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Eartip Modification Greatly Reduces Evanescent Waves.

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Abstract

Introduction. Sounds radiated into the ear canal from a source with a relatively small aperture produce evanescent waves that influence the pressure measured near the source aperture (Keefe and Benade, 1980, JASA; Brass and Locke, 1997, JASA). Because only the plane wave propagates longitudinally along the canal, the pressure measured near the source does not accurately represent the stimulus to the ear.

Methods. The decline in evanescent pressure with distance from the source was measured for an Etymotic Research ER-10X otoacoustic emission probe by advancing a probe tube through the body and central lumen of the replaceable front tube. Sound is emitted through surrounding outer lumens, which all end in the same plane. Pressure at the plane of the probe was also measured using the internal microphone of the ER-10X. In an alternative configuration, the front tube was modified by beveling the most distal ~2 mm of the outer lumens, leaving the central lumen intact. The aperture of the beveled configuration was about twice that of the standard front tube.

Results. The pressure frequency response was measured at longitudinal positions from 0 to 12.7 mm from the end of the probe. Relative to the distant pressure, the pressure measured at the end of the standard front tube increased above 10 kHz to a maximum of ~5 dB at 20 kHz, while the pressure measured 5 mm or more from the source was essentially the same, as expected from theory. In the beveled configuration, the pressure at the end of the front tube remained within 1 dB for all frequencies below 20 kHz. Evidence of evanescent wave reduction was also observed in both the impulse responses and the spectral magnitudes of pressures measured with the internal microphone. Thévenin calibrations in the beveled configuration showed consistently lower errors in the extraction of source pressure and impedance.

Conclusion. Beveling the standard front tube was intended as a first step toward optimizing the source configuration. The reduction in evanescent waves due to this simple modification was greater then expected. This reduction improves the quality of Thévenin calibrations, which should improve the accuracy of ear-canal impedance measurements. Such improvements could be particularly important for ear canals with larger than average diameter for which evanescent wave contributions to the measured pressure are larger.

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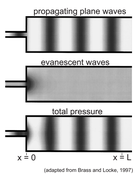
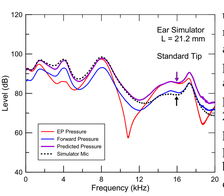
Introduction

A sound source with diameter smaller than that of a cylindrical tube it radiates into generates a sound field composed of plane waves that propagate along the tube and evanescent waves that spread from the source but do not propagate (Brass and Locke, 1997; Zebian, et al., 2012). To study the two components emitted by an otacoustic emission probe it is convenient to place the probe in a long tube with diameter approximating that of the average ear canal. The sound field contains no reflections and so the decay of the evanescent pressure can be measured directly using a probe tube advanced into the long tube from the tip of the emission probe (EP) (x=0) to sample the pressure at any point along the tube (x=L). The decay of the evanescent waves with distance is measured by advancing the probe tube into the long tube until there is little change in the measured pressure and the plane wave becomes dominant. The plane wave declines slowly with distance due to frictional losses.



(adapted from Brass and Locke, 1997)

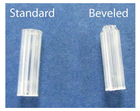


We have often tested the accuracy of stimulus calibration using an EP by comparing the pressure measured by the microphone of a test cavity or an IEC 60318-4 ear simulator and the pressure at the termination predicted from the pressure measured by the EP. This prediction was made by adding the amplitudes of the forward and reflected pressures, referred to as integrated pressure (Lewis, et al., 2009; Scheperle, et al., 2011). In the plot to the left the predicted pressure (purple) becomes ~6 dB larger than the pressure measured by the simulator's microphone (dashed black) above 12 kHz (arrows). It seemed plausible that this discrepancy was caused by evanescent waves which are present near the EP but not at the termination.

Methods

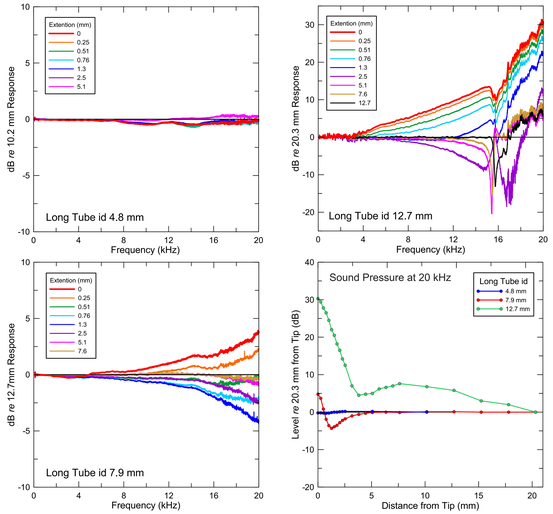
Measurement Procedure. A 1 mm OD stainless steel probe tube, coupled to an electret microphone, was advanced through the access port in the body of an Etymotic Research ER-10X OAE probe under micrometer control (right). Starting with the end of the probe tube flush with the end of the disposable multilumen front tube, the micrometer was advanced in small steps between measurements of the pressure using chirp excitation (Sysres, Neely and Stevenson, 2002). The long tube was a 50' length of clear polyethylene tubing with an ID of 7.9 mm.

Front Tube Configurations. The left figure below shows the two configurations of the multilumen front tube used in the test. The **Standard** tube is as supplied by Etymotic Research. The **Beveled** tube was modified to remove part of the outer tube, leaving the central microphone tube unaltered. The beveled tube allows the sound to be radiated starting at the bottom of the small depression of the rubber ear-tip (right). The modification increases the aperture of the sound source by a factor of about two, allowing the sound to begin to disperse proximal to the microphone inlet. Increasing the aperture of the source should reduce the amplitude of evanescent waves relative to the plane waves.



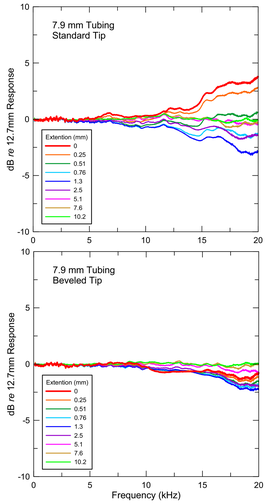
Results

1. Spatial Decline of Evanescent Wave Pressure



The relative amplitude of the evanescent wave pressure increased with the diameter of the long tube. The tube with the smallest id (4.8mm) showed the smallest spatial variation of the pressure (~ +/- 1 dB) for frequencies below 20 kHz (upper left). The pressure in the 7.9 mm tube showed larger (~ +/- 4 dB) variation that increased with frequency (lower left). The pressure in the tube with the largest diameter (12.7 mm) showed much larger spatial variations, as much as 30 dB larger at the probe inlet relative to the distant position where plane waves appeared to dominate (upper right). The pressure at 20 kHz vs distance from front of the emission probe for all three tube diameters shows nonmonotonic changes (lower right). The distance from the emission probe at which plane waves become dominant increases with tube diameter as expected from theory. The range of human ear canal diameters spans the examples shown here. Evanescent waves are likely to be a serious problem in larger ear canals when the pressure measured by the probe is relied on for calibration.

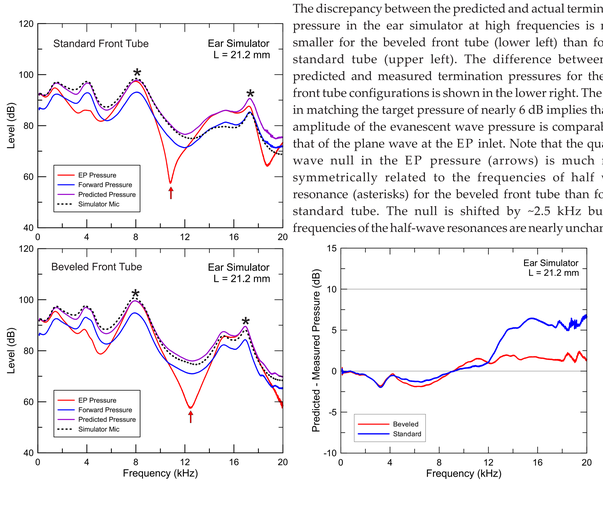
2. Beveling the Front Tube Changes Pressure Responses



Standard multilumen front tube. The red curve in the figure shows the pressure at the end of the front tube, the position of the microphone inlet of the ER-10X. This and other plots are normalized by the pressure measured at 12.7 mm from this point, where the plane wave clearly dominates. The normalized pressure in this example is about 4 dB higher at 20 kHz than at the distant location (x=12.7 mm) and the increase becomes smaller with decreasing frequency. This pressure increase declines steeply as the probe tube is advanced over the first millimeter and the normalized pressure reverses sign, as the probe tube is advanced further. Large changes remain at frequencies above 20 kHz (not shown), but the pressure became almost independent of distance below 20 kHz for extensions of 5 mm or more .

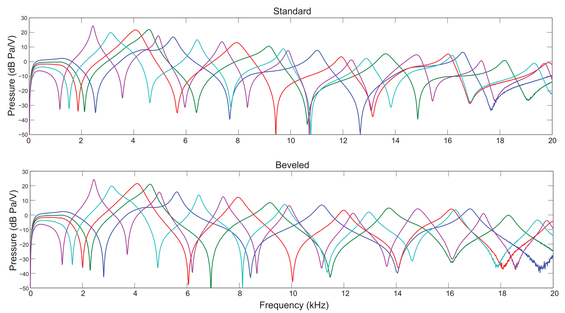
Beveled front tube. Beveling the front tube greatly reduces the change in sound pressure with distance from the end of the front tube. The pressure at the microphone inlet stays (red) within 1 dB of the value 12.7 mm distant from the probe's microphone inlet for frequencies below 20 kHz. Large changes are still observed at higher frequencies (not shown).

3. Effect of Insertion Depth on Thresholds and Emissions in All Ears

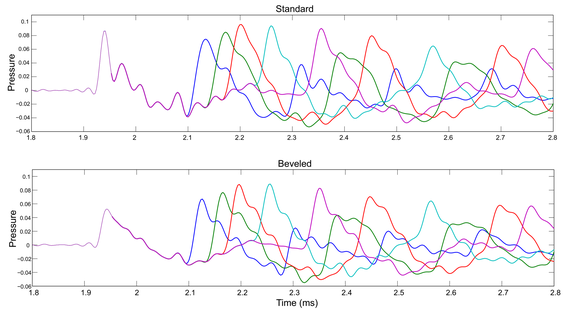


The discrepancy between the predicted and actual termination pressure in the ear simulator at high frequencies is much smaller for the beveled front tube (lower left) than for the standard tube (upper left). The difference between the predicted and measured termination pressures for the two front tube configurations is shown in the lower right. The error in matching the target pressure of nearly 6 dB implies that the amplitude of the evanescent wave pressure is comparable to that of the plane wave at the EP inlet. Note that the quarter-wave null in the EP pressure (arrows) is much more symmetrically related to the frequencies of half wave resonance (asterisks) for the beveled front tube than for the standard tube. The null is shifted by ~2.5 kHz but the frequencies of the half-wave resonances are nearly unchanged.

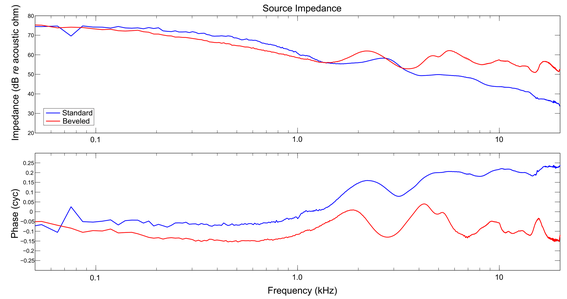
4. Evanescent Waves Contaminate Thévenin Source Calibrations



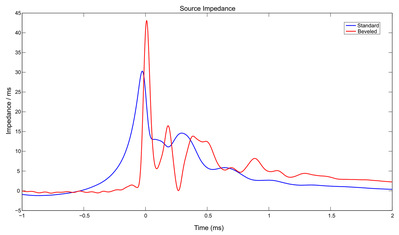
The pressure responses in the set of five cavities used during Thévenin source calibration (Scheperle, et al., 2008; Souza et al., 2014) of the ER-10X probe depended on the configuration of the front tube. In the frequency domain, the differences between the standard and beveled tube are mainly in the nulls above 10 kHz. One could argue that the symmetric appearance of the peaks for the beveled tube are preferable, but that might just be an aesthetic judgement. This assymmetry of the nulls is similar to those seen in the EP pressure response of the ear simulator in Panel 3.



This figure compares cavity pressures in the time domain, an inverse Fourier transform of the pressures in the figure above. Here the differences appear mainly in the first peak (between 1.9 and 2.1 ms). One could argue that the closer similarity between the initial peak and subsequent peaks for the beveled tube is preferable, but again this might just be an aesthetic judgement.



This figure compares source impedances calculated by conventional methods from the cavity pressures. Although there are obvious differences between the standard and beveled tubes, the real part of the impedance remains positive at essentially all frequencies for both tubes, so there is no obvious reason to prefer one tube over the other.



This figure compares source impedances in the time domain. Time-domain impedance will be an unfamiliar concept to most people, but it's simply the inverse Fourier transform of the impedances shown in the previous figure. Much of the impedance for the standard front tube occurs prior to t=0. This is obviously different from impedance for the beveled tube, which is essentially zero for t<0. So, one can argue that the beveled front tube is greatly preferable because the impedance for the standard tube is non-causal.

Summary and Conclusions

1. Deviations between the pressure at the termination of an ear simulator and that predicted from the pressure measured by an otoacoustic emission probe suggested the presence of evanescent waves near the probe inlet that do not propagate to the termination. The decay of the evanescent pressure with distance from the probe inlet was measured in long tubes with different diameters. As expected from theory, the relative amplitude of the evanescent wave *re* the plane wave depends on the diameter of the tube.

2. Changing the shape of the probe's front tube/ear-tip appeared to increase the effective aperture of the source, allowing the sound to begin to disperse before reaching the microphone inlet, reducing the relative amplitude of the evanescent wave pressure.

3. Evanescent waves affect Thévenin source calibrations, increasing the magnitude of the source impedance and flattening the frequency-dependence of its phase at high frequencies. Examining the source impedance in the time domain reveals substantial non-causality. The problem also appears in in-ear stimulus calibrations.

4. Refining the design of the ear-tip and front tube of an emission probe is one way to reduce the relative magnitude of the evanescent wave relative to the plane wave. Another might be to measure and/or model the evanescent pressure so that it might be compensated.

Acknowledgments

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