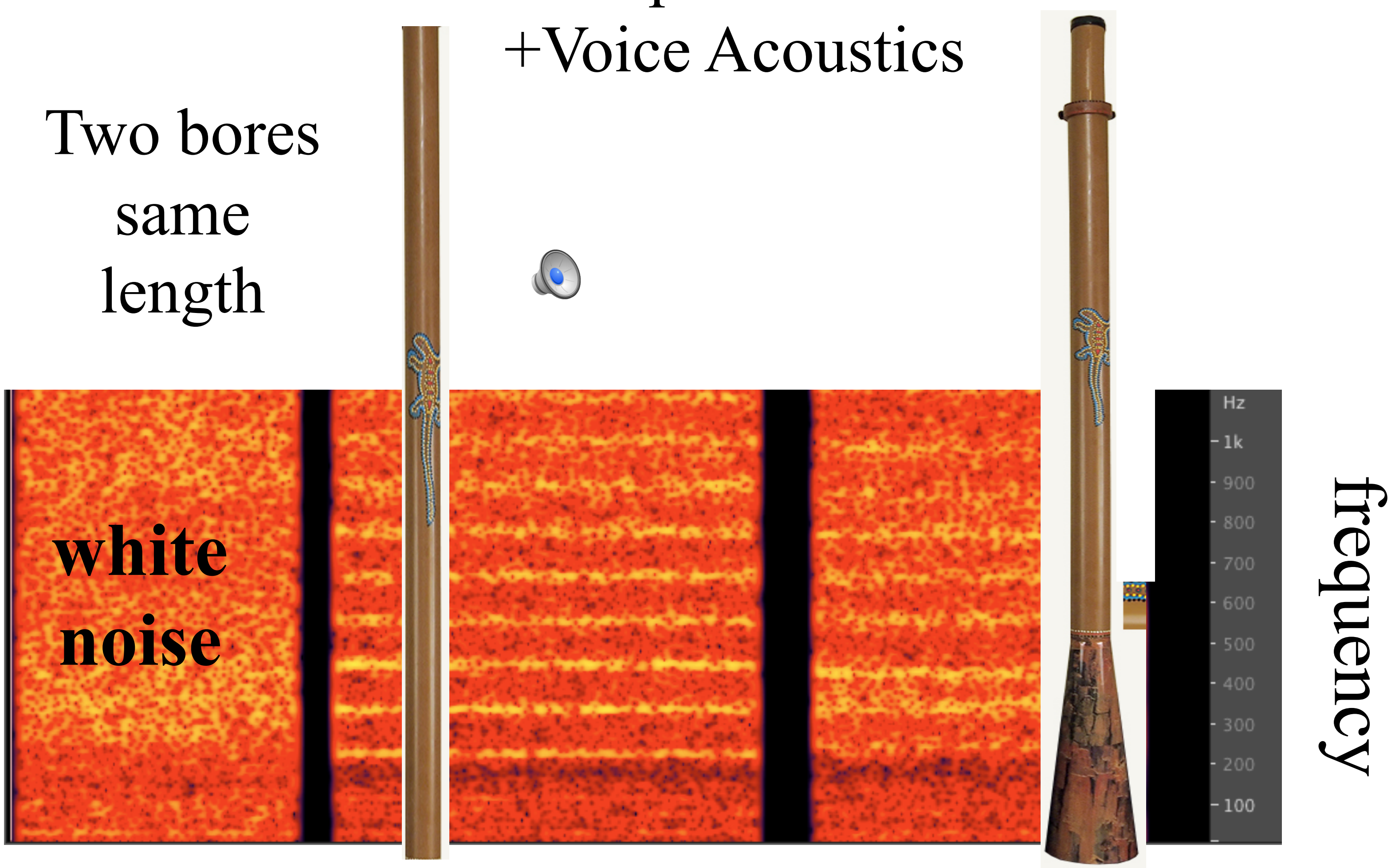
More experiments on a column of air:

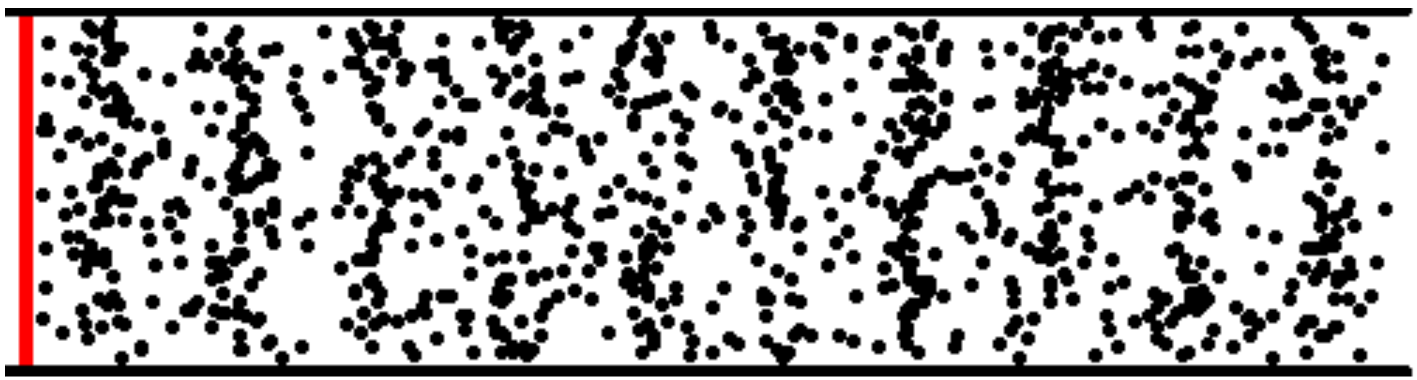
Physics of music
PHY103

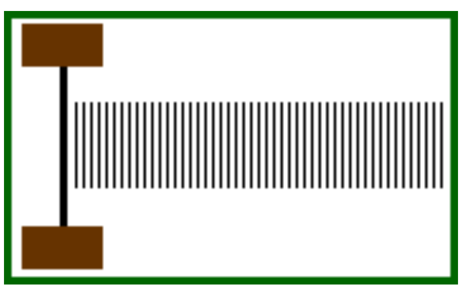
Excitation and Impedance
The speed of Sound
+Voice Acoustics

Two bores same length



Pressure waves in air
Longitudinal waves





Animation from
Dan Russel

Sound as a pressure wave

How fast can information travel in a gas?

Temperature, T, sets the speed of molecules.

Molecules have energy $\sim k_B T$

where k_B is Boltzmann's constant.

How do we estimate a typical velocity?

Sound as a pressure wave

How fast can information travel in a gas?

Temperature, T, sets the speed of molecules.

Molecules have energy $\sim k_B T$

where k_B is Boltzmann's constant.

Energy $E \sim mv^2$ where v is the velocity and m is the mass of a molecule

Solve for v.

$$v \sim \sqrt{\frac{k_B T}{m}}$$

The approximate speed of sound from fundamental physical quantities

$v \sim \sqrt{\frac{k_B T}{m}}$ Let's see if this is about right....

k_B = Boltzmann's constant = 1.4×10^{-16}erg K^{-1}

T = Temperature in Kelvin, room temperature =293K

m = mass of a typical molecule $\sim 2\times 14\times 1.7\times 10^{-24} g$

Where I multipled 2 nitrogens to a hydrogen (N=14AMU)

$$v \sim \sqrt{\frac{k_B T}{m}} = \sqrt{\frac{1.4\times10^{-16}\times 293}{2\times14\times1.7\times10^{-24}}} \sim 3\times10^{4}\,\text{cm/s}$$

This is pretty close! And should not be expected to be exact.

The speed of sound and how it depends on other quantities.

$$v \sim \sqrt{\frac{k_B T}{m}}$$

How does the speed of sound depend on:

- Temperature?
- Gas molecular weight? what if we were breathing Helium?
- Atmospheric pressure?

Speed of sound and Temperature

- How much does a change of 10 degrees Celcius affect the speed of sound?

$$v \propto T^{1/2}$$

- Can we measure sound speed's sensitivity to temperature using the open tube?

The change in the speed of sound caused by a 10 degree Temperature change

$v_1 = AT_1^{1/2} \qquad v_2 = AT_2^{1/2}$

Take the ratio $\dfrac{v_1}{v_2} = \dfrac{AT_1^{1/2}}{AT_1^{1/2}} = \sqrt{\dfrac{T_1}{T_2}}$

Now we put in temperatures

$\sqrt{\dfrac{293}{303}} = 0.983$ 2% change

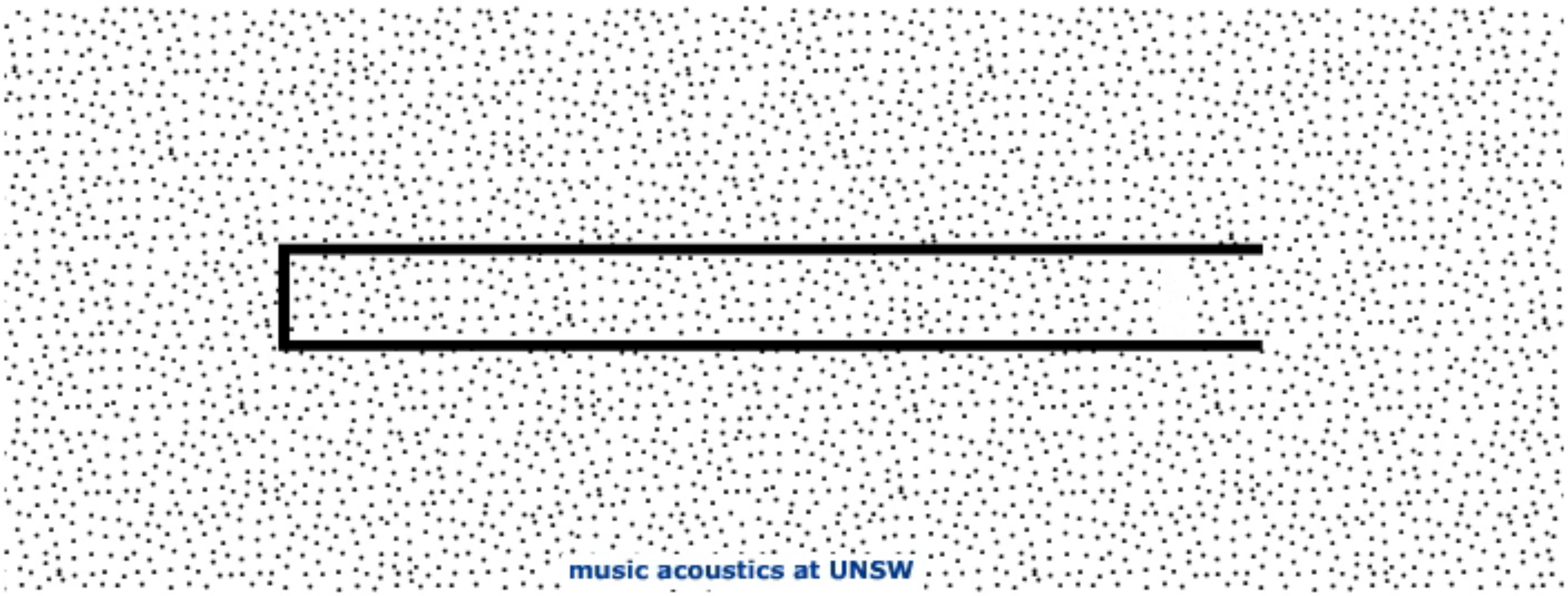
Predicted frequency shifts

- A change in temperature of 10 degrees leads to a shift in frequency by ~2%
- If the fundamental is about 100 Hz this is a shift of a couple Hz
- Probably measurable!

The air column and the speed of sound

- How do we expect the resonant frequencies or modes of a column of air to depend on temperature?
- Experiment with changing temperature: liquid nitrogen and a heat gun
- How does a change in temperature affect wind instruments?

Pulses reflected at end open/closed pipe

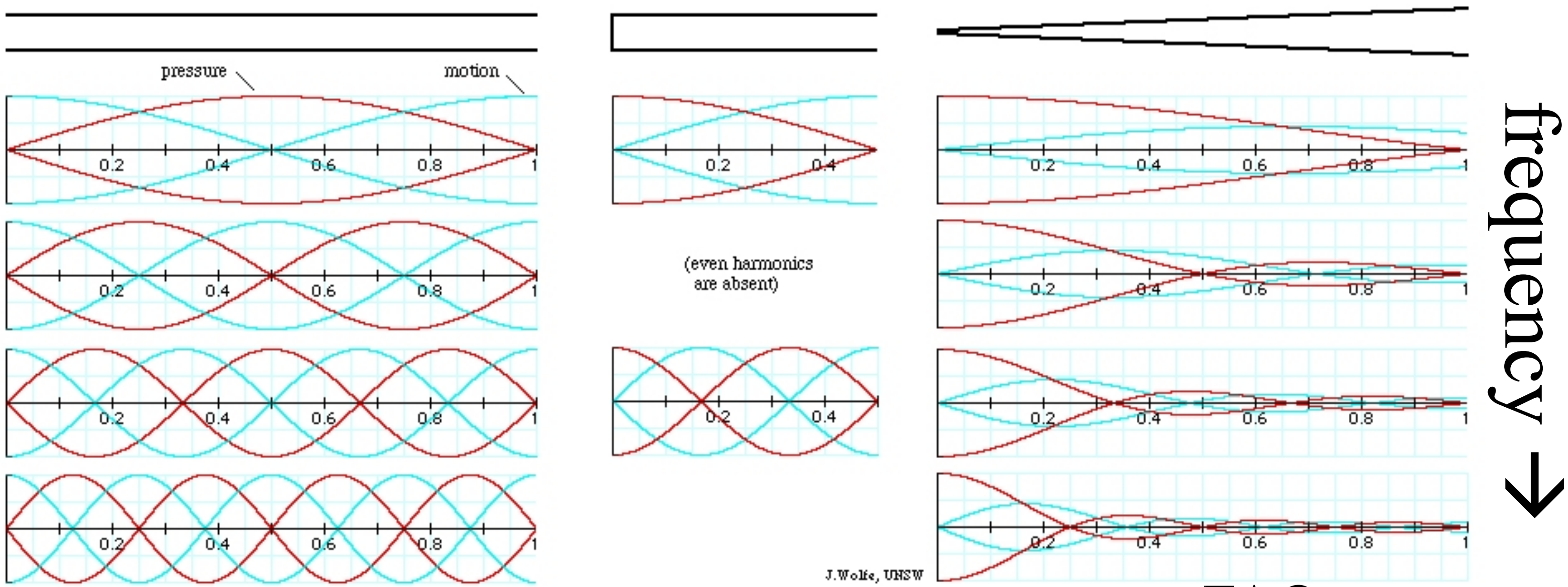


Resonant excitation of a column of air

- How long does it take a disturbance to travel down the length of the tube and come back?

- Correctly timed excitations allow the mode to grow. Incorrectly timed excitations will cancel each other out.

Bore shape and modes



unsw FAQ

Volume varies with position along bore.

Bore area variations → frequency and wavelength in a mode are not linearly related

Which modes will grow?

- If I put random pressure fluctuations into the pipe, some will grow and others will not.
- How do I describe the way the pipe reacts to an input sound?
- Impedance is a way to measure this.
- Relates input pressure to actual air velocity.

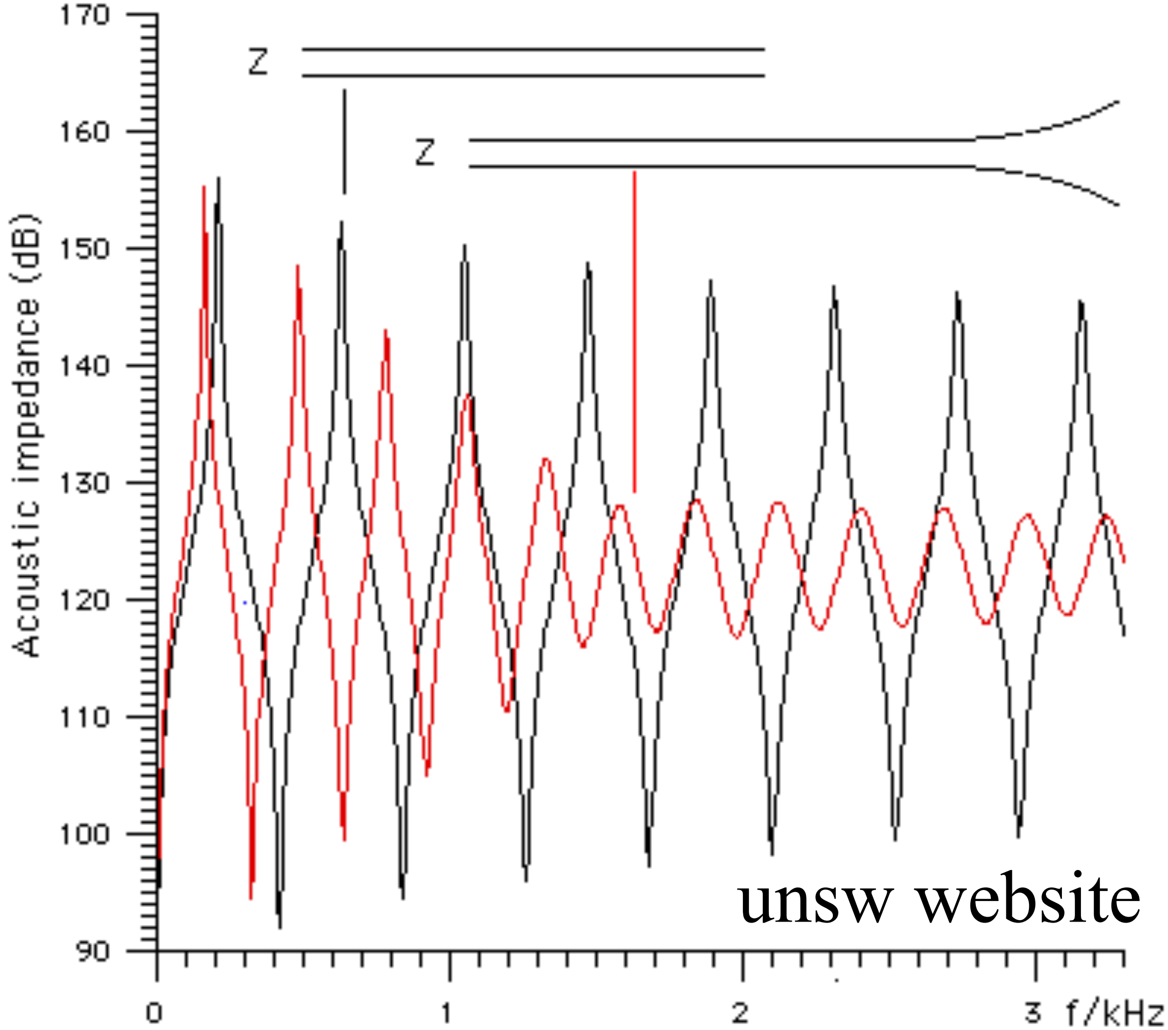
The notion of impedance

- A high impedance means high pressure variation for a small velocity variation
- A low impedance means small pressure variation gives a large velocity variation
- Impedance can be described as a function of frequency.
- You can get a big response at some frequencies but not at others.

The notion of impedance

- Ohm's law relates resistance (R) to Voltage (V) and Current (I): $V=IR$
- Acoustic impedance (Z) is similar to resistance or electric impedance but in this case we use pressure instead of voltage and flow instead of current.
- For alternating electric current (AC) the voltage and the current can be related by a number that depends on frequency (Z). This is also called impedance.

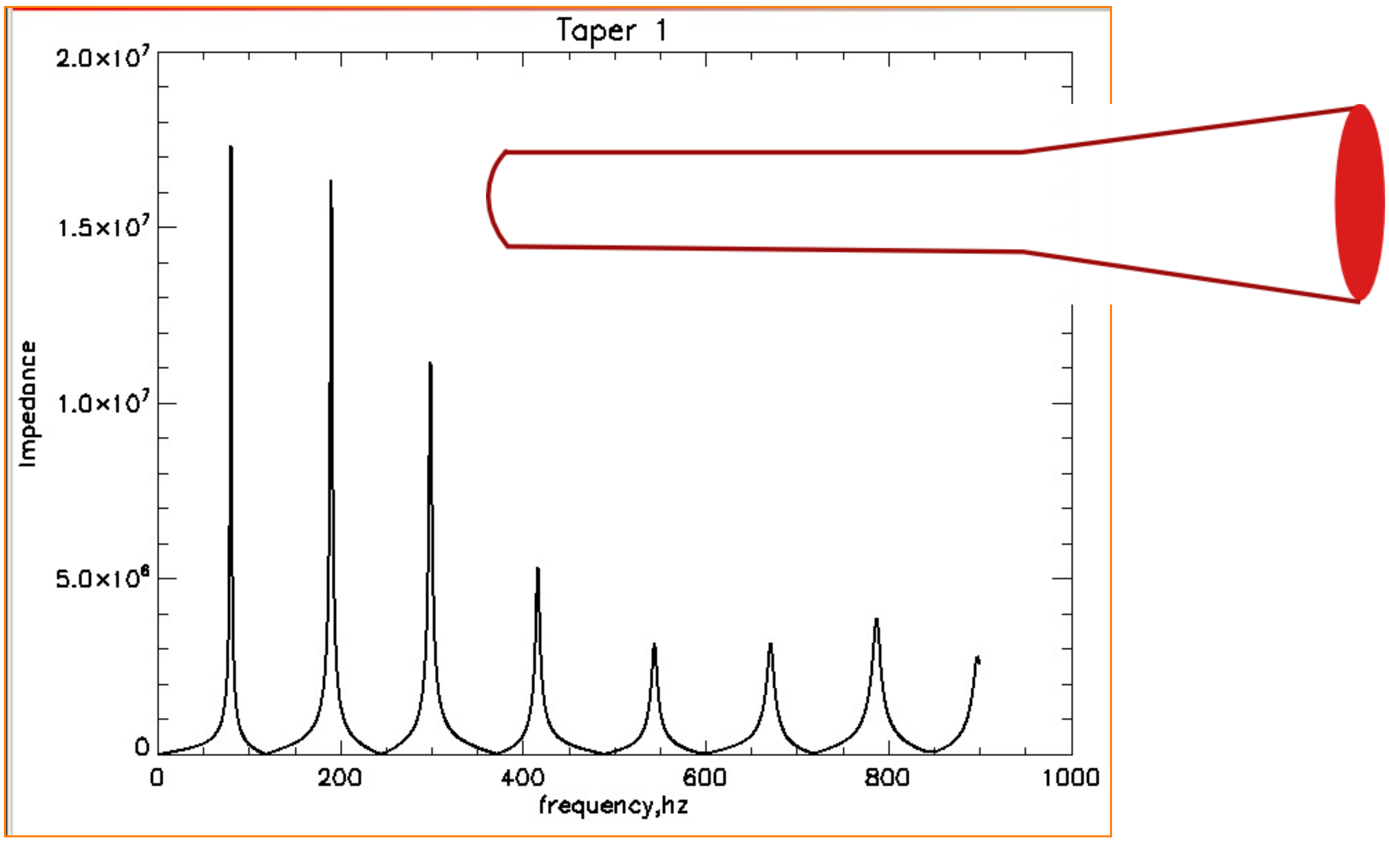
Impedance spectrum and bore shape



Location of peaks tell you the frequencies of modes of oscillation

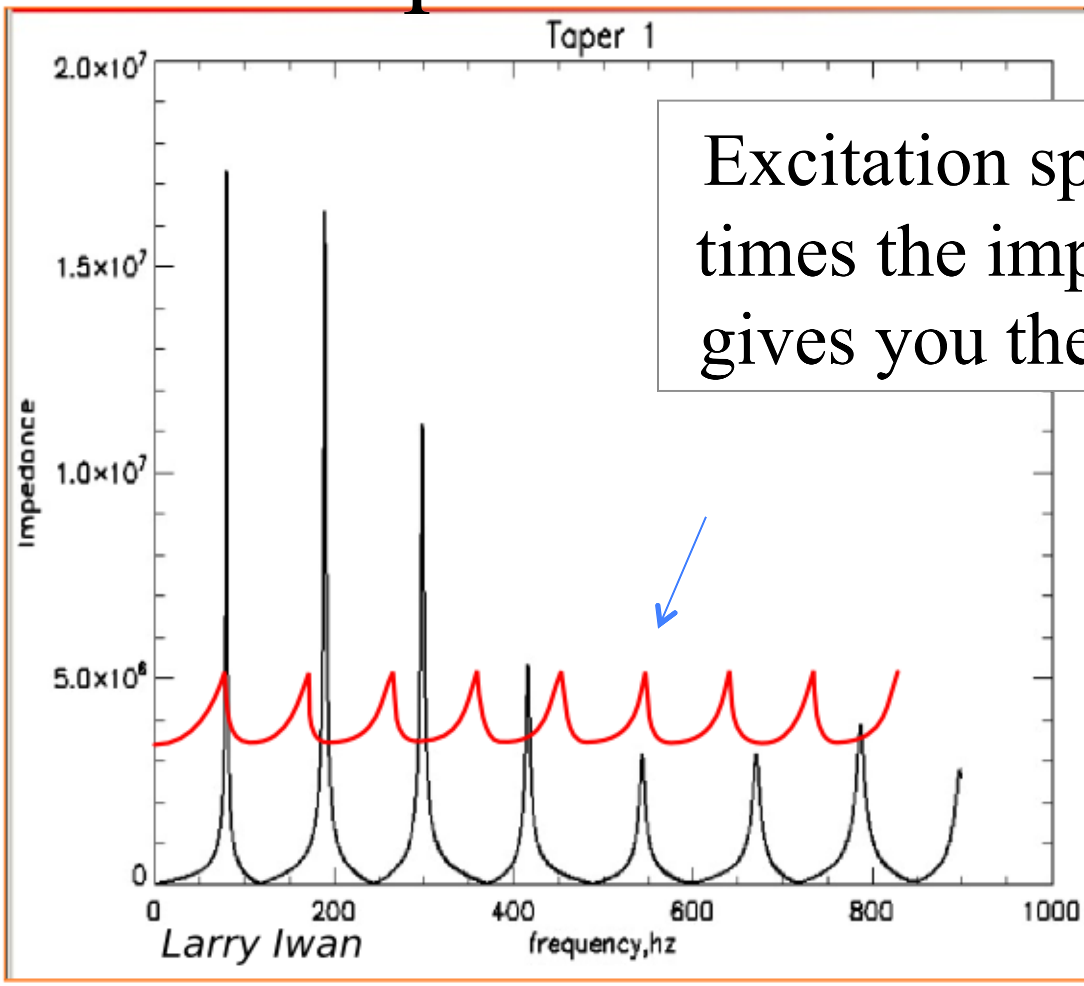
unsw website

Acoustic Impedance for Didjeridu with cone/cylinder bore



From Iwan's lecture

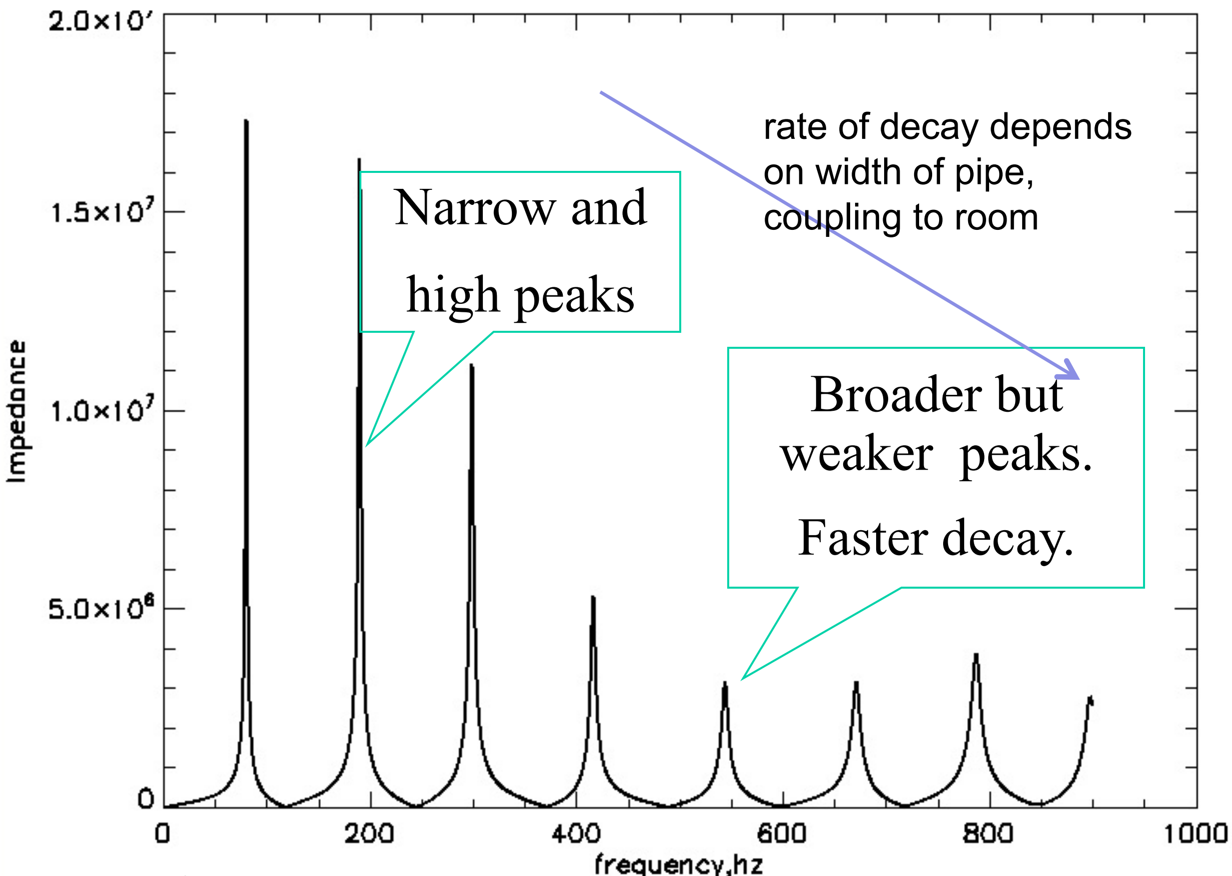
Acoustic Impedance for Didjeridu



Excitation spectrum times the impedance gives you the output

blowing input spectrum

Acoustic Impedance for a flared Didjeridu

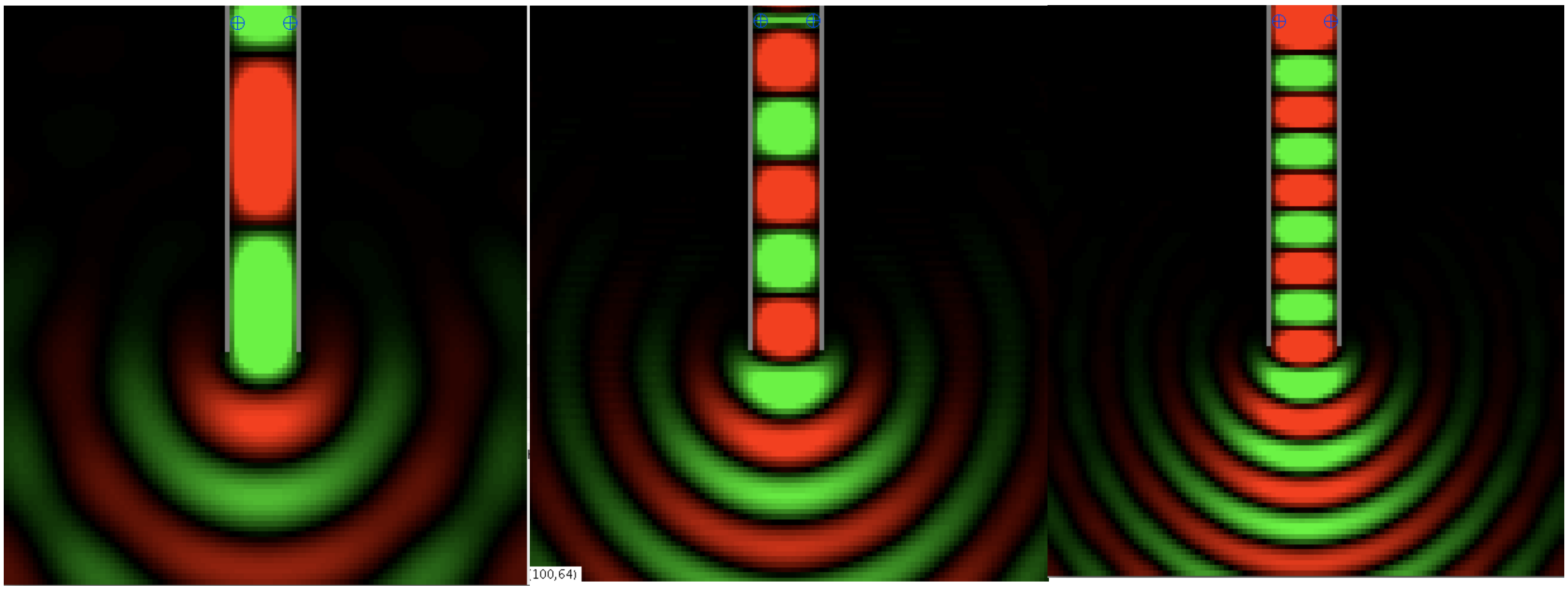


Impedance plot also tells you about the decay of notes. The weaker the peak, the more lossy, the more sound is lost to the room or dissipated in the walls.

Figure: Larry Iwan

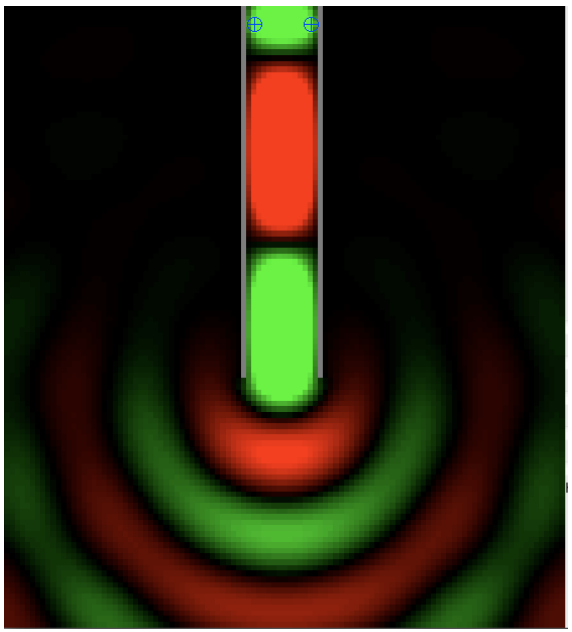
Radiation and reflection

using Faltstad's ripple



more radiation is reflected at the end at low frequencies and less escapes the bore

stronger radiation escapes at high frequencies and less is reflected by the end

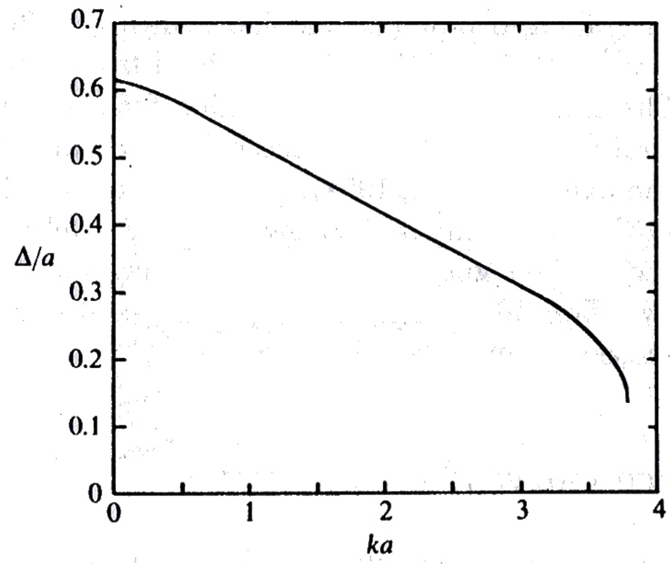


- Wavefront can be thought of as a series of point sources
- Wavelength decreases as exits the bore
- Wave front is curved at the end of the pipe

End correction

Effective length of pipe is $L+\Delta$

from Fletcher and Rossing

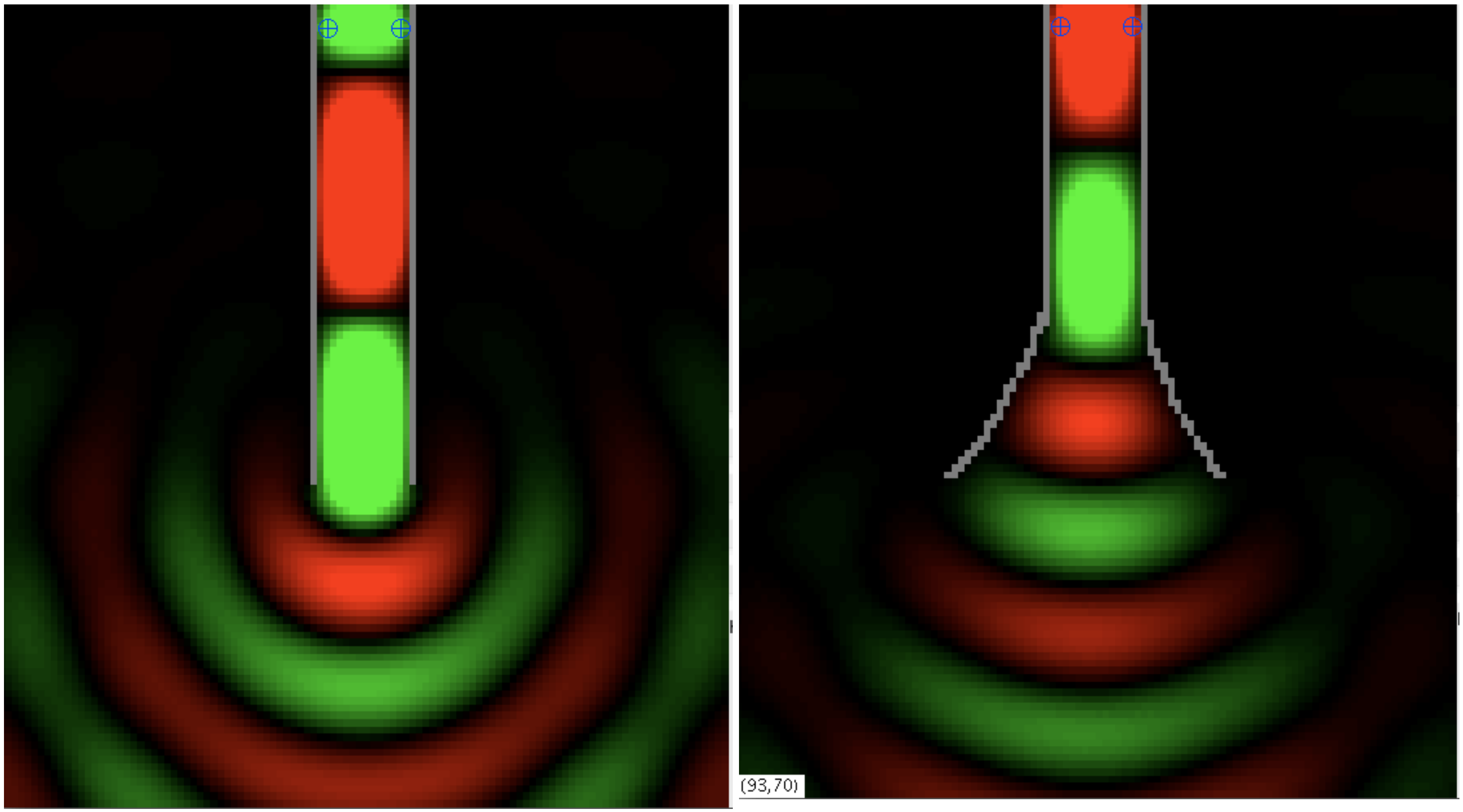


URE 8.9. The calculated end correction Δ for a cylindrical pipe of radius a, ed as Δ/a, as a function of the frequency parameter ka, (after Levine and inger, 1948).

$\Delta \sim 0.61a$ where *a* is the diameter of the pipe

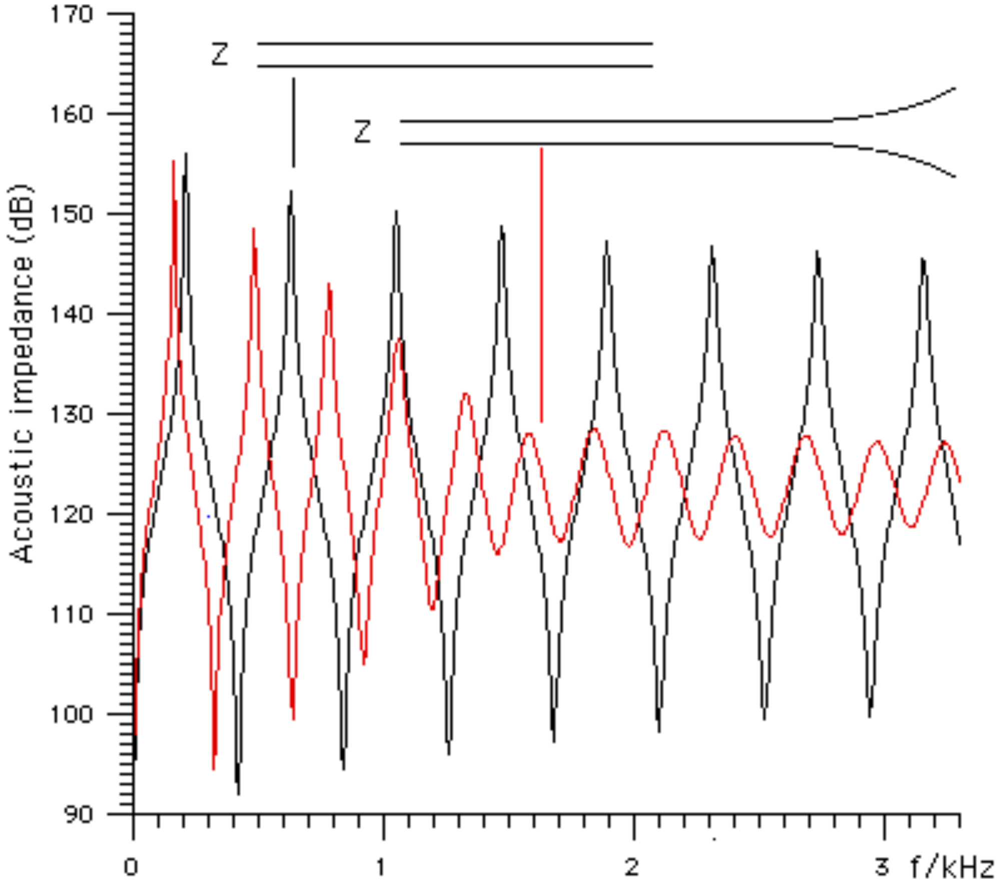
For a flanged pipe *$\Delta \sim 0.85a$*

As the end correction depends on wavelength, a flute is not in pitch across octaves. This leads to the design of tapered ends.



more radiation should escape when the end flares and less is reflected   (though *ripple* is not good at showing this)

Bore diameter and impedance peaks

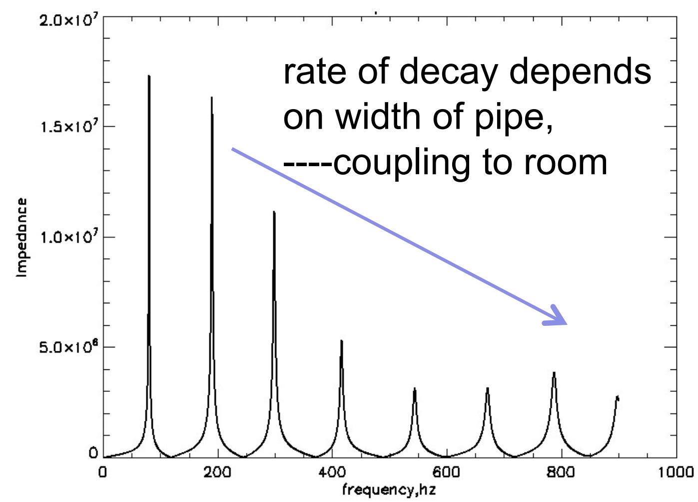


strong narrow peaks when wavelength is big compared to bore diameter (strong peaks due to strong reflections!)

Mode height and width

- Typically short fat bores have weak higher modes
- Thin narrow bores have strong high modes but weaker fundamental

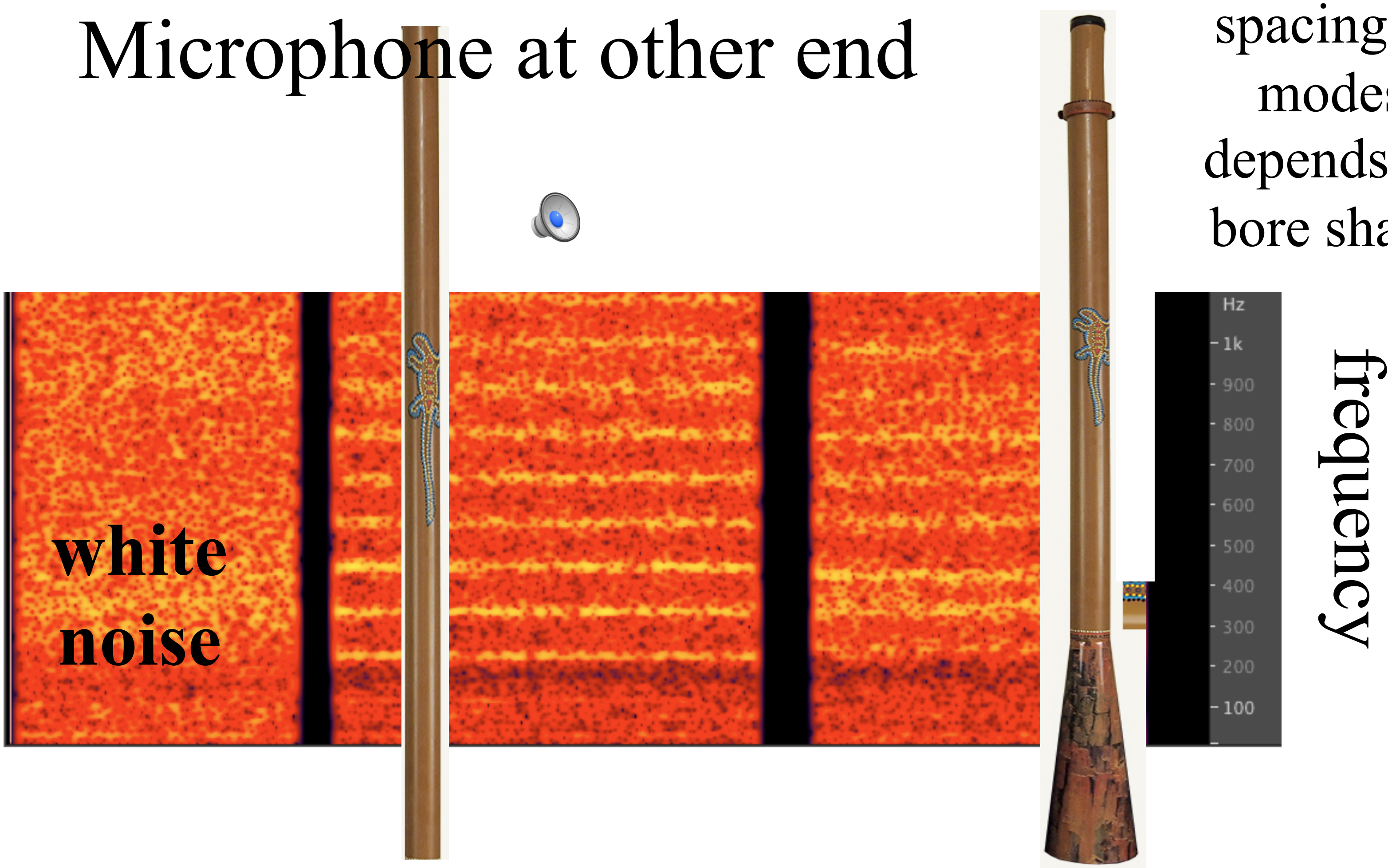
Timber of the instrument depends on the octave (e.g. bassoon)
For organ pipes, lower register sounds are better if the high overtones are strong -> narrower pipes



The sliding whistle had broad peaks when it was short

Two bores same length
White Noise at one end
Microphone at other end

strength and spacing of modes depends on bore shape



Excitation of the open tube

- If we drive the tube with a noise sources frequencies at low impedance will be amplified by the tube
- Instant impedance measurement at all frequencies!

Measuring impedance

- We can roughly measure it with a white noise source.
- Not a very accurate measurement
- More accurately, use a forced oscillating air flow source (with constant amplitude) and measure pressure variations caused by it at the mouthpiece of an instrument.
- Can measure pressure amplitude as well as phase → impedance can be thought of as depending upon both

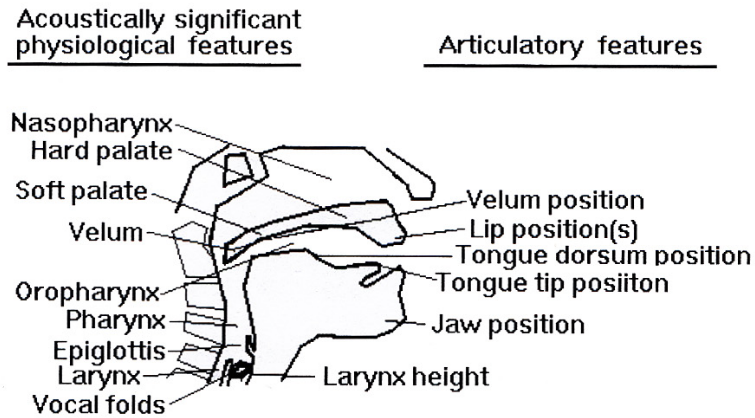
Frequency Domain:

- Impedance as a function of frequency
- Each piece of the bore has a different impedance. Total pipe impedance can be estimated from taking into account impedances of all pieces

Time Domain:

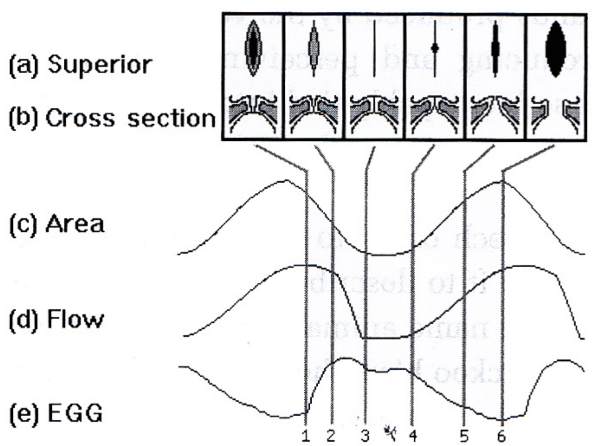
- Response of a small pulse as a function of time
- Each shape change or discontinuity in the bore gives a reflection of a different size
- Back at the mouth piece this gives a series of delays

Voice physiology



From Cook, P.R. Music Cognition and Computerized Sound

9.1 Cross-section view of the human head. Acoustically significant features are labeled on the left side, and speech articulators are labeled on the right.



9.2 Various views of vocal fold vibration, with time proceeding left to right. (a) vocal folds from the top, looking down the throat; (b) cross section as viewed through the neck wall; (c) area of the vocal fold opening; (d) flow through the vocal folds; (e) Electroglottograph (EGG), which measures the electrical admittance between the vocal folds.

Bringing the vocal folds together cases them to beat together and oscillate. Pressure from lungs push them apart, .. air flow causes low pressure and they are drawn closed again ... the cycle is an oscillation!

Tighter vocal cords give “brighter” tone or stronger amplitudes at high frequencies

Bernoulli effect analogy

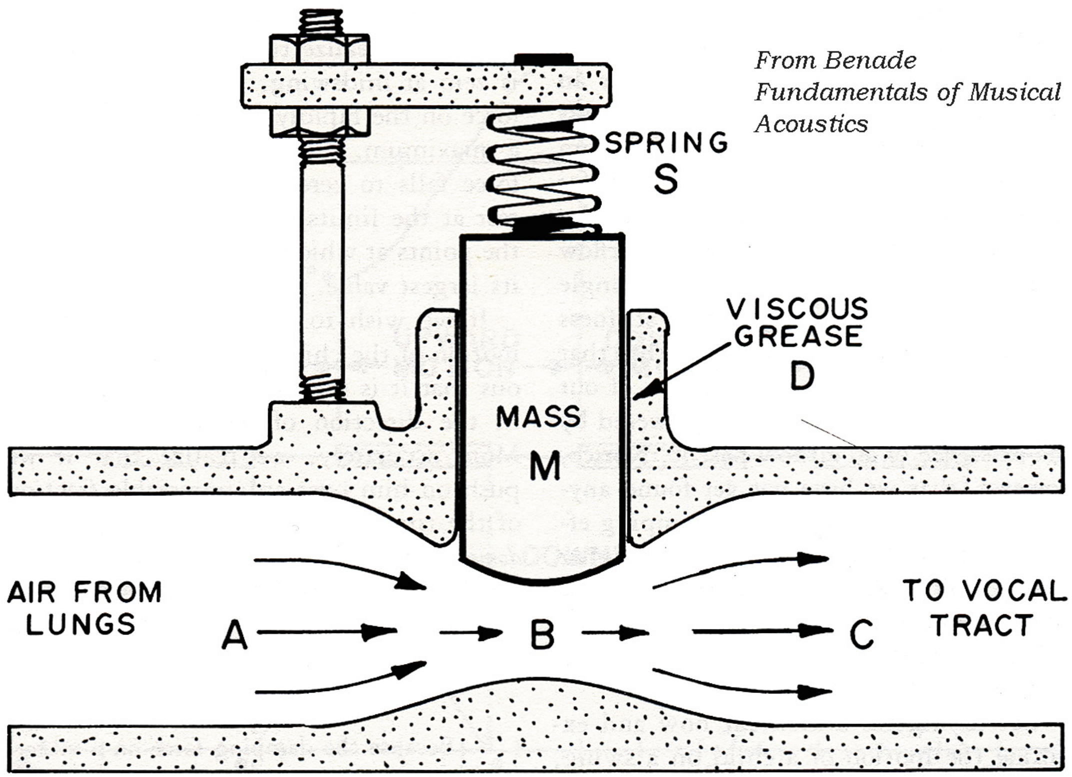


Fig. 19.2. A Mechanical Analog of the Larynx

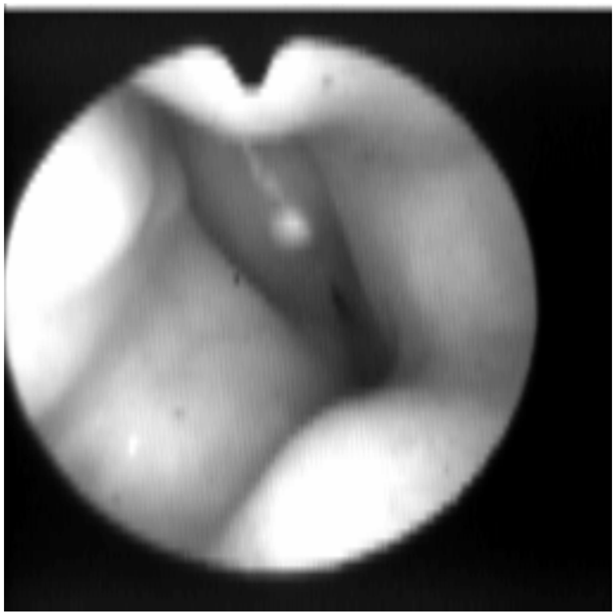
Mechanical Analog of the Larynx

High speed imaging of the larynx

These recordings were made at Huddinge University Hospital, department of Logopedics and Phoniatrics. Recordings were made at approximately 1900 images per second. The images were recorded with a flexible endoscope fed through the nose. The end of the endoscope is positioned centimeters above the glottis. On this page, the playback speed is reduced to about 3 images per second.

Normal phonation. Every cycle is similar to the other. F0 = 115 Hz

(Animation consists of a single cycle within 16 frames that are repeated over and over)



Svante Granqvist,

svante@speech.kth.se

Formants

Harmonics are generated over a large frequency range

From Benade
Fundamentals of Musical Acoustics

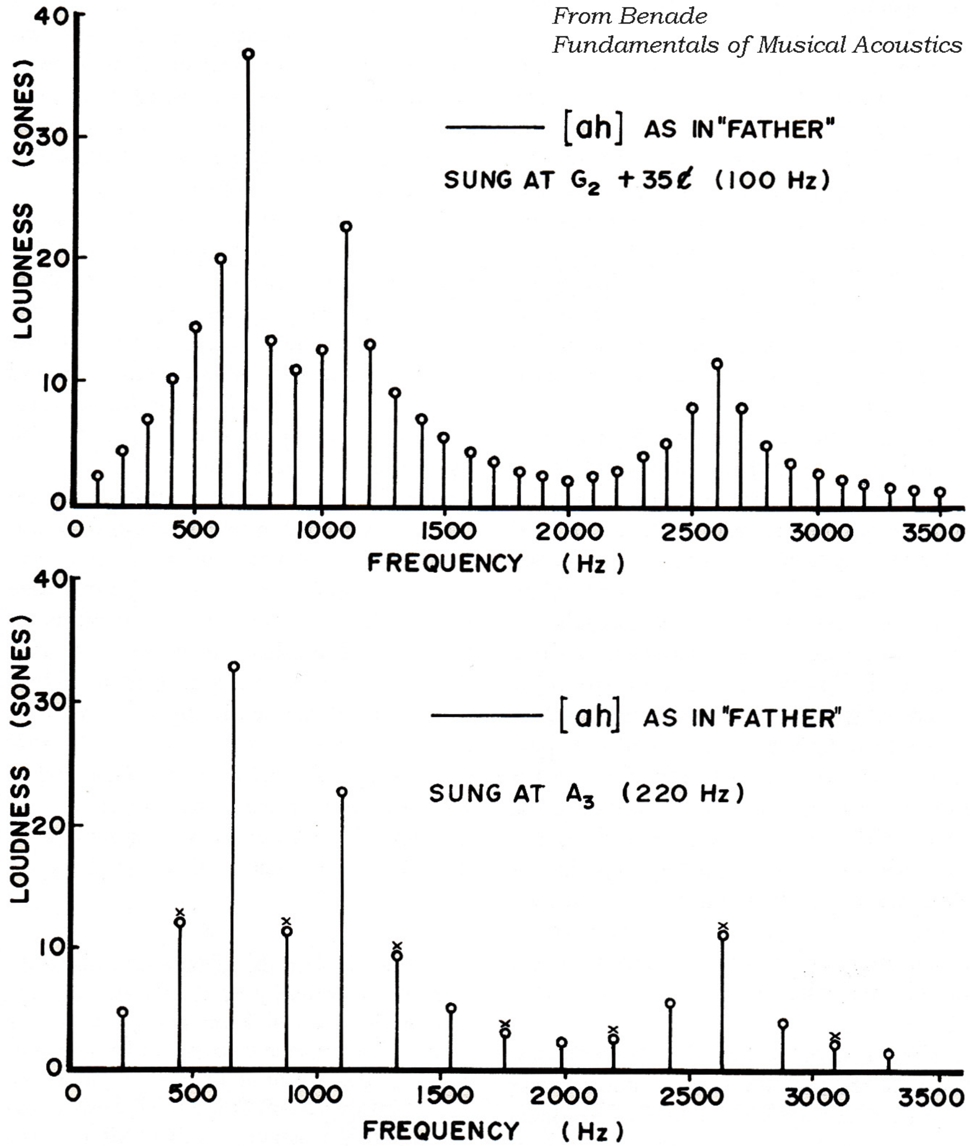


Fig. 19.5. Loudness Recipes for a Vowel Sung at Two Different Pitches

Hz (A_3) tone produced by the same man if he keeps his jaw, tongue, and lip positions unchanged from those used for the 100-Hz tone. The pitch of this tone is somewhat more than an octave higher than the first, but we would still agree that the same [ah] vowel is being produced. Notice that the overall shapes of the

Vocal Tract Acoustics

Vocal tract is a tube that is closed at the vocal fold end and open at the lips

This tube has resonances – high frequency ones because the tube is short

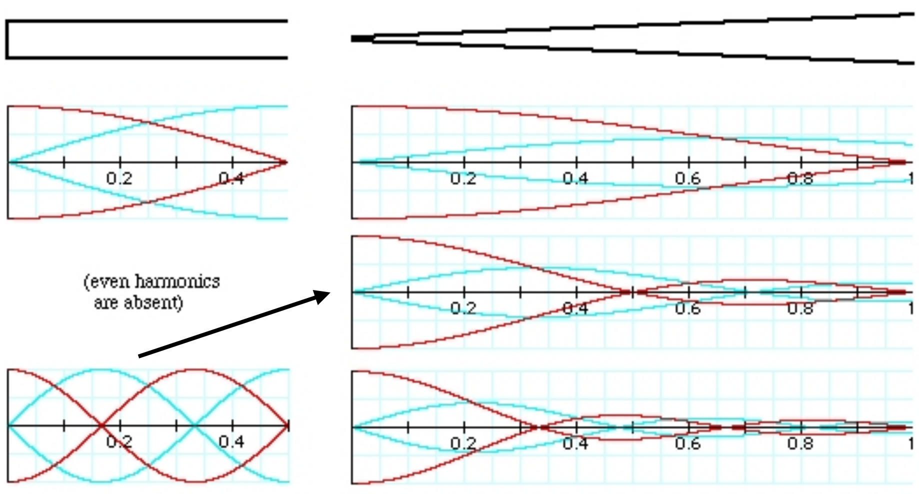
Narrowing the tube at a point

a. raises the frequency of any mode that has a node at that point
b. lowers the frequency at any node that exhibits and anti-node at that point

Opposite for widening the tube at a point

Why? Consider volumes and wavelengths

In analogy a cylindrical open tube vs a cone shaped open tube



Frequency the same if both are the same length

Frequency shifted down by an octave

figure unsw faq

Pipe driven at one end What pressure is required to give a particular flow velocity

- Drive at fundamental mode of open/open pipe
- Easy to drive, a small pressure oscillation gives a big velocity flow response because perturbations add together

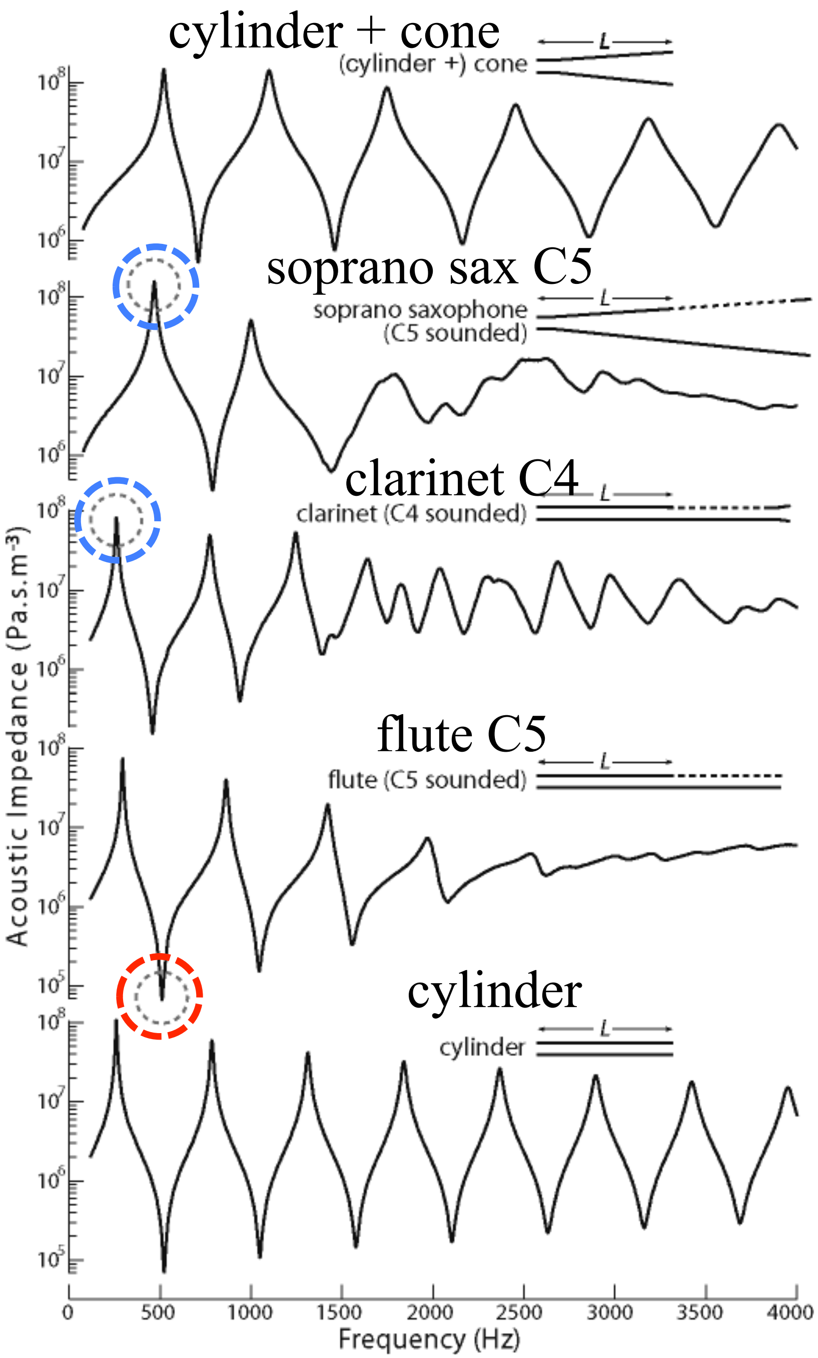
→ Low impedance

Pipe driven at one end

- Driving at half the fundamental mode of the open/open pipe
- high pressure required at the end to give a small flow change
- small flow (from lips) at the end can propagate to build up a high pressure at the end

→ High impedance

Chen et al. Acoustics Australia 2009, Vol 37



Peaks or valleys

flutes, organ
played at low
impedance peaks

digi, reeds, horns
played at high
impedance peaks

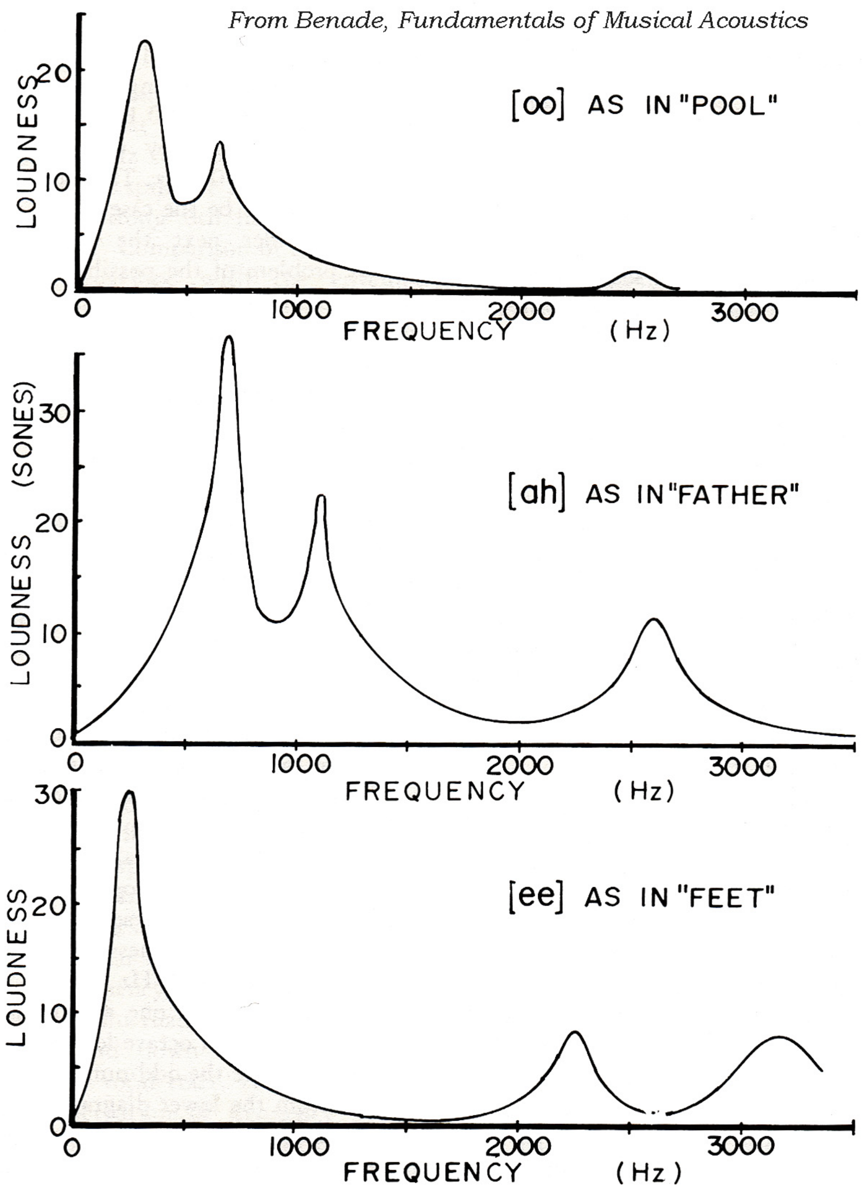


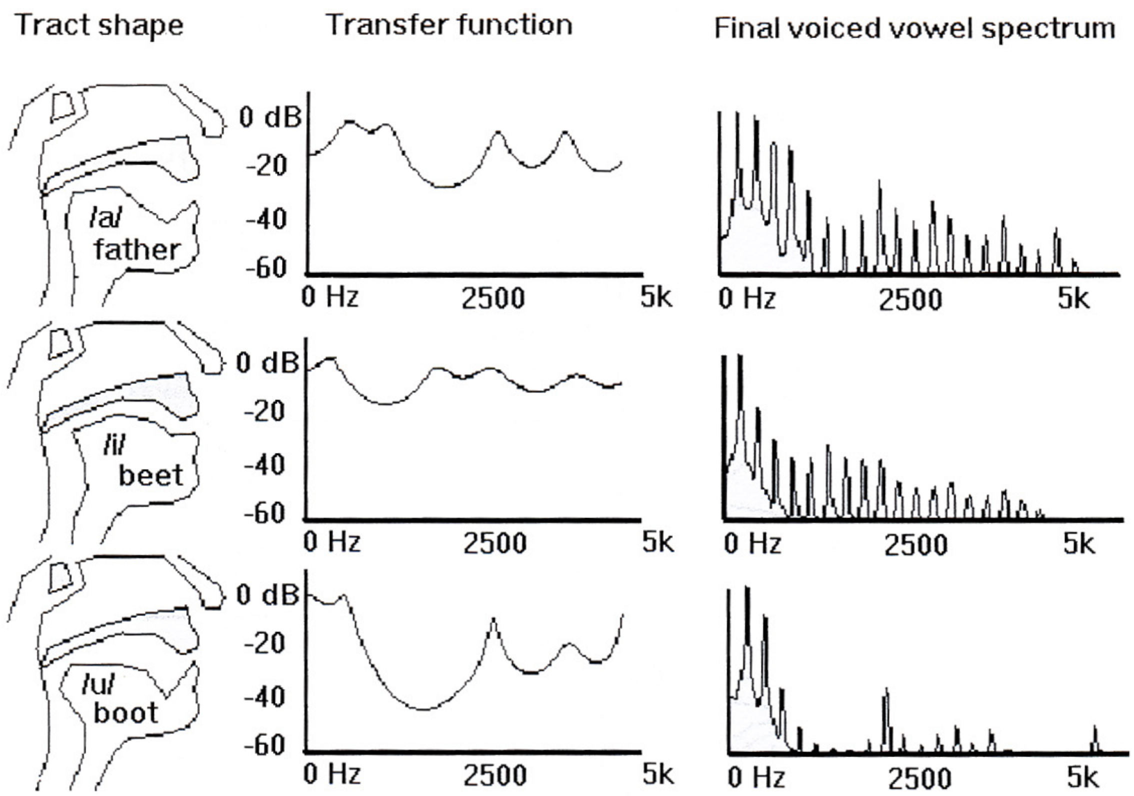
Fig. 19.6. Loudness Spectrum Envelopes for Three Vowels

Formants

- 3 resonance peaks – formants
- Peak frequencies of these formants depends on position of lips, throat and mouth

Front of mouth is narrowed moving 2nd and 3rd resonance to higher frequency

Formants and Vowels



Three vocal tract shapes, transfer functions, and voice output spectra. *Cook, PC*

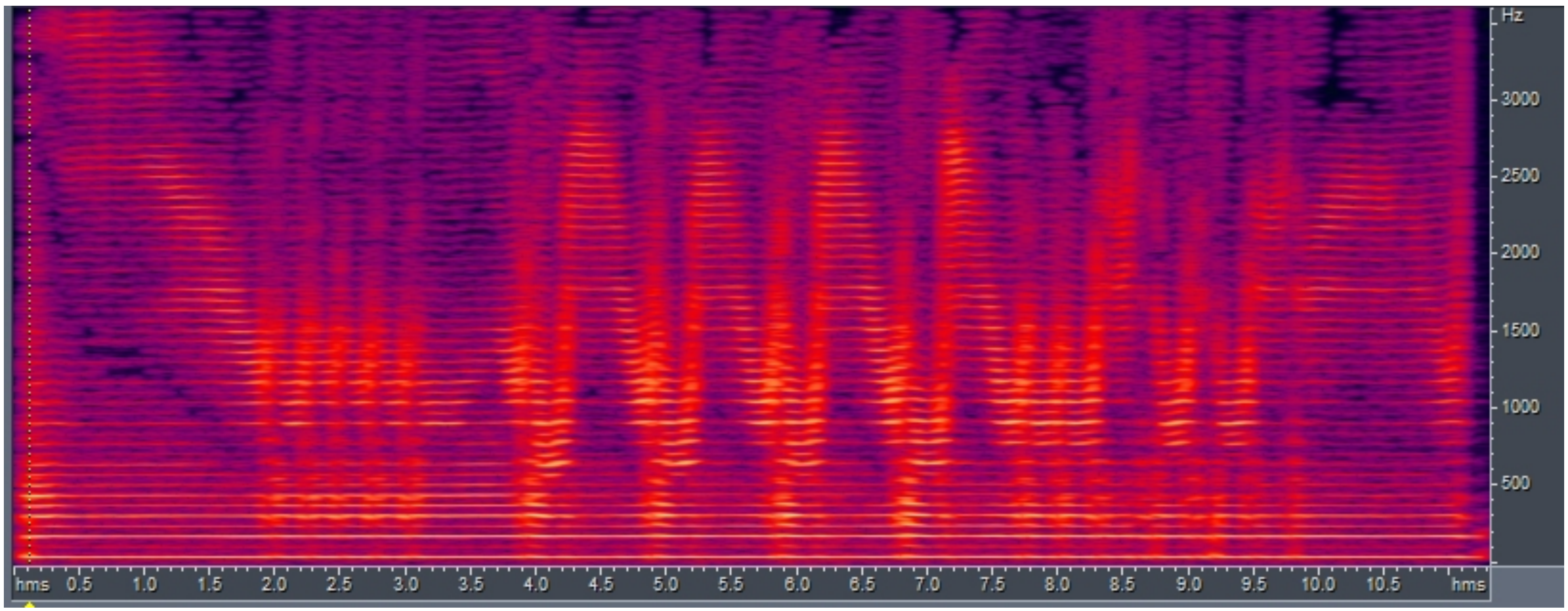
Vocal tract is short so formants are at high frequencies, well above the frequency of the base tone (~100Hz in men and ~150Hz in women)

The peaks are resonances of the vocal tract. The broader higher amplitude bands of pitches are the formants

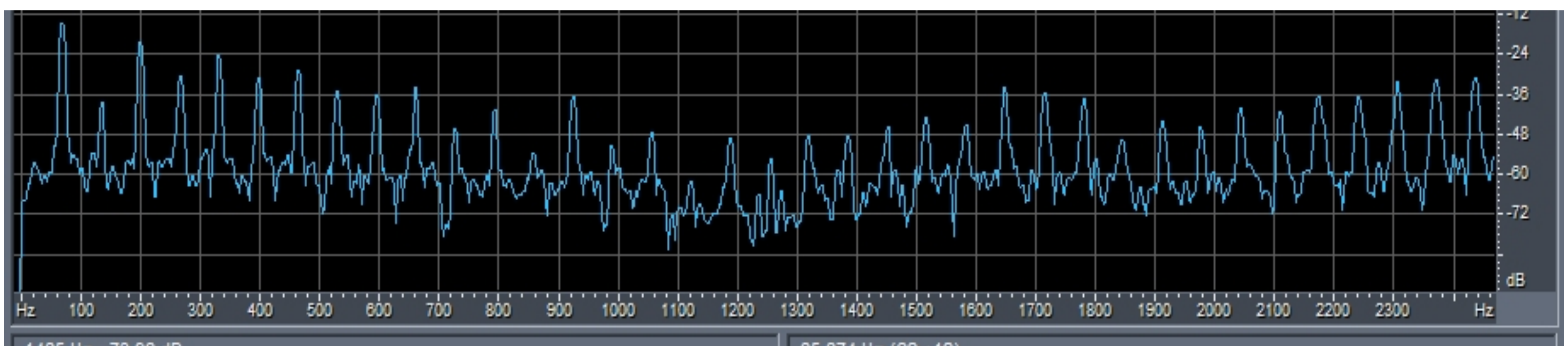
Digderidu

time→

frequency→



loudness→



frequency→

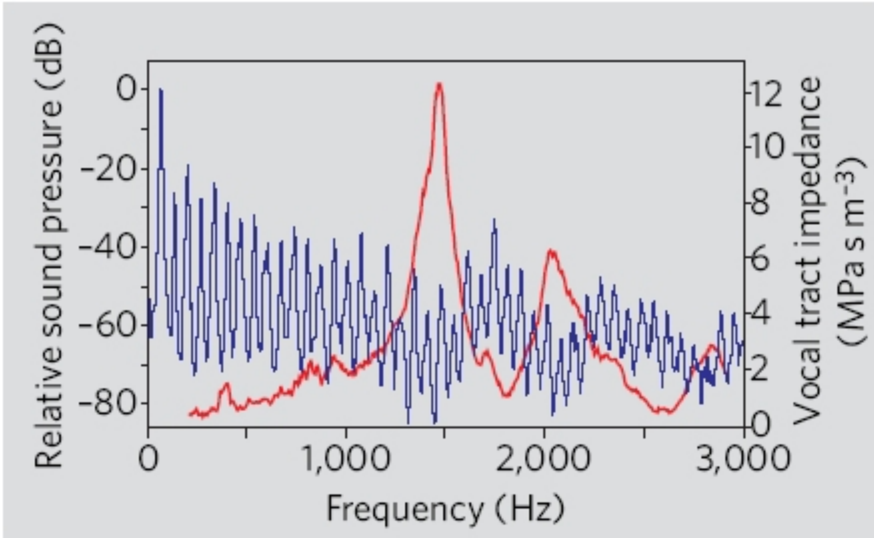


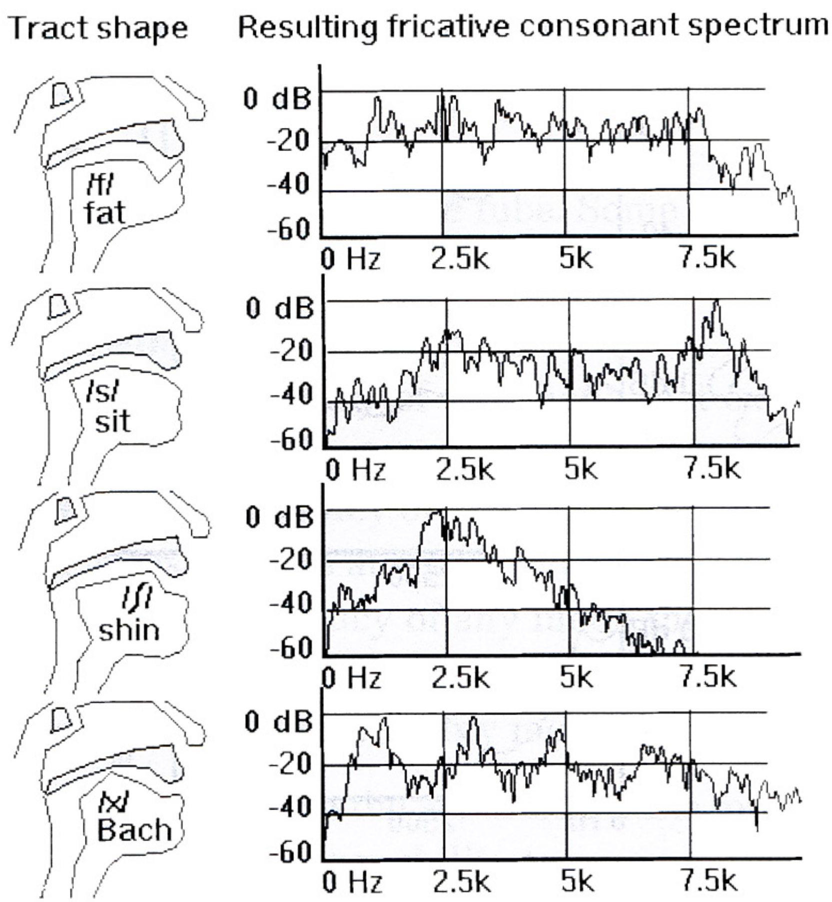
Figure 1 | Acoustic measurements from a didgeridoo performance. Spectrum of radiated sound (blue) and the magnitude of acoustic impedance of the vocal tract (red) measured just inside the lips of a didgeridoo player during performance. The player performs the 'high drone', produced with the tongue close to the hard palate, which generates a characteristic strong formant at 1.8 kHz. Similar measurements with the tongue in the low position revealed no strong impedance maxima and no strong formants. (For sound file and spectra[8], see supplementary information.)

Formants and the Didgeridu

Tarnopolsky et al. Nature, 2005

Turbulence and Consonants

Cook chap 9



9.10 Vocal tract shapes and spectra for four unvoiced fricatives.

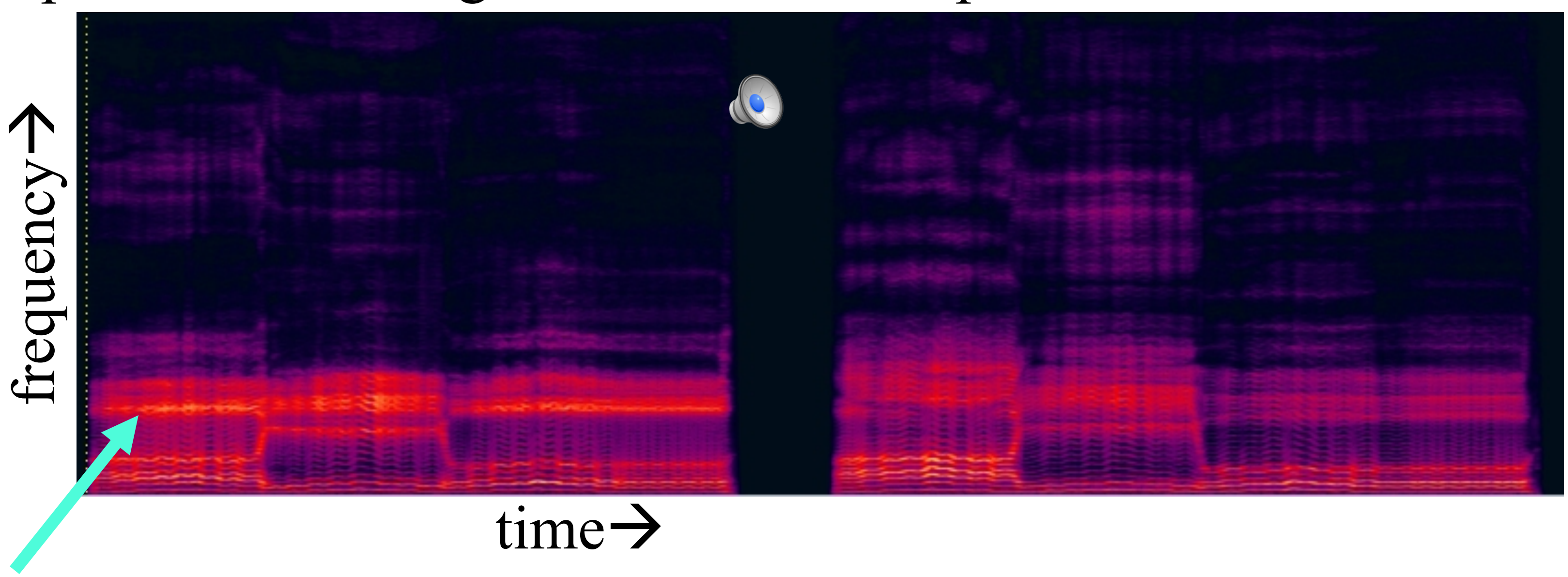
- Blowing harder increases the high frequency mix (try with “s”)
- Shape of track is still important (try with “sh”)

Changes in Timbre
The singer's "formant"

The normal 3 formants are brought close together to form a broad spectral peak between 2500-4000Hz

Cook demo 42 Singing with and without the singer's formant

spectrum with singer's format   spectrum without



Changes in timbre with vocal effort

Cook demo #78

a) Successive vocal tones, amplitude only turned down

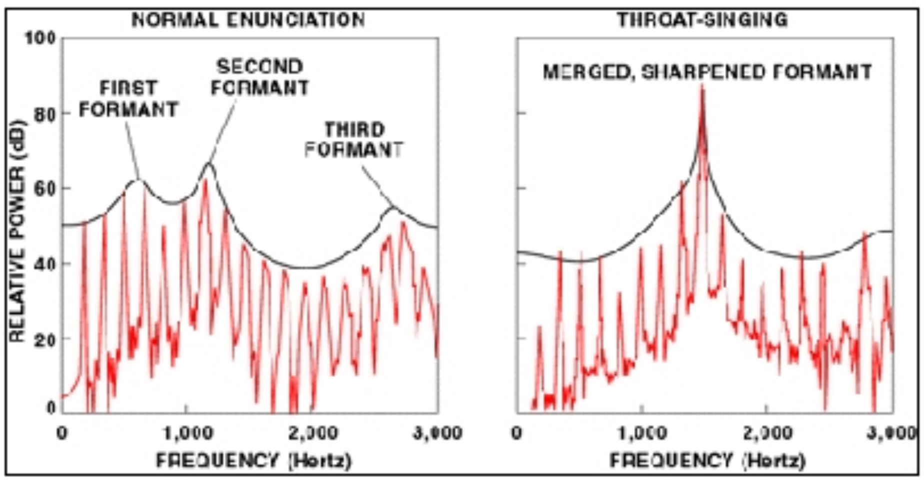
b) Same as a) but high end of spectrum is also turned down, as would happen for decreasing effort

c) Same as b) but with additional reverb that is held constant so voice sounds like it is getting quieter in a fixed location

d) Same as a) but with increasing reverb so the voice sounds as if it is getting further away

Mongolian throat singing

SOUND SPECTRA

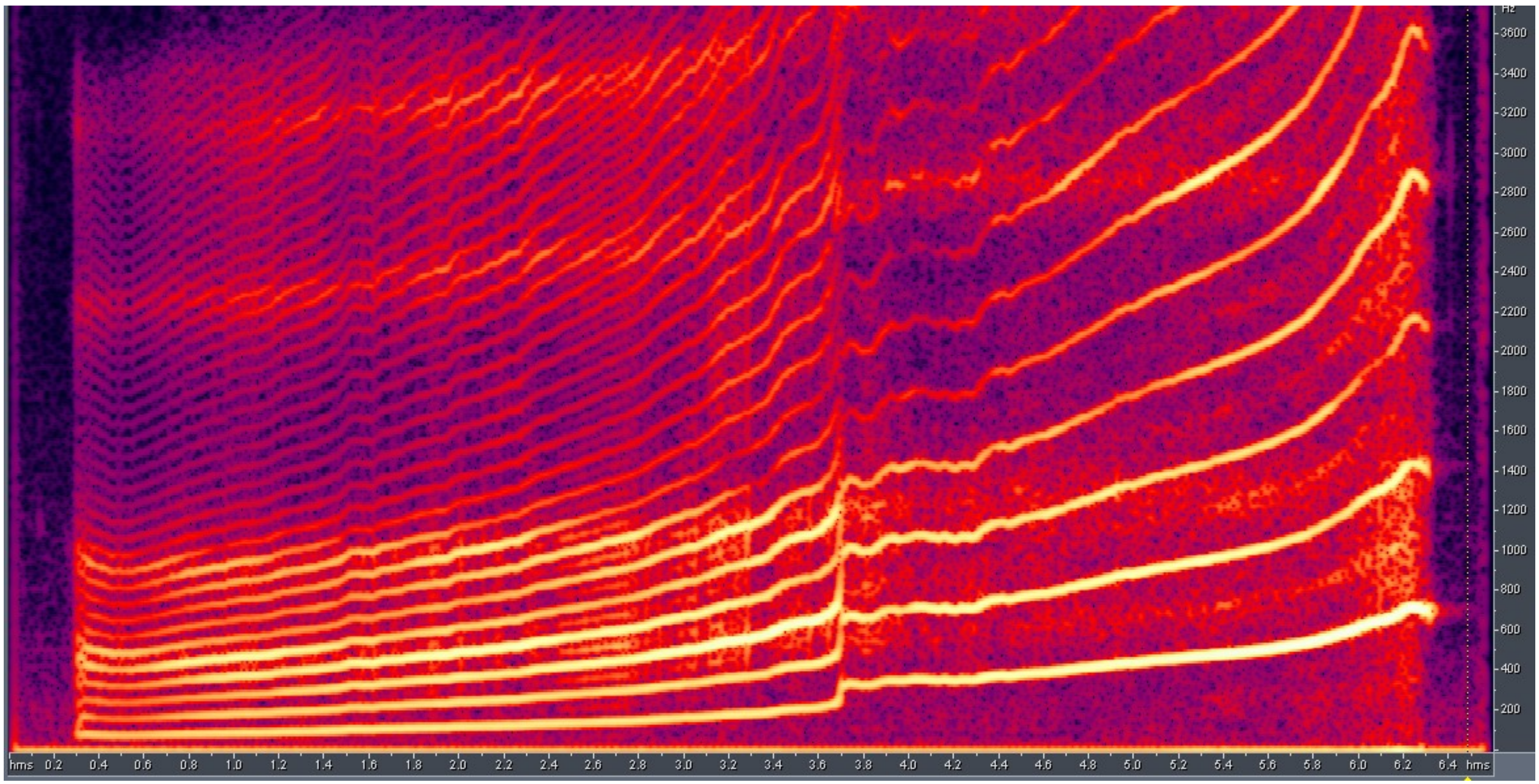


SOUND SPECTRA show the difference between normal enunciation of the vowel /a/ in "hot" *(left)* and throat-singing *(right)*. In both cases the power is concentrated at distinct frequencies--the harmonics produced by the vocal folds *(red)*. When harmonics align with the formant frequencies of the vocal tract *(black)*, they gain in strength.

- Throat-singing Hunhurtu

Falsetto

frequency→



time→

Vocoders

- Create a source sound that has a broad range of frequencies
- Record a voice and measure the broad frequency components (formants)
- Put those variations on to the source

from http://www.epiphyte.ca/code/vocoder/examples.html

carrier = periodic white noise
white noise
strings

Terms introduced

- Resonances
- Resonant excitation
- Impedance
- Formant