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Otoacoustic Emission Simulations

This project simulates two methods of measuring otoacoustic emissions (OAE): click-evoked and tone burst. A transmission line model of the inner and middle ear is being used in place of human subject measurements. Subject number 1, a normal hearing individual, is used for these simulations. Otoacoustic emissions are a key method for assessing the health of the inner ear and can provide insight into the mechanics involved in the active mechanism in the inner ear.

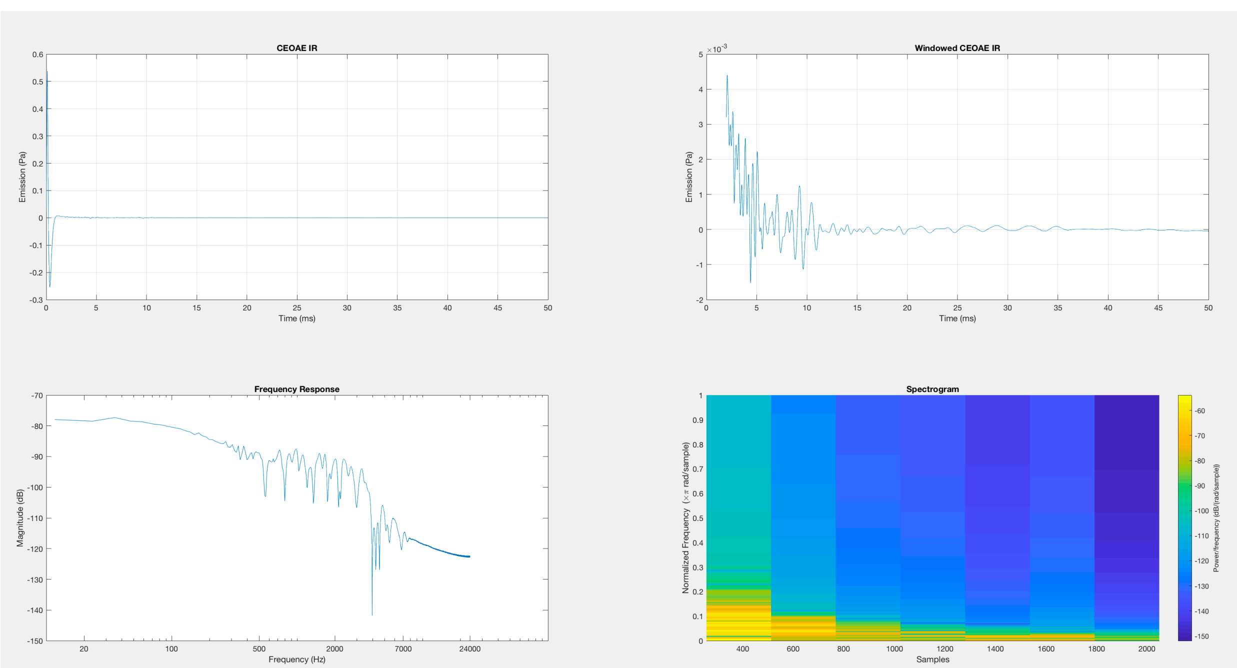
The model: Verhulst2012, from the Auditory Modeling Toolbox
http://amtoolbox.sourceforge.net/amt-0.9.5/doc/monaural/verhulst2012.php

S. Verhulst, T. Dau, and C. A. Shera. Nonlinear time-domain cochlear model for transient stimulation and human otoacoustic emission. *J. Acoust. Soc. Am.*, 132(6):3842 - 3848, 2012.

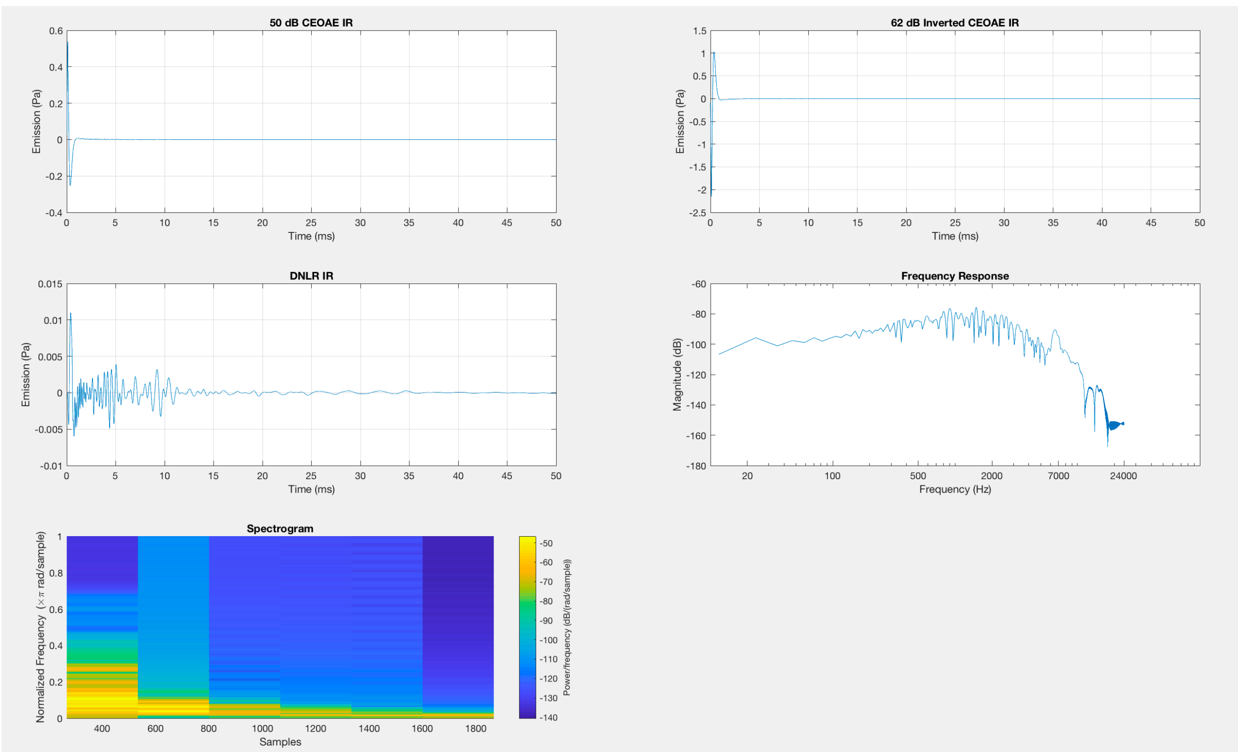
1) Click-Evoked Otoacoustic Emission (CEOAE):

It is believed that the broadband impulse stimulates the cochlear active mechanism outer hair cells all along the basilar membrane, producing a measurable response. The challenge of separating the input stimulus from the otoacoustic emission can be overcome via time windowing or the derived non-linear response (DNLR) technique.

A click (100 us rectangular impulse) at 50 dB SPL was fed into the cochlear model. The pressure 'measured' at the middle ear was windowed and analyzed. The time-windowed impulse response below has the first 2 ms of the emission removed, which is largely the effect of the impulse itself. The following 48 ms contain the approximate OAE response. The impulse response before and after windowing are shown before, along with a FFT and spectrogram plot of the windowed response.



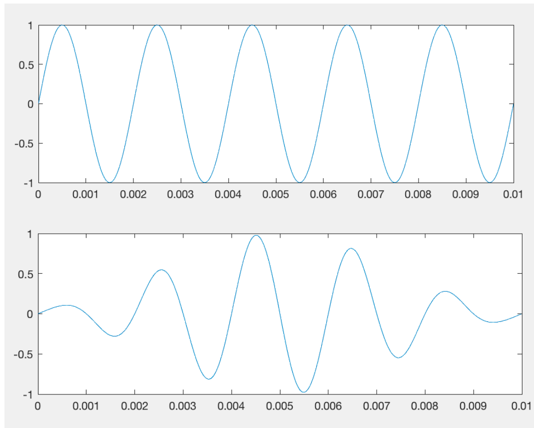
To apply the derived non-linear response technique to capture OAE, two different impulses are sent into the cochlea. One impulse is at 50.0 dB SPL, while the other impulse is at 62.04 dB SPL (4x greater amplitude) with opposite polarity relative to the first impulse. The simulated emission captured from the first pulse is multiplied by a factor of 4, and then summed with the second simulated emission. This should largely negate the linear response components (the impulse) while the non-linear cochlear-generated OAE will be measured in the difference between the two SPL level impulses. The DNLR technique depends on significant active cochlear amplification in this SPL range.



An FFT and spectrogram plot are also shown of the DNLR emission, without any time-windowing needed to remove the impulse. Because high frequency (basally located) OAEs will respond temporally sooner than low-frequency (apically located) OAEs, not needing to remove the early response with a time window will extend our OAE frequency response higher. We can see that our time-windowed CEOAE's frequency response does not show the notches above 7kHz that the DNLR's frequency response has.

2) Tone Burst Otoacoustic Emission (TBOAE):

To simulate a tone burst OAE, short sinusoidal input signals are generated. Each signal lasts 5 periods. A hamming window is applied, in order to achieve a high precision frequency response with a short impulse. Below is the input sinusoid before and after windowing:



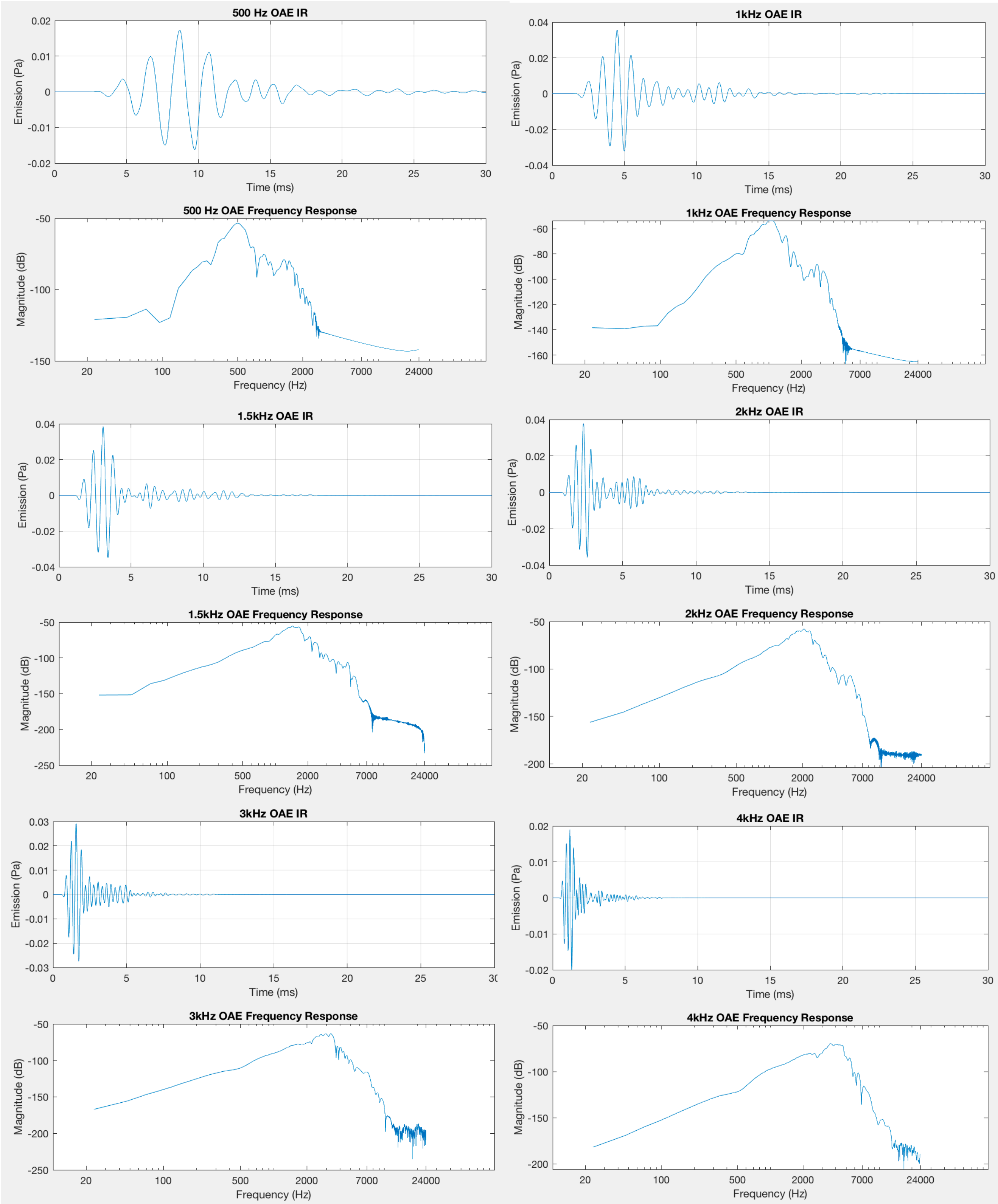
Using the same derived non-linear response technique described in the CEOAE simulation above, the OAE can be isolated from the stimulus. Tone bursts of 500, 1k, 1.5k, 2k, 3k, 4k, and 6kHz are simulated. Impulse responses and frequency responses are shown below.

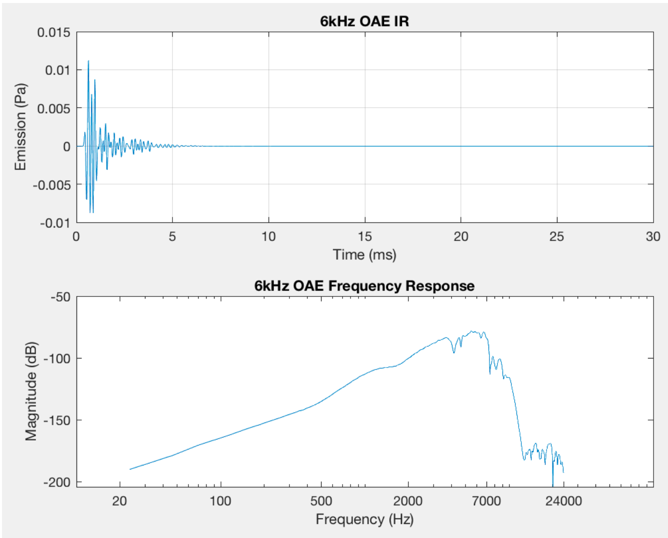
Several observations can be noted with this set of impulse and frequency responses. First, the peak frequency of any OAE response is the same as the stimulus frequency. Second, there is much more time latency in the OAE response of low frequencies than high frequencies. This is to be expected, since the characteristic locations of high frequencies along the basilar membrane are much closer to the base of the cochlea, thus requiring less travel distance (and thus time) than low frequencies. The following table shows the relationship between the stimulus frequency and the temporal latency of the peak of the OAE response.

An exponential curve can be fit to this data quite well (R^2 = 0.984):

$$t_{delay} \propto -e^{-1.337 f_{stim}}$$

Frequency (Hz)	OAE Latency (ms)
0.5k	8.7
1k	4.5
1.5k	3.1
2k	2.5
3k	1.7
4k	1.3
6k	0.6


500 Hz OAE IR
Emission (Pa)
Time (ms)
1kHz OAE IR
Emission (Pa)
Time (ms)
500 Hz OAE Frequency Response
Magnitude (dB)
Frequency (Hz)
1kHz OAE Frequency Response
Magnitude (dB)
Frequency (Hz)
1.5kHz OAE IR
Emission (Pa)
Time (ms)
2kHz OAE IR
Emission (Pa)
Time (ms)
1.5kHz OAE Frequency Response
Magnitude (dB)
Frequency (Hz)
2kHz OAE Frequency Response
Magnitude (dB)
Frequency (Hz)
3kHz OAE IR
Emission (Pa)
Time (ms)
4kHz OAE IR
Emission (Pa)
Time (ms)
3kHz OAE Frequency Response
Magnitude (dB)
Frequency (Hz)
4kHz OAE Frequency Response
Magnitude (dB)
Frequency (Hz)


6kHz OAE IR
Emission (Pa)
0.015
0.01
0.005
0
-0.005
-0.01
0
5
10
15
20
25
30
Time (ms)
6kHz OAE Frequency Response
Magnitude (dB)
-50
-100
-150
-200
20
100
500
2000
7000
24000
Frequency (Hz)