment (MLA)

The least complex way to assign landmarks to the response curves is by choosing them manually. This is done by visually inspecting the data curves, choosing a curve feature, and noting the frequency at which this feature occurs for each curve. This can be done for several features. If a feature is not present in an individual curve, the landmark point is not assigned.

Up to 5 landmark points were used, which will be described in detail in the results section.

2.2.2. Semi-automatic landmark assignment (SLA)

In semi-automatic assignment, peaks in the curve are automatically detected. Then, conditions are set to filter the found peaks such that only the peaks of interest remain.

To find the peaks we have used the MATLAB function *findpeaks*. We then applied mathematical conditions to limit the number of found peaks to three landmarks. The conditions for each landmark were:

- The peak frequency was required to be lower than 1.5 kHz. In addition, the peak frequency was required to be close to 1 kHz, and preferred to have a high peak prominence. These last two conditions were applied using weighting. This landmark is indicated by a circle in Fig. 2.
- The peak with highest amplitude (indicated by an asterisk in Fig. 2).
- The peak frequency was required to be higher than that of the peak with highest amplitude. In addition, the peak frequency was required to be the closest to 5 kHz (indicated by a diamond in Fig. 2).

The resulting landmarks are displayed in the results section in Fig. 2. And the corresponding frequencies are given in Table 1.

2.3. Curve alignment

2.3.1. Warping functions

In this section, we describe different warping functions and their properties. Warping functions are used to transform the data along the frequency-axis. The original frequency-axis should be projected on a new frequency-axis such that the landmarks of all curves are aligned.

The warping function $X(f)$ needs to be monotonic because each frequency f needs to be projected onto a unique frequency and the projected frequencies need to remain monotonically increasing. In other words, aligning the curves could mean we either shift them, and/or stretch/squeeze them but we cannot change the order of curve segments. As an analogy, for time-related data this criterion would imply the preservation of causality.

Several types of functions obey this criterion. A first example is the linear warping function.

$$X(f) = \alpha + \beta f \tag{1}$$

If $\alpha > 0$ the curve will shift to lower frequencies. When $\beta > 0$ the curve will be squeezed together; conversely, when $\beta < 0$, the curve will be stretched out. This type of warping function does not fix the end points of the curves and thus warped frequencies can exceed the minimal and maximal value of the original frequency range. If this occurs, data has to be estimated for frequencies outside the measured frequency range. This is no problem if all curves converge to a constant value or a similar slope at the boundaries of the data set. For our data set, this is not the case. At the upper boundary of the measured frequency range, some curves go up, and some go down. Extrapolation of the data will result in very different values and curve shapes for different curves and thus the use of a linear warping function is not advisable.

A second class of warping functions, satisfying monotonicity, is

$$X(f) = \frac{(f_{MAX} - f_{MIN}) \int_{f_{MIN}}^{f} \exp(g(s))\, ds}{\int_{f_{MIN}}^{f_{MAX}} \exp(g(s))\, ds} + f_{MIN} \tag{2}$$

Table 1
Frequencies in Hertz of the landmarks assigned using MLA and SLA. Landmarks that were not assigned are depicted as a dash (–). Landmarks that have been placed at a significantly different frequency for the MLA and SLA methods are shaded.

Method	Curve	Landmark				
		o	□	*	◊	Δ
MLA	1	988	1698	4211	5452	6441
	2	901	1523	3810	4732	6076
	3	750	1216	3335	4732	7001
	4	**1013**	1390	3419	**6550**	–
	5	843	1268	2685	4390	5976
	6	1091	–	4577	6335	–
SLA	1	979	–	4211	5498	–
	2	901	–	3810	4654	–
	3	756	–	3335	4693	–
	4	**1378**	–	3419	**5544**	–
	5	857	–	2685	4390	–
	6	1091	–	4577	6335	–

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