Acoustics of Speech and Hearing

Week 2-10

Hearing 3: Auditory Filtering

Hearing Lectures

1. Loudness
   - of sinusoids mainly
   - (see Web tutorial for more)
2. Pitch
   - of sinusoids mainly
   - (see Web tutorial for more)
3. Timbre
   - of complex sounds

Facts about Timbre

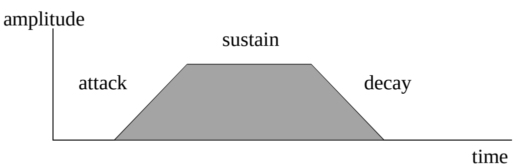
- Timbre is defined as all the sound differences that are not due to loudness or pitch
  - a “wastebasket” category
- For example
  - – two musical instruments playing the same note
  - – two different vowels spoken on same pitch
- Mark’s patented “lighthouse” analogy

Auditory Lighthouse

- Loudness
  - – brightness of flashes
- Pitch
  - – repetition rate of flashes
- Timbre
  - – colour of flashes
- Although …

There is more to timbre than colour

- Timbre also has a temporal dimension: a musical note has a different timbre when played backwards
- How a sound starts & stops is also important.

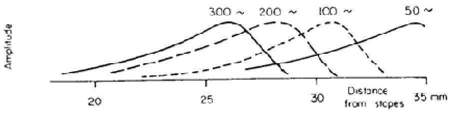


Analysis of Complex Sounds

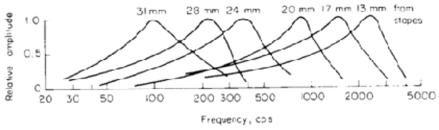
- So far we have concentrated on processing of single sinusoids in cochlea
- But to study timbre we need to consider how the cochlea deals with complex sounds made up from many sinusoids
- So instead of asking how does a **single sinusoid** excite **all parts** of the basilar membrane, we need to ask how does a **single part** of the basilar membrane respond to **all sinusoids** in a complex sound?

Change of View

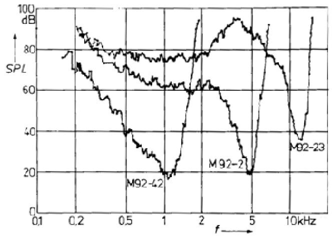
Excitation of all places by different sinusoids



Excitation of different places by all sinusoids



Audiogram of a Single Fibre

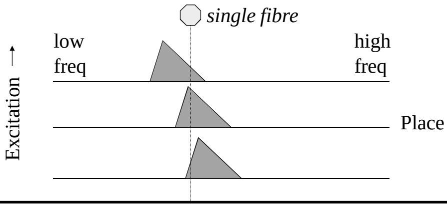


This is called a "Physiological Tuning Curve" or PTC.

By putting a fine electrode into a single nerve fibre, we can find the "threshold of audibility" for a single region on the basilar membrane.

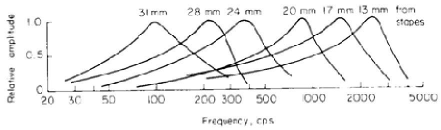
BM Region = Band-Pass Filter

- From PTC can see that each region of the basilar membrane is excited by a range of frequencies, but is most sensitive to frequencies that match preferred frequency of vibration
- Just like a band-pass filter!



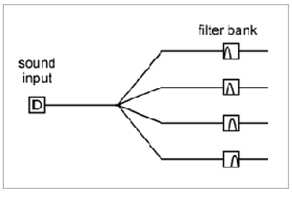
Basilar Membrane = Filterbank

- Hair cells on each region of the BM fire when that part of the BM vibrates
- But each sinusoid vibrates a number of regions
- Or conversely, each region is excited by a range of frequencies (but to different degrees)



Filterbank analysis

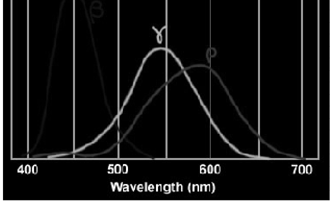
Vibrations enter cochlea



Nerve impulses from each BM region encode energy in signal that falls within band of frequencies

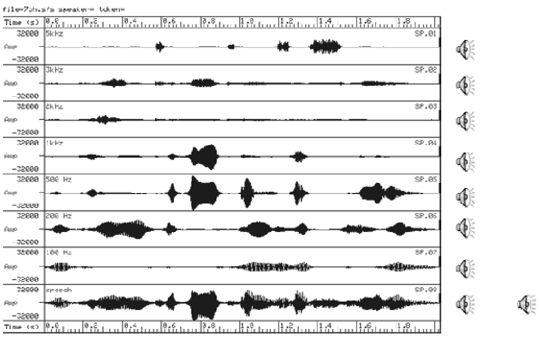
- In filterbank analysis, a sound signal is input to a bank of band-pass filters, each sensitive to a different frequency region
- Output encodes how much energy falls in each band

Just like colour sensation!

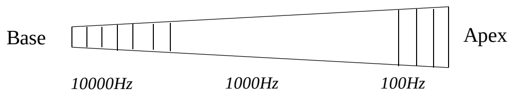


- Three types of colour sensitive cell in eye: red (580nm), green (540nm) and blue (450nm)
- Any given colour excites these three band-pass filters to different degrees

How a filterbank analyses a sound

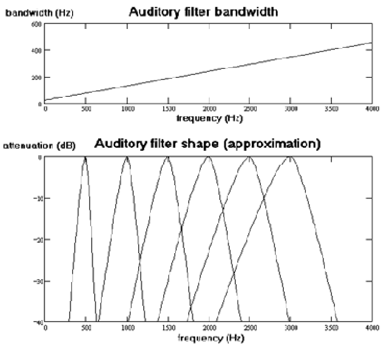


Possibly helpful mental picture



- Treat each 1mm section of basilar membrane as a separate resonator
- Each has its own resonant frequency = centre frequency of band-pass filter
- But because logarithmic mapping from Hertz to Place, 1mm at apex responds to a narrow region of low frequencies, but 1mm at base responds to a wide region of high frequencies
- So resonators are both spaced logarithmically and have increasing bandwidth with frequency.

Characteristics of Auditory Filters



Bandwidth of filters increases as centre frequency increases.

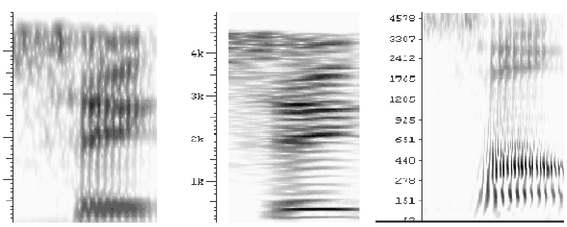
***Narrow** filters at low frequency. **Wide** filters at high frequency.*

Compare Cochlear Analysis to Spectrographic Analysis

- Spectrography
  - Filter bandwidth is the same at all frequencies, either narrow (45Hz) or wide (300Hz)
  - Filters are spaced linearly in Hertz along the frequency scale
- Cochlear Analysis
  - Filter bandwidth is narrow (100Hz) at low frequencies, and wide (500Hz) at high frequencies
  - Filters are spaced logarithmically in Hertz along the basilar membrane

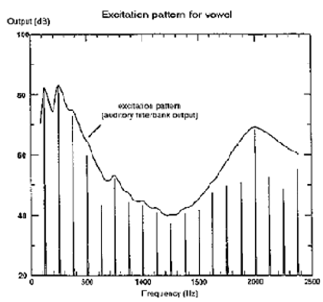
Types of Spectrogram

Wide-band | Narrow-band | Auditory-band



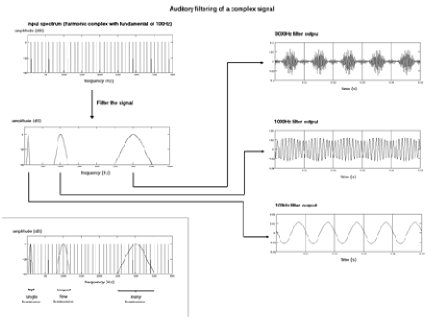
Auditory-band spectrogram looks like a narrow-band spectrogram at low frequencies and a wide-band spectrogram at high frequencies

Back to Timbre



- Excitation pattern for a vowel reflects auditory filtering
- At low frequencies harmonics are resolved
- At high frequencies the excitation pattern follows the spectral envelope

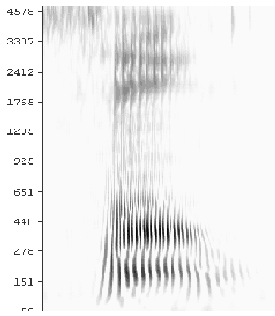
Temporal aspects of filtering



Low-frequency filters pass a single harmonic, while high frequency filters pass multiple harmonics.

Mixtures of harmonics maintain the periodicity of the original signal.

Temporal aspects of filtering



- Can see in the auditory spectrogram that firing at low frequency matches harmonic frequency, while firing at high frequency follows fundamental frequency of input signal
- Explains why pitch of signal is perceivable even when individual harmonics are not resolved.

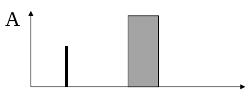
Filterbank Summary

- As far as processing complex sounds is concerned, it is best to treat cochlea as a filterbank
  - with say 30 filters rather than 30,000 hair cells
- The filters in the cochlea filterbank are logarithmically spaced and have a bandwidth that increases with frequency
- The excitation pattern on the auditory nerve reflects this filtering, with harmonics being resolved only at low frequency, and with the spectral envelope being encoded at high frequency

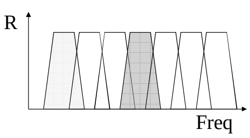
Importance of Filterbank Model - 1

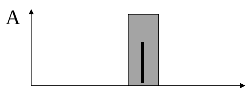
- Combination of narrow and wide band analysis explains how we can be sensitive to pitch and timbre simultaneously
- Model explains why formant frequencies are so important – they affect spectral envelope at mid to high frequencies
- Model explains auditory masking
- Model explains why speech is less intelligible in noisy situations

Filterbank explanation of masking

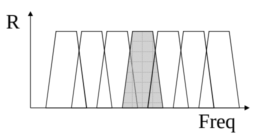


If tone and noise occupy different frequencies they fall into separate filters and are distinguished





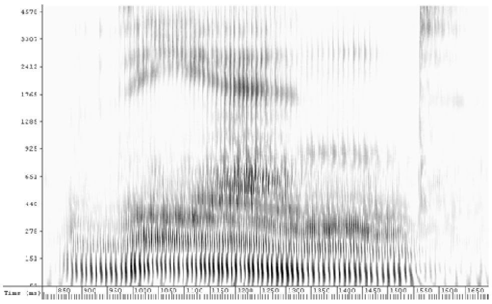
If tone and noise occupy similar frequencies they fall into the same filter and are not distinguished



Importance of Filterbank Model – 2

- Model explains why listeners with sensorineural deafness have difficulty in discriminating sounds
  - they have an increase in auditory analysis bandwidths
  - this makes the spectral envelope smoother
  - and worsens the masking caused by noise
- Model has influenced design of hearing aids and cochlear implants

The Final Picture



Summer Term

- Revision Day: Tuesday 23rd April
  - 9-10 Review lecture (118)
  - 10-12 Review tutorials
  - 12-1 Examination advice
- Examination: XXXday YYth ZZZZZ (check!)
- Hand in coursework folder for moderation of marks