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Negative-delay sources in distortion product otoacoustic emissions

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ABSTRACT

Long-delay components showing a symmetrical pattern with positive and negative delays can be observed in the time-frequency representation (or in the inverse Fourier transform) of distortion product otoacoustic emissions. Positive-only phase-gradient delays are predicted by place-fixed backscattering mechanisms, such as coherent reflection due to roughness, whereas the nonlinear distortion wave-fixed mechanism should generate an almost null-delay component. The symmetrical delay pattern arises whenever spectral amplitude fluctuations are not fully correlated to phase fluctuations. An interpretation of this phenomenon is proposed, involving place-fixed modulation of the spectral strength of the wave −fixed nonlinear generator.

Experimental data are shown in which these negative-delay sources are particularly strong, and further amplified by contralateral stimulation, suggesting that this effect could be dynamically enhanced. Analytical solutions of a linear 1-d transmission line model, in which cubic nonlinearity and roughness were added as small perturbations, have been used to test this hypothesis.

1. Introduction

According to a widely accepted interpretation scheme (Shera and Guinan, 1999), the spectral structure of the $2f_1-f_2$ distortion-product otoacoustic emission (DPOAEs) reflects the interference between two components: 1) a "distortion" component with almost constant phase, generated by nonlinear distortion in the cochlear region where the primary waves overlap and 2) a "reflection" component with rapidly-rotating phase, arising by scattering from micromechanical irregularity ("roughness") in the tonotopic region of the distortion product. The DPOAE spectrum indeed shows a characteristic pattern of quasi-periodic amplitude and phase oscillations, named fine-structure. These oscillation patterns appear consistent with the frequency dependence of a complex quantity given by the vector sum of a constant-phase component and of a rotating-phase component. Experiments and theoretical models show that the relative magnitude of the rotating-phase component is maximal at small ratios f_2/f_1 and low stimulus levels. These observations are also in agreement with the above mentioned scheme, because 1) the reflection generation strength increases more slowly with stimulus level than the distortion generation in a compressive cochlea, and 2) because it is much less sensitive than the distortion mechanism to the coherence loss associated with the spatial width of the distortion generation region (Shera and Guinan, 2007; Botti et al., 2016).

For simplicity, this interpretive scheme idealizes the distortion and reflection mechanisms as, respectively, purely wave-fixed (and therefore constant-phase) and purely place-fixed (rotating-phase). In the real cochlea, however, this distinction may become murky as the mechanisms interpenetrate. For example, micromechanical irregularity undoubtedly takes many forms, and spatial fluctuations in the gain or operating point of the cochlear amplifier presumably act not only to scatter traveling waves but also to modulate the effective strength of local distortion sources. Thus, the distortion generator would acquire a place-fixed component.

Time-frequency analysis (e.g., Moleti et al., 2012b) provides an effective way to visualize and to separate DPOAE components based

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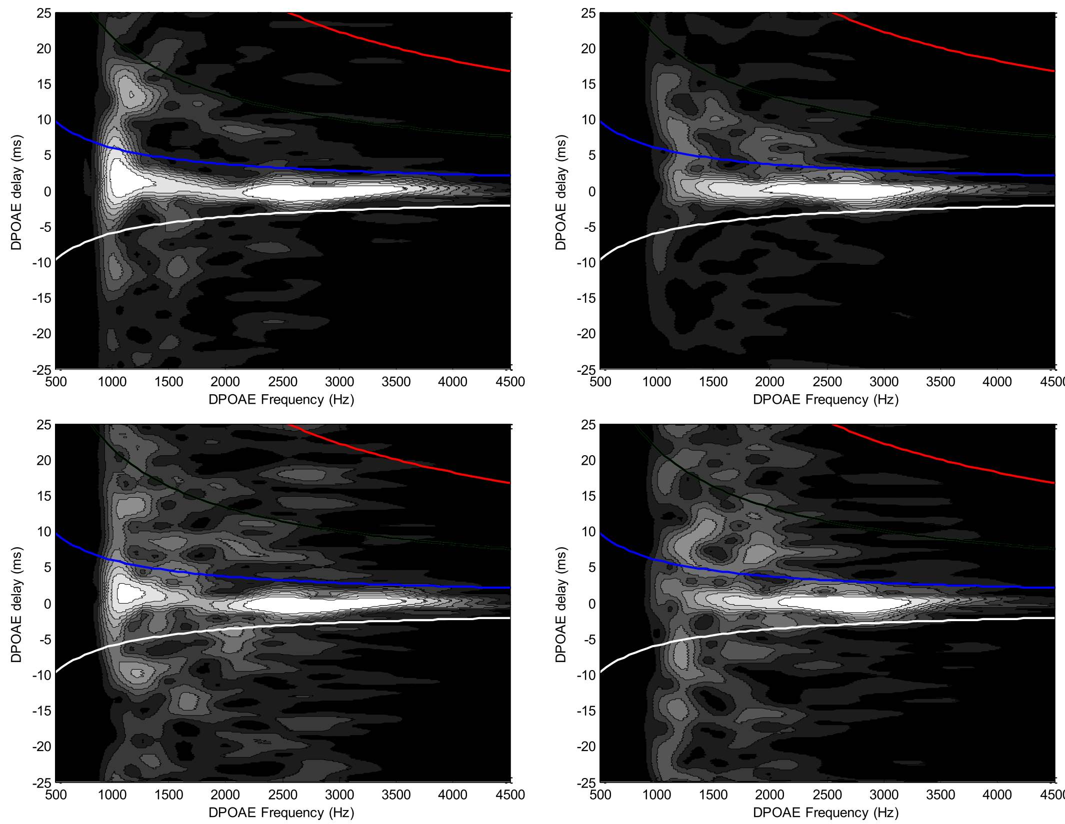

Fig. 1. DPOAEs time-frequency distribution of two subjects (left, age = 50, and right, age = 63) without (top) and with CAS (bottom). DPOAE spectra were re-analyzed, coming from a data set already analyzed in previous studies (Moleti and Sisto, 2016), recorded with high frequency-resolution (20 Hz) using slow chirp stimuli with instantaneous frequency functions $f_1(t)$ and $f_2(t)$, in a constant ratio $f_2/f_1 = 1.22$. The parameters of the two chirp stimuli were set in order to get $df_{dp}/dt = 800$ Hz/s. The primary stimulus levels were set at (L_1, L_2) = (65, 55) dB. Time-frequency analysis was performed using the wavelet transform, as described in Moleti et al. (2012b). Following the standard hypothesis, which we will relax in this paper, that all distortion components have null phase-gradient delay, the solid lines separate regions of the t-f plane associated with the distortion component (between white and blue line) single reflection from the f_{dp} tonotopic region (between blue and green) and double intra-cochlear reflection (between green and red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

on their phase-gradient delays.[1] In this analysis, constant-phase components concentrate at short delays close to the time axis and rotating-phase components appear at longer delays, usually within a curved quasi-hyperbolic region whose centroid decreases with frequency. Although this is the common pattern, some experimental cases show an emission spectrum that is not fully consistent with a sum of components from simple short- and long-delay sources. The discrepancy appears clearly in the time-frequency representation of the complex emission spectrum. Fig. 1 shows example time-frequency plots from two subjects in which components with apparently negative delay occur with a distribution almost symmetrical to that of the positive delay components. In such cases, part of the long-delay response consists of energy at positive delay with no counterpart at negative delays, while another part consists of "mirrored" energy symmetrically distributed between positive and negative delays. The solid lines separate regions of the t-f plane hypothetically associated with the distortion component (between white and blue line) single reflection from the f_{dp} tonotopic region (between blue and green) and double intra-cochlear reflection (between green and red), in a standard interpretative scheme assuming that distortion components have null phase-gradient delay.

The time-frequency plots in Fig. 1 are from subjects with a particularly rich distribution of long-latency negative-delay sources. Interestingly, the figure shows that the symmetrical components are enhanced by contralateral acoustic stimulation (CAS), suggesting that the source of this component is sensitive to dynamic changes of the cochlear gain driven by the medio-olivocochlear mechanism.

Symmetrical time-frequency delay patterns can be obtained from a "normal" DPOAE spectrum (in which the time-frequency representation shows only zero- and positive-delay components) by artificially setting the phase of the complex DPOAE spectrum to a constant value (e.g., zero) before computing the wavelet transform. By modifying the DPOAE phase, altering the relation between amplitude and phase fluctuations, one generates a complex spectrum that is not consistent with the sum of a zero-delay and a positive-delay component, and thereby induces symmetrical delay patterns in the time-frequency plot. In other words, spectral amplitude oscillations that are not exactly matched by the phase oscillations predicted by interference between a constant phase

[1] DPOAE "spectra" are actually a collection of complex nonlinear responses at different frequencies; they do not represent the Fourier transform of a measurable, time-domain waveform. Nevertheless, time-frequency analysis of DPOAE spectra performed as though the responses arose from a linear system remains useful and, to a significant extent, physically meaningful. For example, it may be shown (e.g., Moleti et al., 2012a) that when the rotating-phase component is assumed to be generated by place-fixed reflection in the DP tonotopic region, it must show a positive differential delay (with respect to the distortion component), almost equal to the physical round-trip transmission delay. These results are confirmed by experimental comparisons between stimulus-frequency-OAE (SFOAE) and reflection-DPOAE delays (e.g., Kalluri and Shera, 2001; Moleti and Sisto, 2016).

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