The Effect of Sweep Rate on Estimates of Distortion Product Otoacoustic Emission (DPOAE) Fine Structure and Properties of Separated DPOAE Components obtained with Continuously Sweeping Primaries. Simon Henin1, Glenis Long1, Carrick Talmadge2

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Abstract
Continuously sweeping primaries provide an efficient tool for measuring DPOAE amplitude and phase over a wide range of frequencies (Long et al., JASA, 105, 1471-1476, 2000). Different analyses of data collected in this way permits one to either extract the total DPOAEs providing information about the DPOAE fine structure generated by the interaction of the two primary DPOAE components, or to separate the two components separately. When using sweeps of 2.5 octaves or less there is little difference between the pattern of DPOAEs maximums and minima obtained with up- and down sweeps. When the sweep rate is increased in an attempt to collect more data, the overlap of each column, e.g., 5% per octave to 0.25% per second, frequency shifts of the DPOAE fine structure are seen, which result from the phase distortion associated with the dispersive nature of oticule wave propagation. The frequency maximums and minimums are higher than the frequency of the maximums obtained with the sweep frequency, and the maximums obtained with down-sweeps are lower. These frequency shifts can be modeled using the known frequency-sweep signal and the measured group delay of the device such that estimates of the function that would be obtained using constant frequency primaries permitting the use of faster sweep rates to collect data. Reconstruction of the DPOAE fine structure paradigm using the fast-sweep and comparison to data collection using the continuous fine DPOAE paradigm will be presented. (This work was supported in part by the Graduate Center of the City University of New York and the Navy).

Background
The use of continuous, logarithmically sweeping primaries (see methods) for the measurement of distortion product otoacoustic emissions (DPOAEs) has been shown to be an efficient measurement procedure (Long et al., 2009). In addition, both upward and downward sweeps have been used to provide separate independent measures. All sweeps take an at least 3 seconds per DPOAE sweeps are consistent with DPOAEs measured using a discrete frequency measurement paradigm (see Figure 1).

However, as the sweep rate is increased beyond 2 seconds per DPOAE, a noticeable decrease in the data obtained from the sweep direction becomes evident. Specifically, as the sweep rate is increased, the DPOAE fine structure shifts upward or downward in frequency for both up- and downward sweeps, respectively (Figure 2). The effect of sweep rate was investigated by examining the effects of sweep rate on the two DPOAE sweeps.

Two-Source Model of DPOAE
DPOAE consists of a complex interaction between at least two components.

Generator Component
Steering from the ear to near the region of maximal overlap of the primaries. This varies slightly with frequency (near fixed).

Reflection Component
Steering from the region near the distortion product characteristic-frequency. This varies rapidly with frequency (place fixed). Shera and Gashan, 1999. Talmadge et al., 1995.

Methods
DPOAE (2 subjects)
DPOAE sweeps: 200-1000 Hz sweep rates: 20, 1, 0.1, 0.05 seconds per DPOAE (200-1000 Hz sweep rates: 20, 1, 0.1, 0.05 seconds per DPOAE). Subject 1, 90 dB SPL, Subject 2, 95 dB SPL (Sciorson paradox, Kummer et al., 1998).

Data Analysis
A least-squares fit (LS) analysis was used (Vinosky, Talmadge, & Long, 2010) to estimate the fine structure, as well as the separated components. The LSF technique results in a bandpass filter with a moving center frequency. The bandwidth of the DPOAE fine structure model (see Figure 3) is determined by the analysis window in order to extract the fine structure (see Figure 4) which is used to estimate the DPOAE fine structure (see Figure 5).

Figure 1. Comparison between DPOAE level measured using fast-sweeping primaries and discrete frequency points

Figure 2. Effect of increasing sweep rate on DPOAE fine structure for up- and down sweeps (solid line, left) and down sweeps (dashed, right). Data indicate modified location of maxima

Figure 3. Comparison of the two-source model: Vector summation of the Generator Component (solid line) and Reflection Component (dashed line) of the DPOAE fine structure (solid line) with the observed DPOAE fine structure (dashed line) for the fourth harmonic (1000 Hz).

Figure 4. Example of data collected using the same stimulus as for Figure 1, where the frequency of 500 Hz was used to form the stimulus. The changes in the data are due to changes in sweep rate. The data shows that the changes in sweep rate are due to changes in the frequency of the DPOAE fine structure (solid line).

Figure 5. Examples of changes in sweep rate on the DPOAE fine structure. The changes in the data are due to changes in sweep rate. The data shows that the changes in sweep rate are due to changes in the frequency of the DPOAE fine structure (solid line).

Figure 6. Example of changes in sweep rate on the DPOAE fine structure. The changes in the data are due to changes in sweep rate. The data shows that the changes in sweep rate are due to changes in the frequency of the DPOAE fine structure (solid line).

Figure 7. Example of changes in sweep rate on the DPOAE fine structure. The changes in the data are due to changes in sweep rate. The data shows that the changes in sweep rate are due to changes in the frequency of the DPOAE fine structure (solid line).

Figure 8. Example of changes in sweep rate on the DPOAE fine structure. The changes in the data are due to changes in sweep rate. The data shows that the changes in sweep rate are due to changes in the frequency of the DPOAE fine structure (solid line).

Figure 9. Example of changes in sweep rate on the DPOAE fine structure. The changes in the data are due to changes in sweep rate. The data shows that the changes in sweep rate are due to changes in the frequency of the DPOAE fine structure (solid line).

Figure 10. Example of changes in sweep rate on the DPOAE fine structure. The changes in the data are due to changes in sweep rate. The data shows that the changes in sweep rate are due to changes in the frequency of the DPOAE fine structure (solid line).

Results
The frequency of the stable maxima (e.g., observed at all sweep rates) were extracted from those obtained at 2 seconds per DPOAE (200-1000 Hz).

SFOAE
• Similar amount of shift observed in both up- and down sweep direction.
• Similar changes in slopes for both up- and down sweeps observed to increase with the sweep rate.
• Simulation results using AM modulated test stimuli at various sweep rates (1.5, 0.5, 0.26 seconds per DPOAE) showed a similar decreased frequency shift in amplitude maxima (Figure 6), confirming the validity of the data analysis.

DPOAE
• Similar frequency shifts observed in DPOAE fine structure.
• Fewer maxima were available for analysis in the Generator Component because this component is mostly monaurally. The variance in the data probably reflects errors in the estimated information.
• The patterns for the Reflection Component are similar to those observed in SFOAE data, as expected because of their similar generation mechanisms. However, DPOAE were generally larger than the Reflection Component at these primary levels. Frequency shifts increased systematically with sweep rate, except for subject SRF whose Reflection Component approached the noise floor, making reliable estimates difficult.
• It was hypothesized that correcting for phase shifts in the Reflection Component alone (not shown) could reduce the observed frequency shifts in the total DPOAE fine structure. When the phase shift was corrected for (Figure 7, left column), and the total DPOAE was reconstructed using a weighted addition of the two components, the frequency shifts in total DPOAE fine structure maxima were greatly reduced (Figure 7, right column).

MODEL
In a dispersive cochlear model, the frequency dispersion can be expressed as:

\[ \Delta f = \frac{n_i f_i f_s}{f_T} \]

(1)

where \( n_i \) is the number of waves-to-peaks, \( f_s \) is the total sweep duration, and \( f_T \) and \( f_s \) are the starting and ending frequencies, respectively (Talmadge et al., 1996). Therefore, frequency shifts as a function of the sweep rate (octaves/T) would be predicted.

To this end, SFOAE simulations were performed using a 1.0 cochlear model (Talmadge et al., 1996) using the same approach as the data from human subjects.

• Similar shifts in SFOAE frequency maxima were observed in the model (Figure 8).

The relationship between frequency shift as a function of a wide range of sweep rates at a single maximum is shown in Figure 9, showing that the relationship can be described by a constant slope, as predicted by equation (1).

Conclusions
When continuously sweeping primaries are used to measure SFOAE and DPOAE, as the sweep rate increases, the frequency of the fine structure moves in the direction of the sweep.

• Frequency shifts in DPOAE fine structure can be attributed to shifts in the Reflection Component. By removing the phase of the Reflection Component before combining the two sources nearly eliminated the frequency shifts in DPOAE fine structure.

• It is hypothesized that increased dispersion along the cochlear with sweep rate is due to the frequency shifts observed observed in the data. When a sweep rate below 0.25 Hz was used, this dispersion is small; as the sweep rate increases the amount of dispersion becomes larger. Simulations provide supporting evidence for this hypothesis and suggest variable sweep rates could be used to investigate more complex cochlear mechanical properties, such as scale invariance.

• The frequency shifts do not prohibit the use of these faster sweep paradigms as a more efficient method of data collection.

References