Today's lab uses Excel to demonstrate to you how you can add different frequencies together to make complex sounds, and how the ear filters complex sounds to recover their component frequencies. It shows you how the bandwidth of the ear's filters increase with frequency, and the consequences of this for the way the basilar membrane vibrates.

To open the file freqfilt.xlt go to http://www.biols.susx.ac.uk/home/Chris_Darwin/Perception/Lecture_Notes/Hearing_Index.html and click on Excel Workbook – save the excel file on your N: drive (or hardisk if at home) and then open it in Excel. The workbook has three sheets ("freqs", "aud filt" & "excit") which you can access with the tabs at the bottom of the screen.

To change a value in a cell: click on the cell, type the new value and then either click on another cell, or click the green tick, or press Enter. There is a short pause while Excel calculates the new values and updates the graphs.

A. Frequencies and Waves.
First, go to the View menu and activate “Full Screen”. To go to the Frequencies and Waves sheet, click on the "freqs" tab. This sheet allows you to add together any of the first 10 harmonics of a complex tone, and shows the spectrum of the sound (in linear and in dB units) and the waveform of the sound.

You can set the fundamental frequency of the sound in the yellow box in the top left-hand corner. The boxes underneath show you the corresponding period of the waveform in seconds and milliseconds. The numbers in the column headed "freq" show the first 10 harmonic frequencies of that fundamental.

You can also set the amplitudes of the individual (sine wave) frequency components in the yellow column headed "%amp". To start with they are all set to 100. The numbers in the yellow column are plotted in the yellow graph showing the amplitude spectrum of the sound in linear (amplitude) units. The blue column of numbers converts these amplitudes to a logarithmic (decibel) scale, with the arbitrary convention that 100% is equivalent to 20 dB. (When the amplitude is zero the dB value should be minus infinity, but I have arbitrarily set it to -200 to stop Excel getting worried). The frequency axes of both graphs adjust automatically to the frequency range.

The graph at the bottom shows the waveform of the sound made by adding together all 10 different sine waves. The time axis is in seconds; the y-axis is in linear units of amplitude (pressure). The time axis covers 0.025 s or 25 ms.

Work through the following exercises and answer the questions as you go along. Get your answers checked by one of the demonstrators.
1. Set the fundamental frequency to 200 Hz. What is the period? [ ] ms.
   How many cycles of the waveform are there in 0.01s? [ ]
   What is the frequency of the 7th harmonic? [ ] Hz.
   What is the frequency-spacing of the harmonics? [ ] Hz.

2. Now remove the fundamental frequency (harmonic number =1) by setting its amplitude to zero. Notice that the shape of the waveform has changed.
   Look at the waveform graph; has the period of the waveform changed? [ ]

2. Look at some of the component sine waves by setting the amplitudes of all the other frequencies to zero.
   How many cycles of the 1000 Hz sine-wave are there in 10ms? [ ]

3. Halve the amplitude of one component (eg from 100 to 50).
   By how many dB does it decrease? [ ] dB.

4. Set all the amplitudes back to 100 (change the top one to 100 and then select it and drag the bottom right-hand corner of its box down to cover all 10 entries). Change the fundamental to 100 Hz.
   How many periods of the waveform are there in 10ms now? [ ]

5. Change the amplitudes of some of the harmonics and notice the changes in the shape, but not of the period of the waveform. Now set the fundamental to 200 Hz, the amplitudes of harmonics 6 and 7 to 100 and all the other amplitudes to zero. Notice that the waveform "beats" (ie has slow, regular changes in amplitude).
   What is the rate of the "beating"? [ ] Hz

6. Finally, set the amplitudes all back to 100 (the fundamental should still be 200 Hz). Now change one of the frequency values to a non-harmonic value (eg the second harmonic from 400 to 450). (You may need to use Tools menu: Unlock first). Notice that the waveform does not now have a period of 5ms. (This change will have destroyed the calculation in that frequency cell; you can replace it by selecting the top frequency cell and dragging its bottom right-hand corner down to the changed cell).
B. Auditory filters.
To go to the Auditory filtering sheet, click on the "aud filt" tab.

There are only two numbers for you to change - the two in yellow boxes. The upper number is the fundamental frequency (as in the previous worksheet). This number is used to calculate a waveform with 20 equal-amplitude harmonics whose spectra and waveform are shown in blue.

The lower number is the center frequency of the auditory filter. The bandwidth of the filter is shown automatically below it. The pink waveform and the corresponding pink spectra are the result of filtering the blue waveform through an auditory filter at this frequency. In other words, the waveform shows you (roughly) how the basilar membrane vibrates at the place that resonates at this frequency, when you play the blue waveform into the ear.

1. Set both the auditory filter and the fundamental to 200 Hz. (Wait for the calculations to finish) and look at the new spectra and the new waveforms.

   What frequency sine-wave comes through the filter?   Hz.
   What is the bandwidth of the auditory filter?   Hz.

2. Change the auditory filter to 400 Hz (leave the fundamental at 200 Hz).

   What frequency sine-wave comes through the filter?   Hz.
   What is the bandwidth of the auditory filter?   Hz.

3. Change the auditory filter to 600 Hz (leave the fundamental at 200 Hz).

   What frequency sine-wave comes through the filter?   Hz.
   What is the bandwidth of the auditory filter?   Hz.

4. Now change the auditory filter to 3200 Hz.

   What is the bandwidth of the auditory filter?   Hz.
   What is the frequency-spacing of the harmonics?   Hz.
   What is the period of this waveform?   ms
   Why is the waveform not now (roughly) a sine wave?
At roughly what frequency is the auditory bandwidth the same as the spacing between harmonics? \( \boxed{\text{Hz}} \) 

Roughly what harmonic number does this correspond to? \( \boxed{} \)

5. Now change the fundamental to 100 Hz.
At roughly what frequency is the auditory bandwidth the same as the spacing between harmonics? \( \boxed{\text{Hz}} \) 

Roughly what harmonic number does this correspond to? \( \boxed{} \)

C. Excitation patterns.
To go to the Excitation patterns sheet, click on the "excit" tab. The graph shows an excitation pattern produced by the complex tone whose fundamental frequency and harmonic amplitudes you set in the yellow boxes. The excitation pattern shows you by how much the basilar membrane is vibrating at each point along its length. So each point on the excitation pattern plots the energy coming out of the auditory filter at that frequency (ie the energy in the bottom graph on the "aud filt" worksheet. The graph plots the excitation pattern on a linear (Hz) scale so that you can see the relationship between the excitation peaks and the individual harmonic frequencies, the actual basilar membrane is more nearly a logarithmic scale. The graph is plotted with frequency reversed so that the high frequencies are on the left. The y-axis is in deciBels (dB). A large peak in the excitation pattern shows that the auditory system is resolving that harmonic from its neighbours. Where there is no clear peak (eg at 1800 Hz when the fundamental is at 120 Hz) then the harmonics are not being resolved.

1. For a 120-Hz fundamental tone with all the harmonics set to 100%, how many individual peaks can you see (where a peak is > 1dB above its valleys). \( \boxed{} \)

2. How many for a 200-Hz fundamental? \( \boxed{} \)

3. Why are these two numbers about the same? \( \boxed{} \)

4. Set some of the harmonic amplitudes to zero and see how the excitation pattern changes. Now change the bandwidth widening factor from 1 to 3 to see the result of wider bandwidths on the excitation pattern.

The answers to all the questions are available from the same web page as the Excel file. If you have problems with these questions which you cannot get answered during the class, then please call in at my office (JMS 4D19) and I will try to help you.

Chris Darwin, Oct 2002