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The Generation Mechanisms and Repeatability of 2F1−F2 Distortion Product Otoacoustic Emissions: study on normally hearing subjects

M. Parazzini, H. K. Wilson, S. Bell, G. Tognola, P. Ravazzani and M. E. Lutman

Abstract— **The 2F1−F2 distortion product otoacoustic emission (DPOAE) is considered to consist of two generation mechanisms, the so-called place-fixed and wave-fixed mechanisms, depending on the frequency ratio F2/F1. The general assumption is that for a small frequency ratio there is a predominantly place-fixed emission mechanism, while with a larger frequency ratio there is a predominantly wave-fixed mechanism. There is also a lack of published data on the repeatability of the two components when separated.**

One aim of this study was therefore to identify the wave-fixed and place-fixed components of the 2F1−F2 DPOAE using a time-window separation method. The second aim was to quantify the test-retest repeatability of the separated 2F1-F2 DPOAE components in a group of normally hearing subjects.

Results confirmed the presence of wave-fixed and place-fixed components for 2F1−F2 and a predominance of place- or wave-fixed DPOAE as a function of frequency ratio. This pattern varied somewhat among subjects. Moreover, regardless of which component was stronger for any F2/F1, both components were highly repeatable across time within individual ears.

I. Introduction

Current theories suggest that distortion product otoacoustic emissions arise from two possible generation mechanisms, the so-called place-fixed and wave-fixed mechanisms [1-6].

The general assumption with a wave-fixed mechanism is that the emission is generated by distortion at a site that is an integral part of and moves smoothly with the primary stimulus travelling wave envelopes in the cochlea as stimulus frequency is swept [5]. The phase at any point moving with the travelling wave envelope changes little; therefore, any distortion giving rise to an OAE contribution from that point has a shallow phase gradient when using fixed frequency ratio sweeps. The distortion generated not only travels back to the ear canal but may also create a secondary travelling wave at the distortion product frequency, which leads to a further OAE component via the place-fixed mechanism.

In the placed-fixed mechanism a series of reflecting or scattering sites is supposed to exist at fixed locations along the basilar membrane [6]. As a stimulus is swept in frequency and its excitation pattern moves along the basilar membrane, the stimulus phase at the reflection site will change. Therefore OAEs created by reflection also change in phase, creating a steep phase gradient.

Steep and shallow phase gradients have been observed in the 2F1−F2 DPOAE [1]: this emission appears to change depending on whether a large or small frequency ratio is used. In particular, for a small frequency ratio, the phase gradient is steep, consistent with a predominantly place-fixed emission mechanism, while with a larger frequency ratio, the phase gradient becomes shallow and is more consistent with a wave-fixed mechanism.

The wave- and place-fixed components are combined in the measured DPOAE. However, they may be separated by signal processing techniques described below. Knight and Kemp [3] separated the components and found in their two subjects that the DPOAE was predominantly place-fixed for small F2/F1 ratios and predominantly wave-fixed at higher F2/F1 ratios. It is unclear how consistent this finding may be of whether it is repeatable within subjects.

This study therefore aimed to address two questions: i) whether the 2F1−F2 DP components are stable when repeated measures are performed; ii) whether the pattern of predominance of place-fixed and wave-fixed components does occur consistently by testing a larger group of subjects.

II. Materials and Methods

A. DPOAE Measurements

The DPOAE were recorded using custom laboratory apparatus. Primary frequencies are denoted by F1 and F2, while primary levels are denoted by L1 and L2. An Etymotic ER-10B+ microphone probe and pre-amplifier (+40 dB) were used for recording ear canal sound pressure. Two Etymotic ER-2 insert earphones were used to deliver the primary tone stimuli to the subject via the probe. The amplified microphone signal was digitised (16-bit resolution, 32.768-kHz sample rate) by an external A/D and

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M. Parazzini, G. Tognola, and P. Ravazzani are with the Istituto di Ingegneria Biomedica del Consiglio Nazionale delle Ricerche, ISIB-CNR, Milano, Italy, (corresponding author phone: +390223993359; fax: +390223993367; email: marta.parazzini@polimi.it).

H. K. Wilson is with the Audiology Department, Royal Gwent Hospital, Cardiff Road, Newport, UK.

S. Bell and M. E. Lutman are with the Institute of Sound and Vibration Research, University of Southampton, Southampton, UK.

D/A converter unit (Institute of Hearing Research DSP remote converter module) that also generated the primaries. Signal processing by custom software running on a TMS-320 DSP card converted consecutive 62.5-ms epochs of the microphone signal to the frequency domain by performing FFT with a bin width of 16 Hz. The complex FFT was averaged after rejection of epochs in which the estimated noise level was greater than 10 dB SPL in the frequency range close to the DP. The amplitude and phase of the DP were estimated from the real and imaginary FFT components corresponding to the single bin centred on the DP frequency. Noise at the DP frequency was estimated by averaging the power in 10 spectral lines either side of the DP. Recording of a DPOAE for a particular frequency was stopped after a minimum number of epochs had been acquired and a minimum SNR was reached; these minima were set at 20 epochs and a SNR of 10 dB. If neither criterion was met, averaging was curtailed after 100 non-rejected epochs.

DP-grams were recorded over a restricted frequency range and using frequency-scaled stimuli. Frequency sweeps were performed with the primary-frequency ratio F2/F1 and the F1 frequency step held constant. Two separate studies were performed. In the first study, the following stimulus parameters were used for the recording of the 2F1−F2 DP: L1/L2 of 60/50, F2/F1 ratio of 1.22, 1.15 or 1.05, and frequency ranges of approximately 1-3 kHz, with sweeps having steps of 32 Hz. All the recordings were repeated in two sessions on separate days in a group of 12 normally hearing subjects to allow repeatability to be assessed.

The following stimulus parameters were used in the second study: L1/L2 of 65/60, F2/F1 ratio of 1.32, 1.22, 1.10, 1.05, and range of frequencies was approximately 1-3 kHz, with data collected every 16 Hz. All these recordings were performed in a separate group of 20 normally hearing subjects.

B. *DPOAE Data Processing*

When stimulus frequency ratio is held fixed and stimulus frequency swept, a complex amplitude time series is obtained as a function of 2F1−F2 frequency. Using Fourier analysis, this time series can be separated into two components based on their differing phase properties; that is, the wave-fixed and place-fixed components can be unmixed. An inverse Fast Fourier Transform (IFFT) analysis and time-domain windowing were applied to separate the two generation mechanisms of DPOAE, using the method described in [7]. This method, based on spectral smoothing or time-windowing, is suggested by the correspondence (in a linear system) between phase gradient in the frequency domain and latency in the time domain [8].

As explained above, the two DPOAE emission components have very different phase gradients, reflecting fundamental differences in their mechanisms of generation. Consequently, if inverse Fourier analysis is applied to the frequency domain measurements of DPOAE, it is expected to see two segments of very different latencies in the delay domain: a short latency segment corresponds to the wave-fixed component and a long latency segment corresponds to the place-fixed component. Therefore, the two components can be separated by appropriate windowing to separate the segments in the time domain, or by using a convolution with a smoothing function in the frequency domain. Here, the two DPOAE emission components were extracted using Fourier analysis and time-domain windowing. The original complex amplitude DPOAE time series as a function of 2F1−F2 were converted to their analogous time domain representation by performing an inverse Fast Fourier Transform (IFFT). The IFFT was then windowed using a recursive exponential filter, developed by [4], to remove longer latency components attributed to reflections within the cochlea. FFT of the windowed components provided the complex amplitude in the frequency domain of the wave-fixed components. Subtraction of the complex amplitude of the FFT of the time-domain filtered response from the original complex amplitude data gave the place-fixed component.

DPOAE amplitude averaged across frequency and phase gradient were then calculated, both considering mixed and unmixed components. As phase can only be defined within the range ±180°, the phase data sequences were "unwrapped" to avoid phase jumps of more than 180° between two consecutive measurements. The phase was unwrapped by adding or subtracting multiples of 360° so as to minimize adjacent phase steps. Subsequently, the unwrapped DPOAE phase data were plotted as a function of 2F1−F2 and the gradient of the line of best fit was computed.

C. *Statistical Analysis*

Test-retest repeatability (i.e. stability) of the 2F1−F2 DPOAE amplitude and phase gradients, both considering the two components mixed and unmixed, was quantified using the data from the first study. One indicator of repeatability between measures is the within-subject SD on replication. This was estimated by dividing the standard deviation of the difference between the DPOAE data obtained in the two sessions by √2. The reason for dividing by √2 is because the standard deviation of the difference incorporates the pooled uncertainty of the two measurements and if each replication has the same uncertainty (within-subject variance) the difference has double the variance.

III. Results

A. *Repeatability*

The repeatability of amplitude and phase gradient of the 2F1−F2 DP and of its components over the two sessions was calculated. Tables I-III summarize the replication SD obtained for each F2/F1. On the basis of the values in Tables

TABLE I
2F1−F2 DPOAE REPLICATION SD

F2/F1	Amplitude	Phase Gradient
1.05	1.08	0.004
1.15	1.30	0.003
1.22	1.80	0.003

Replication SD of the DPOAE amplitude (dB SPL) and phase gradients (radians/Hz) for the unmixed components.

TABLE II
2F1−F2 PLACE-FIXED REPLICATION SD

F2/F1	Amplitude	Phase Gradient
1.05	1.13	0.004
1.15	1.45	0.005
1.22	1.39	0.007

Replication SD of the DPOAE amplitude (dB SPL) and phase gradients (radians/Hz) for the place-fixed component.

TABLE III
2F1−F2 WAVE-FIXED REPLICATION SD

F2/F1	Amplitude	Phase Gradient
1.05	1.10	0.0030
1.15	2.19	0.0004
1.22	2.25	0.0013

Replication SD of the DPOAE amplitude (dB SPL) and phase gradients (radians/Hz) for the wave-fixed components.

I-III (less than 2.50 dB SPL and less than 0.007 radians/Hz for the amplitude and phase gradient, respectively), it appears that the DPOAE data were fairly repeatable over time, with the poorest repeatability at the F2/F1=1.22, considering the two components both mixed and unmixed.

As an indicator of scale, the difference in phase gradient between a completely wave-fixed and a completely place-fixed DP at these frequencies is in the region of 0.03 radians/Hz.

B. Relative Amplitudes of Components

The data from this study show that the predominance of place- or wave- fixed DP as a function of frequency ratio varies among subjects. Fig. 1 shows how many subjects from the first study gave predominantly wave-fixed or place-fixed DP results at each frequency ratio. The general trend indicates that (for the 2F1−F2 DPOAE in humans) there tends to be a predominance of the place-fixed component if F2/F1 is equal to 1.05 while there tends to be a predominance of the wave-fixed component if F2/F1 is equal to 1.22 (Fig. 1). This is consistent with the outcome of [1]-[2], which employed only two subjects.

In the case of F2/F1=1.15, there was substantial variation. The predominance of the wave-fixed component shown in Fig. 1, which agrees with [1-2], was less pronounced. Subjects were found in which there was a clear predominance of a place-fixed component or intermediate results suggesting neither a predominantly wave-fixed or predominantly place-fixed DP. The larger sample used in our study has highlighted this variation.

These findings were confirmed in the second study, which used closer spacing of frequency steps and hence less ambiguity in the phase unwrapping process. The F2/F1 ratios were also slightly different: 1.10 was used instead of 1.15 and a higher ratio of 1.32 was introduced. Results showed that the place-fixed component was larger in all 20 subjects at F2/F1 ratios of 1.05 and 1.10. The situation was almost completely reversed for an F2/F1 ratio of 1.22 where for 19 out of 20 subjects the wave-fixed component was larger. At an F2/F1 ratio of 1.32 the wave-fixed component was larger in 14 out of 20 subjects. The reason why the wave-fixed component is less dominant at this frequency ratio may be because the overlap between the primaries is reduced. This will reduce the amount of distortion generated leading to a smaller wave-fixed component. Due to the nonlinearity of cochlear wave propagation, the place-fixed component would reduce by a relatively smaller amount.

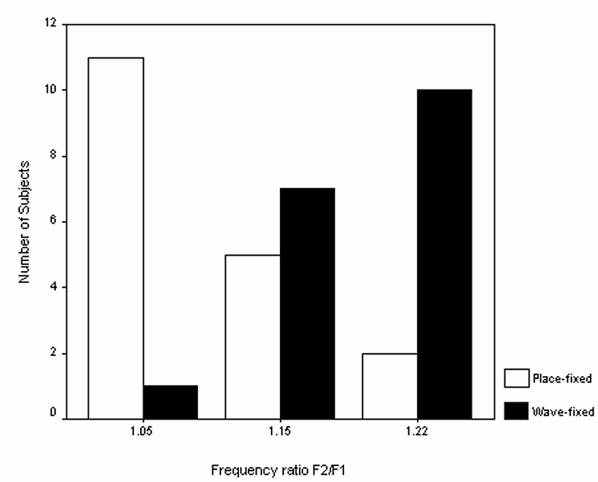

Fig. 1. Number of subjects in which there was a larger wave-fixed or place-fixed component for each frequency ratio.

IV. CONCLUSIONS

In this study, the DPOAE components have been separated from each other using a time-domain windowing of the IFFT of the DP-gram, following the method proposed in [7]. Our results extend the work of [1, 2]. Specifically, our findings show that there is some variation among subjects concerning which is the predominant 2F1−F2 DP emission component, in relation to the frequency ratio used to evoke it. The general trend for F2/F1=1.22 and above is a predominance of the wave-fixed component, while for F2/F1=1.10 or below there is a predominance of the place-fixed component. This supports previous studies. However, there are exceptions to this rule. It also follows that when F2/F1=1.15 there is greater variation: this frequency ratio appears to be a region of transition at which either emission can predominate (Fig. 1). The relative amplitudes of the two components, therefore, seem to be determined by stimulus conditions and also by subject-related factors. However, whichever component is stronger for any F2/F1, it appears that both components are repeatable over time within an individual ear (Tables I-III).

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