Spectral Response Measurements of a Simulated Human Ear Canal

The average length of the human ear canal is $L \sim 2.5$ *cm* (1"), it is slightly shorter (longer) for women (men). The human ear canal is also not perfectly circular, but ~ elliptical in shape – it is wider vertically (~ 8.5 *mm*) than horizontally (~ 6 *mm*), with a mean diameter of $D \sim 7.25$ *mm*.

We simulated a human ear canal with a short piece ($L \sim 3.0$ *cm*) of flexible plastic (tygon) tubing (inner diameter $D \sim 2.6$ *mm*), placing one of our UIUC Physics 406 "nano-p_{mic}" at the far end of the plastic tygon tube, where the ear drum is located.

We carried out spectral measurements in the POM lab (6105 ESB) using the HP 3562A Dynamic Signal Analyzer. First, we measured the ambient noise floor of the lab – due to ~ $1/f^2$ noise fluctuations in the air flow of the room's ventilation system and the cooling fan noise from the HP 3562A DSA. Then, we repeated the spectral measurement again using ambient room noise, but with the nano-p_{mic} inserted into the far end of the plastic tygon tube. The two spectral noise measurements are shown/compared in the figures below:
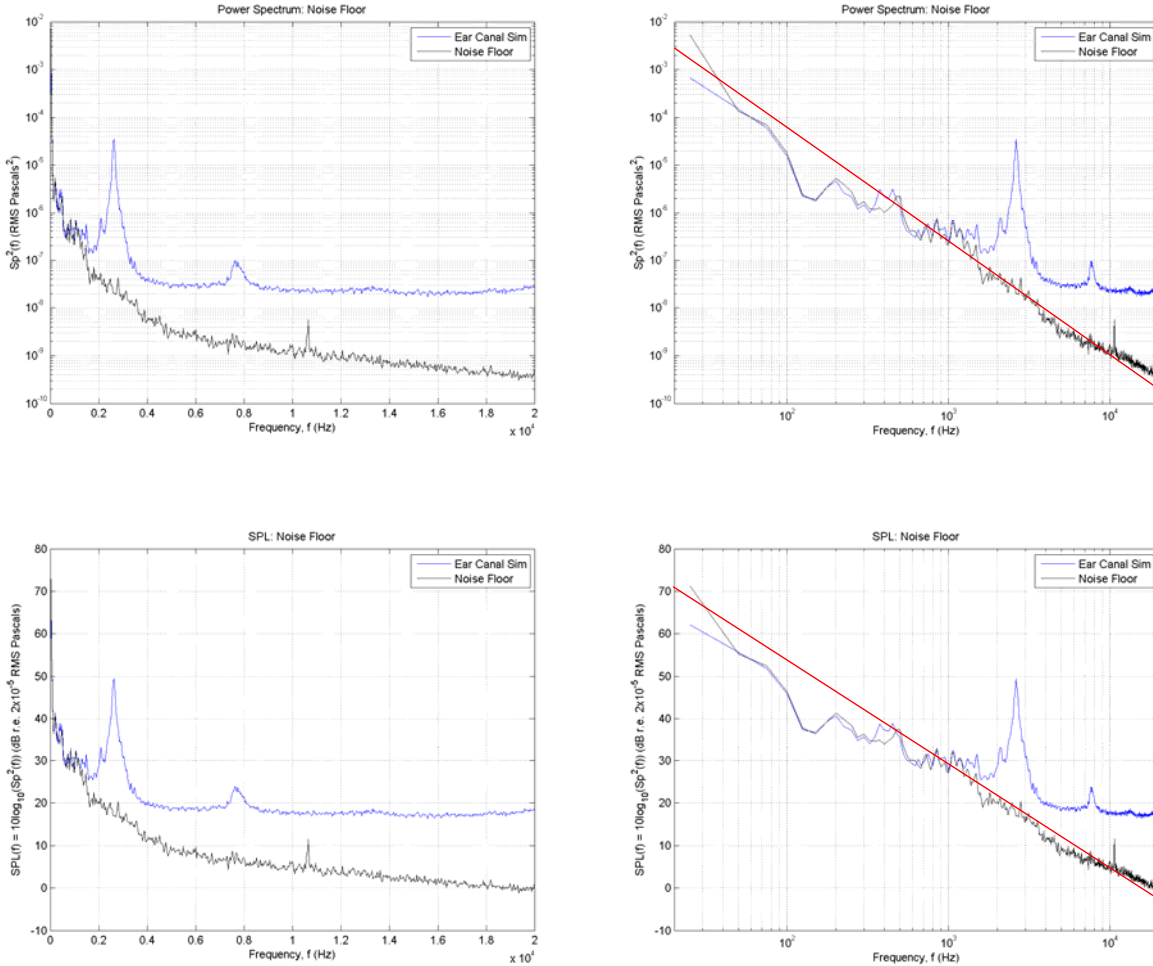

The red line on the log-log plots shows that the ambient noise ~ obeys a power law relation.

The raw spectral data $S_V^2(f) = \left|\tilde{V}_{rms}(f)\right|^2$ from the HP 3562A DSA has units of $(RMS\ Volts)^2$. The measured sensitivity of the nano-p_{mic} is $S_{p\text{-}mic}$ = 198.6 $RMS\ mV/RMS\ Pascal$ (using an Extech 407744 94 dB Sound Calibrator and a Fluke 87 DMM on $AC\ RMS\ Volts$ scale).

An acoustic over-pressure level $SPL(f) = 94.0\ dB = 10\log_{10}\left(\left|\tilde{p}_{rms}(f)\right|^2 / p_{o_{rms}}^2\right)$ corresponds to an over-pressure amplitude of $\left|\tilde{p}_{rms}(f)\right| = 1.0\ RMS\ Pascals$ at NTP, where $p_{o_{rms}} = 2.0\times10^{-5}\ RMS\ Pascals$ is the {reference} threshold over-pressure amplitude of human hearing {corresponding to a sound pressure level SPL = 0 dB}.Thus, the absolutely-calibrated over-pressure spectral data is $S_p^2(f) = \left|p_{rms}(f)\right|^2 = S_V^2(f)/S_{p\text{-}mic}^2\ (RMS\ Pascals)^2$.

The acoustical properties of the human ear canal is functionally that of a short open-closed organ pipe. Thus, it has resonance frequencies of $f_{n_{odd}} = n_{odd}v/4L_{eff}$, where $n_{odd} = 1,3,5...$ and $L_{eff} = L + \delta_{end} \sim L + 0.6D\ (m)$ is the {effective} acoustic length of ear canal, $L\ (m)$ is the physical length of the ear canal, $\delta_{end} \sim 0.6D\ (m)$ is the so-called end-effect correction associated with the open end of the ear canal, and $D\ (m)$ is the {mean} diameter of the ear canal. The above figures show these first three resonances of the ear canal $f_1 \sim 2625\ Hz$, $f_3 \sim 7675\ Hz$ and $f_5 \sim 13150\ Hz$ excited purely by $\sim 1/f^2$ ambient room noise! The average $L_{eff} \sim 3.3\ cm$. The narrow resonances at low frequencies (below f_1) are due to the harmonics of the rotating cooling fan blade in the HP 3562A DSA. Note further that the noise floor of the simulated ear canal is raised significantly - at all frequencies - due to the use of the ear canal as part of our hearing system. This limits the lower limit/threshold of our human hearing.

We can explicitly subtract the ambient noise (no ear canal) data from the ear canal spectral data, but this does **_not_** totally remove the ambient noise from the ear canal spectral measurement – because the acoustic energy density in the ear canal gets "loaded up" by the ambient noise – storing it up due to its {frequency-dependent} quality factor, $Q(f)$. The noise floor-subtracted results are shown in the figures below:


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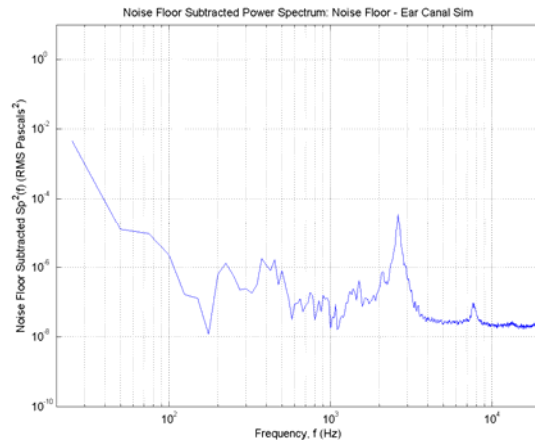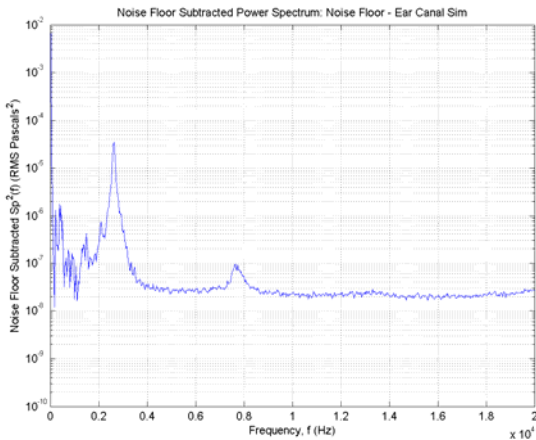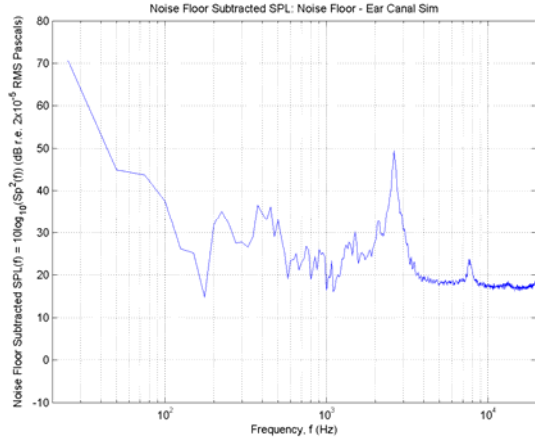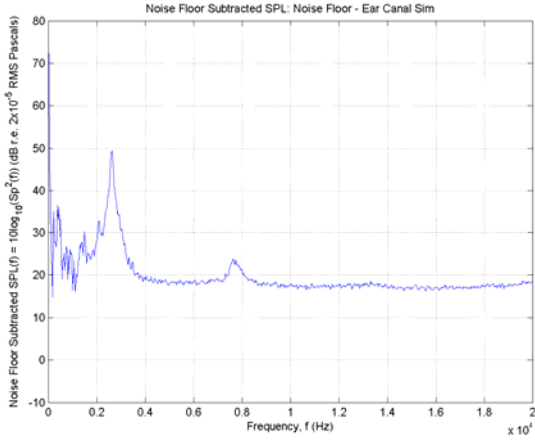
The so-called quality factor $Q(f)$ {*aka Q*-factor} associated with the ear canal can be obtained *e.g.* from the full width at half maximum (*FWHM*) associated with the above three resonances, but we can also equivalently obtain the *Q*-factor *e.g.* by taking 2π times the ratio of the noise floor-subtracted simulated ear canal spectra to the ambient noise spectra, *i.e.*

$$Q(f) \equiv 2\pi \left[S_p^2(f) \Big|_{NFSubtr} \Big/ S_p^2(f) \Big|_{AmbNF} \right] = 2\pi \left[Acoustic\ Energy\ Stored \big/ Acoustic\ Energy\ Input \right].$$

These results are shown in the figures below:
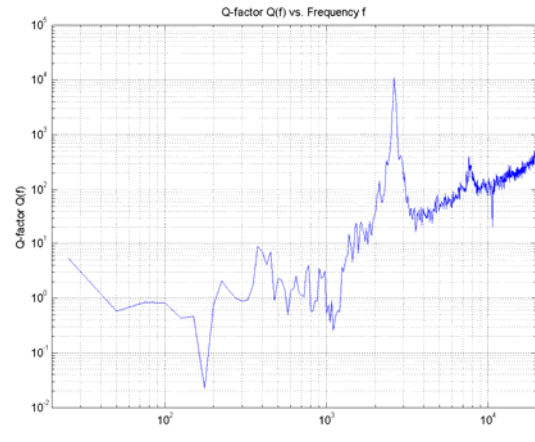
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