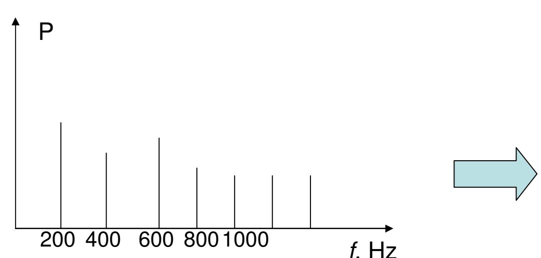
Lecture 7
Pitch perception of complex tones: tracking of missing fundamental

Pitch of pure tones

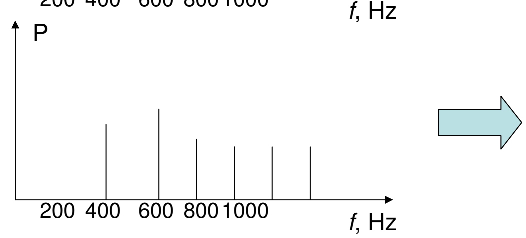
- Pitch correlates with frequency: the higher the frequency the higher the pitch
- Two models of pitch perception: place and temporal
- Pitch can't be perceived accurately above 5kHz

Pitch of complex tones

- Most musical sound are harmonic – partials are multiples of the fundamental
- **Fusion -** processes by which the brain combines a set of pure tones (forming the musical sounds) into a sound with only one pitch
- The perceived **<u>pitch of the fused tone corresponds to the fundamental</u>** for the harmonic sound
  (“Classical” explanation: because its amplitude is the highest of all)
- The pitch of non-harmonic sound is less defined
  (more explanations later!)



The perceived pitch of complex tone with this spectrum is that of a 200Hz pure tone



What happens if we remove the fundamental from the spectrum? How the perceived pitch will change?

You might expect that it becomes an octave higher.

Demonstration of the residue pitch

You will hear a complex tone with 10 harmonics of 200Hz, first complete and then with the lower harmonics successively removed.

What happens to the sound?
Does the pitch of the complex change?

Tracking of missing fundamental (residue pitch)

- Even when the fundamental frequency is physically removed from the signal through filtering, the pitch perception does not change
- The pitch we hear in this case is called **residue** (or **virtual**, **subjective**, **periodicity**) pitch
- Hearing residue pitches is not unusual. Residue pitches are what we normally hear when listen to complex tones

WHAT IS THE MECHANISM OF RESIDUE PITCH?

Is the effect due to nonlinear distortion (combination tone)?

Experiment which might prove or disapprove the hypothesis:

Several harmonics of 200Hz are present (fundamental removed from the spectrum).

We hear pitch corresponding to 200Hz. If it is a combination tone then:

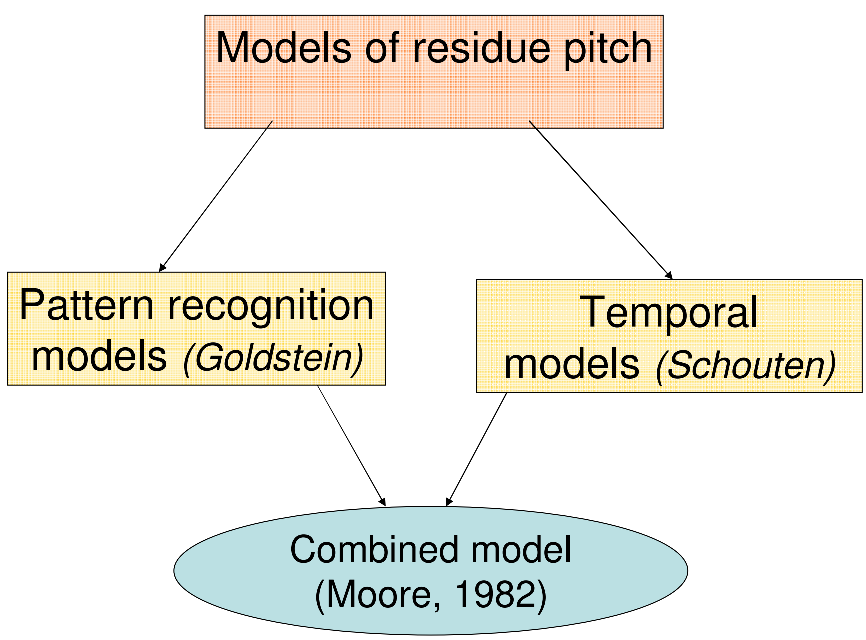
- The corresponding "place" on the BM is excited. So there is indeed energy present at frequency 200HZ
- If we present tone with frequency close to 200Hz (say 204Hz) we will hear 1st order beats

(You can experiment with this effect using Matlab command SOUND)

RESULT:

NO BEATS ARE HEARD ⟶ THERE IS NO ENERGY AT THE FREQUENCY OF THE MISSING FUNDAMENTAL

IT IS NOT A COMBINATION TONE



Pattern recognition models

•Frequency analysis to determine the frequencies of individual components of the complex tone – **assumes individually resolved regions of excitation on the BM** (based on place model of pitch perception)

•"Pattern recogniser" determines the pitch of the complex tones from frequencies of the resolved components

The most challenging task is to find the rules which "pattern recogniser" uses to deduce the pitch.

Possible rules for the "pattern recogniser" – rule 1

"Pattern recogniser" spots the difference between the adjacent components and returns the pitch corresponding to it

If the rule is correct then:

1. **Harmonic** complex tone with components: 800, 1000, 1200 Hz → Pitch corresponding to 200Hz tone

TRUE! THAT IS WHAT WE HEAR!

2. **Non harmonic** complex tone with components: 900, 1100, 1300 Hz → Pitch corresponding to 200Hz tone

IS THIS CORRECT?

Pitch of non-harmonic tones – Audio demonstration

In this demonstration, the three partials of the complex tone are shifted upward in ten 20Hz steps while maintaining 200Hz spacing between partials (so that first and final tones are harmonic)

Notice pitch shift!

1 partials: **800, 1000 and 1200 Hz**
2 **820, 1020 and 10220 Hz**
3 **840, 1040 and 1240 Hz**
4 **860, 1060 and 1260 Hz**
5 **880, 1080 and 1280 Hz**
6 **900, 1100 and 1300 Hz** Do those tones have the same pitch?
7 **920, 1120 and 1320 Hz**
8 **940, 1140 and 1340 Hz**
9 **960, 1160 and 1360 Hz**
10 **980, 1180 and 1380 Hz**
11 **1000, 1200 and 1400Hz**

Another possible rule for the "pattern recogniser" – rule 2

For harmonic sound it finds the **highest common factor** of the components present in spectrum , *i.e. the highest number that divides into all the frequencies present giving an integer result*

For non-harmonic sound it looks for the closest set of values and average it, i.e.tries to approximate it with harmonic sound.

Harmonic sound

f_n, Hz	**:2**	**:3**	**:4**	**:5**	**:6**
800	400	267	**200**	160	133
1000	500	333	250	**200**	167
1200	600	400	300	240	**200**

PITCH of 200HZ

Non-harmonic sound

f_n, Hz	**:2**	**:3**	**:4**	**:5**	**:6**
850	425	283	**213**	170	142
1050	525	350	263	**210**	175
1250	625	417	313	250	**208**

PITCH is (213+210+208)/3=210HZ

This rule seems to work

Extension to Rule 2 (Goldstein, 1973) – pitch of non-harmonic sounds

"Pattern recogniser" tries to find the harmonic series which provides the "best fit" to the series of components actually presented and other "possible fits".

Non-harmonic sound

f_n, Hz	:2	:3	:4	:5	:6	:7	:8
900	450	300	222	180	150	129	113
1100	550	367	275	220	183	157	138
1300	650	433	325	260	217	186	163

Pitch 220Hz =approximation by harmonic tone 880Hz, 1100Hz, 1320Hz – **BEST FIT**

Pitch 183Hz=approximation by harmonic tone 915Hz, 1098Hz, 1281Hz – **ANOTHER POSSIBLE FIT**

Some degree of ambiguity in pitch perception of non-harmonic (and even harmonic!) tones is confirmed experimentally.

The limitations of the pattern recognition models

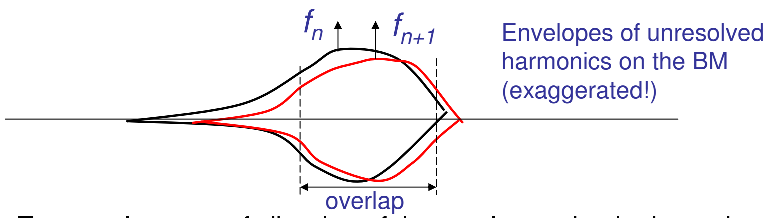
- All components are assumed to be resolved on the BM (i.e. frequency separation between them exceeds the critical band)
- In reality for higher harmonics the regions of excitations on the BM overlap: they fall into the critical bands of the adjacent harmonics

Harmonic	Critical band Δf_{CB}	Resolved?
110	38.87Hz	**YES**
220	49.37Hz	**YES**
330	60.02Hz	**YES**
440	70.82Hz	**YES**
550	81.77Hz	**YES**
660	92.87Hz	**YES**
770	104.1Hz	**YES**
880	115.5Hz	**NO**
990	127.1Hz	**NO**

WE CAN STILL PERCEIVE RESIDUE PITCH OF HIGHER HARMONIC SERIES

Temporal model

• Harmonics are assumed not to be resolved individually – overlapping excitation regions on the BM



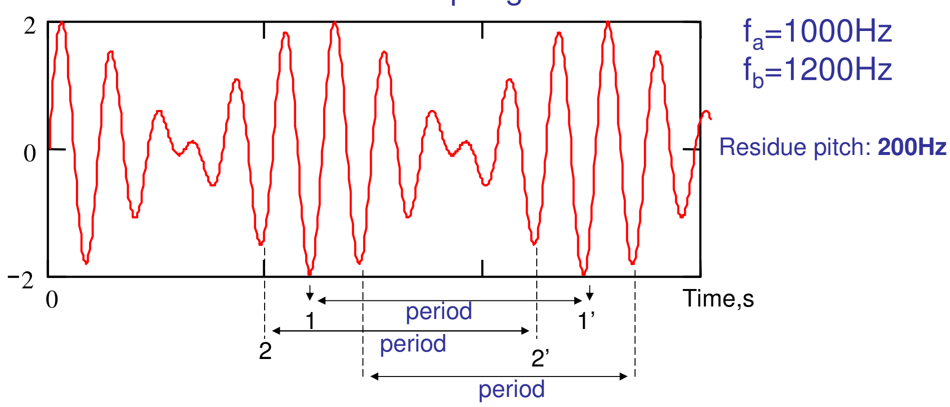
• Temporal pattern of vibration of the overlap region is determined by a sum of two vibrations: similar to 1st order beats
Period of "beats"corresponds to the fundamental

• Periodic features of the vibration are spotted by "phase locking" mechanism

•Missing fundamental is returned as **1/(period)** of the complex waveform

Temporal models – illustration 1

Harmonic tone – adjacent harmonics
Vibrations of BM in the "overlap region"

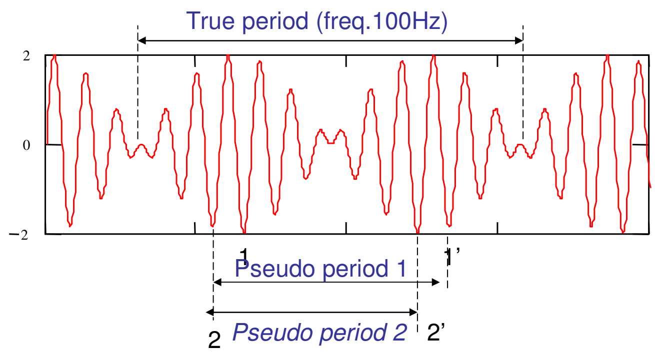


The repetition period derived from inter-spike interval histogram is 5ms. This gives residue pitch of 200Hz

Temporal models – illustration 2

Non harmonic tone – adjacent components

Vibrations of BM in the "overlap region"



f_a=1100Hz
f_b=1300Hz

Residue pitch: 220Hz
(with some ambiguity)

Nerve spikes can occur at any of the prominent peaks of the waveform (2,1,1',2'). "Pseudo periods" will be deduced: 2-2', 1-1' etc.
One of them corresponds to 220Hz pitch

Main limitation of the temporal model

It can not explain the hearing of the residue pitch when harmonics are fully resolved

Combined model *(Moore, 1982)*

Acoustic input
↓
Filter bank analysis
↓
Analysis of neuron inter-spike intervals and place
↓
Combine inter-spike intervals keeping place → Pick most prominent intervals
↓
PITCH

(*BCJ Moore, pp.217-226*)

You need to know

- What is complex tone: harmonic and non-harmonic
- What is tone fusion
- What is residue pitch
- How the pitch of complex tone is perceived: pattern recognition and temporal models
- Limitations of both types of models

Further reading

- BCJ Moore “An Introduction to the psychology of hearing”, pp.206-226
- Howard and Angus “Acoustics and psychoacoustics”, pp.119-134
- JG Roederer “The physics and psychophysics of music”, pp.43-50