Practical Acoustics for Pipers and Pipemakers

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topics

- basics of an air column
  - sound propagation and music
  - 'standing wave'
  - time-domain 'impulse' model
- definitions of frequency, spectrum, harmonics
- fourier and harmonic series
- analysis of “tone”
- impedance/admittance and resonance
  - resonance curve vs. harmonics
  - peak width, 'damping'
- reed/air column interactions – forced oscillations
- nodes and antinodes
- 'musically useful bores' (and why they are not 'ideal cones')
  - bore perturbations
- stopped pipes and the limitations of simple 'tonehole lattice' models
- tonehole size effects
- boundary layer and materials effects
- nonlinear behavior
- characteristics of the reed itself
- tuning, temperament, and meters; limits to perfection
- scaling and its limitations

practical application

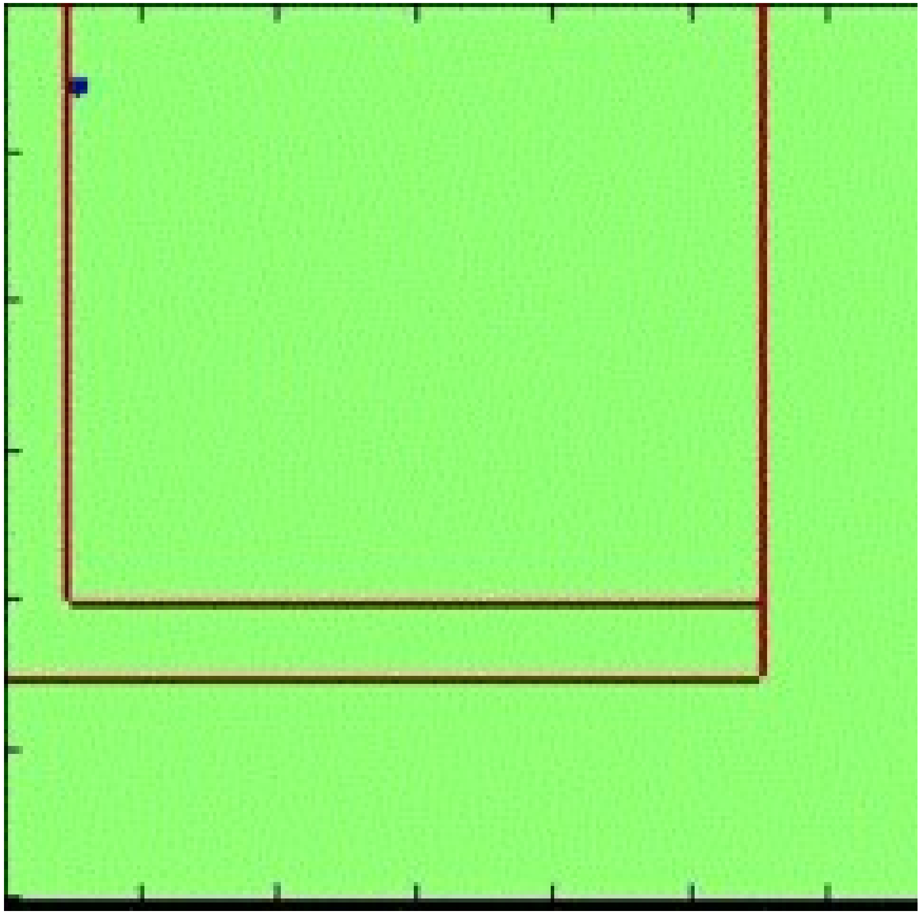
- understanding apparent tuning paradoxes
- the E note (and some reasons why it can be troublesome)
- how undercutting, tonehole enlargement, and scalloping can differ in effect
- making educated guesses about where bore perturbations can help tuning
- knowing the limits of current, simplified models, so as not to misuse them
- provides a conceptual framework for reed adjustment, drone stabilization, and rushing of chanters and regulators
- improves understanding tuning and temperament
- suggests possible roles of features such as 'chambers', end-cap restrictions, etc.
- suggests ways of modifying the pitch of an instrument's design (and limitations thereof)

disclaimer

- mostly, I don't know
- yeah, maybe, but really I'm not sure
- the answers to all sorts of questions, including the ones you're going to ask, are probably deep inside this theory somewhere, but for the most part I haven't teased them out

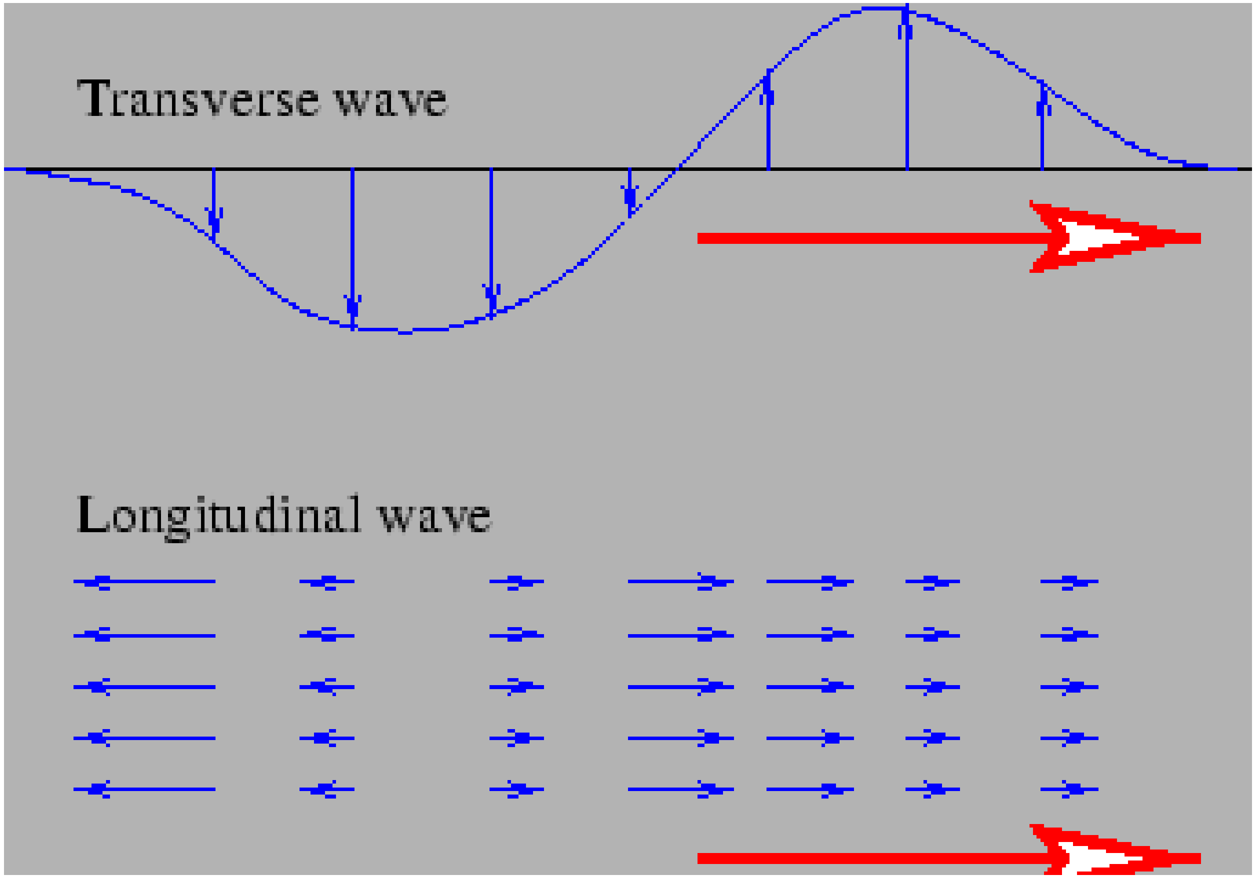
Sound propagation and music

- sound propagates as a pressure wave from source to user
- spherical waveforms
  - thus pressure drops by $1/r^2$
- waveform doesn't change with difference
- interaction with observer, walls, etc. is significant
- *balloon demo*



musical tones are wave phenomena

- analogous to waves in water, but 'longitudinal'

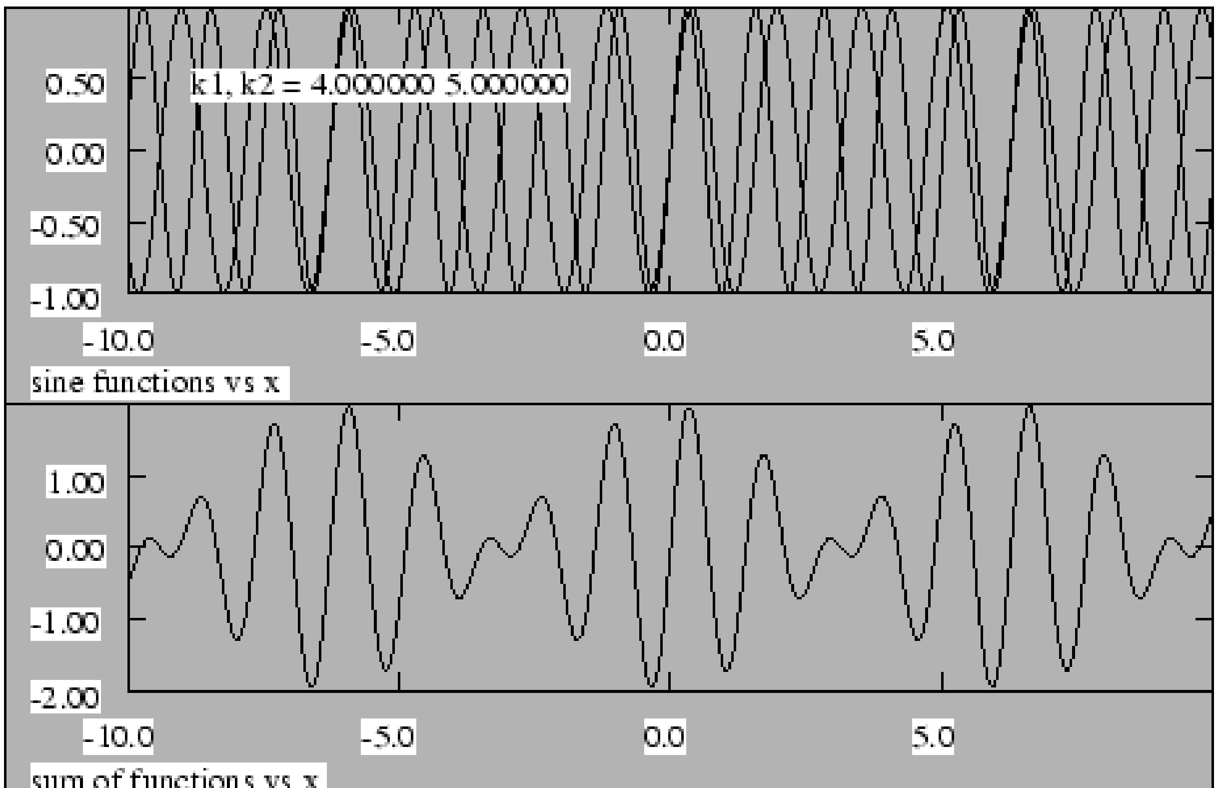


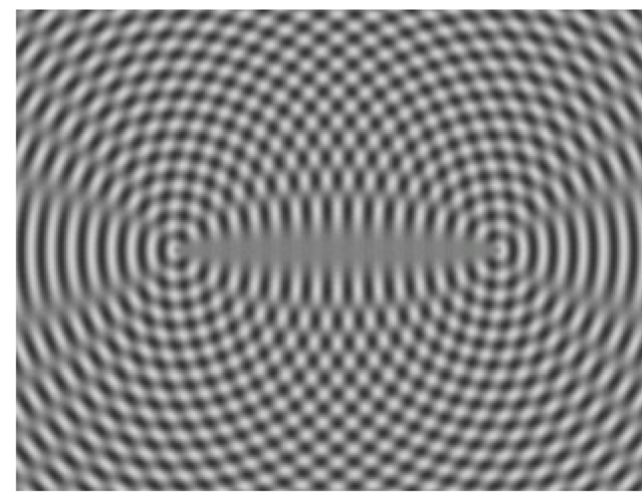
Time-domain/pulse behavior

- 'traveling wave'
- reflected by change in medium
  - reflection is 'reversed', i.e. pressure pulse is reflected as rarefaction and vice-versa
- *bungee cord video*

pulse/wave interference

- 'superposition' – wave heights add
- may be “constructive” or “destructive”





Air column basics

- pressure wave in cylinder is analogous to vibrating string
- weighted beads are analogous to pressure wave in cone

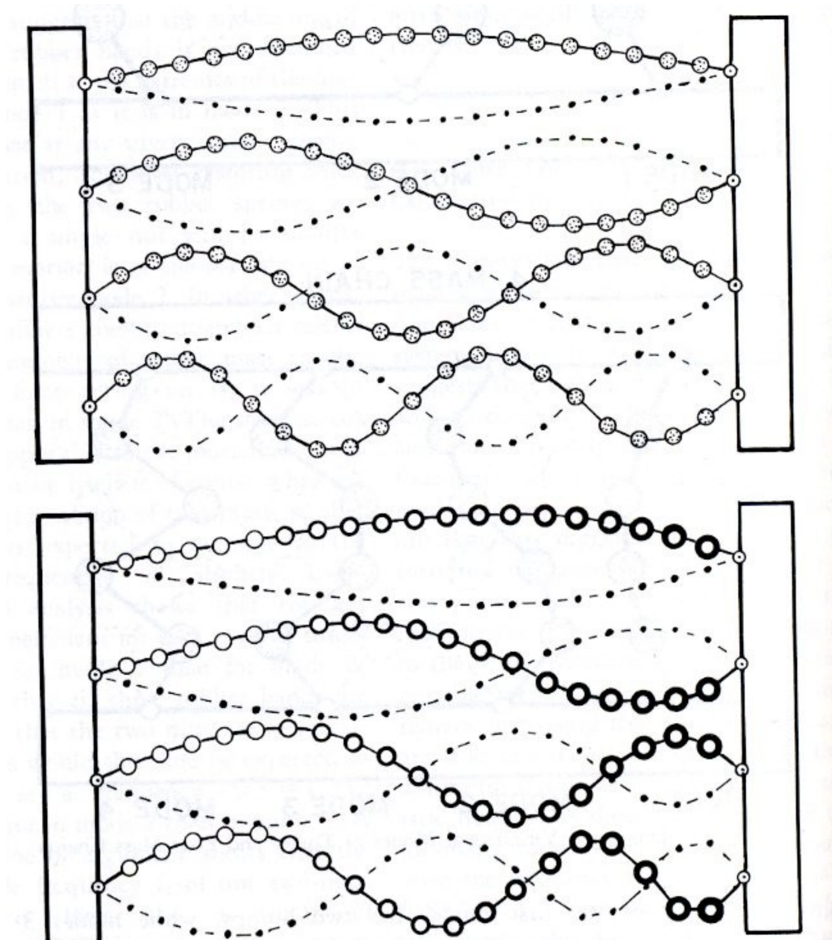
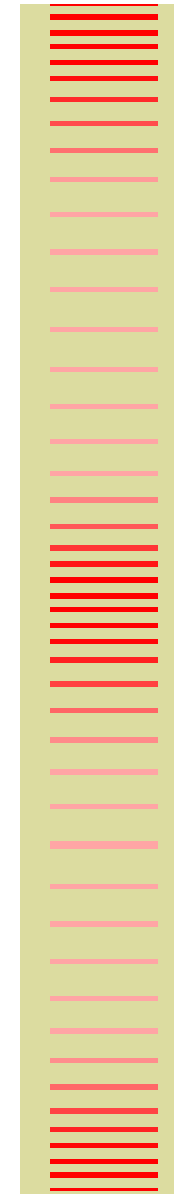


Fig. 6.9. Characteristic Modes of Vibration of a Beadlike Sequence of Masses

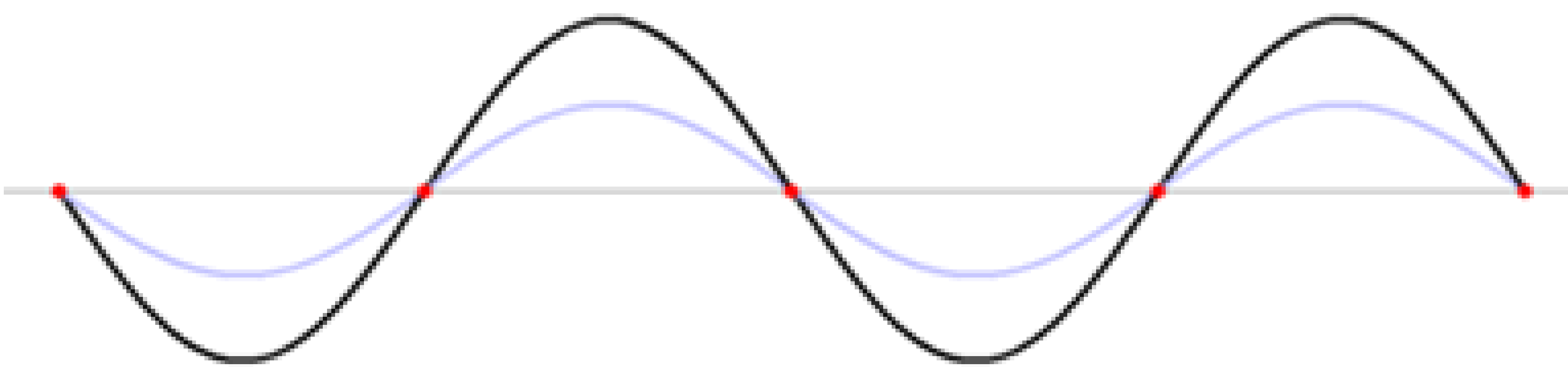


Wave reflection due to change in impedance

- sudden change in air column diameter causes partial reflection – for instance at open end of tube or side hole
- can be seen in a ripple tank where depth changes suddenly
- refraction also takes place

standing waves

- amplitude ebbs and flows, but 'wave' appears to stay stationary
  - actually it's two moving waves, superimposed
  - when their speed and shape match *just so*, result appears to stand still
  - such waves are self-reinforcing, thus are the dominant pressure waveforms in instruments
    - (waveforms not of this special type die out)
    - in our example so far we are neglecting re-reflection at originating end, subsequent amplification, and damping



Modes

- wave media can support multiple configurations of standing wave motion, which we call 'modes'

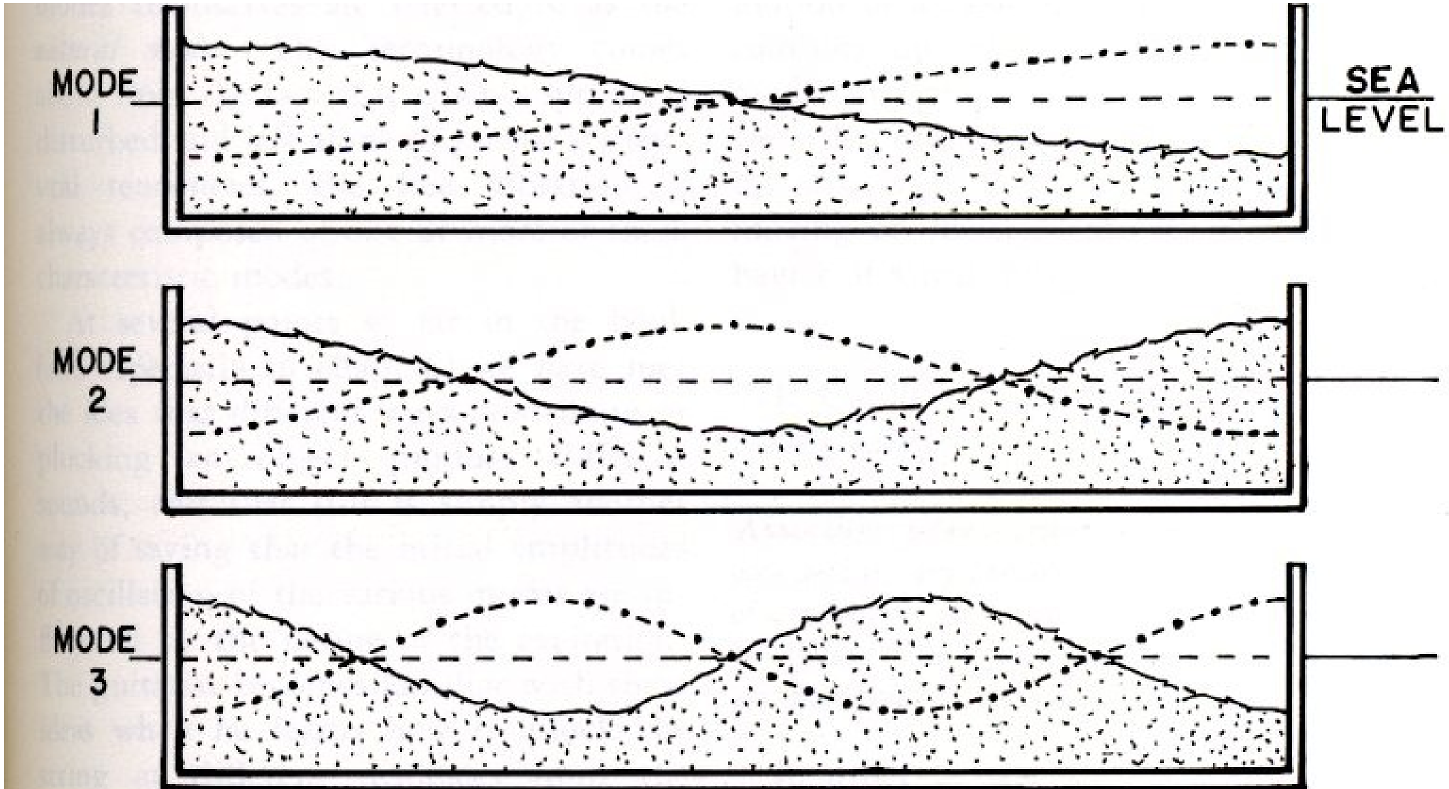
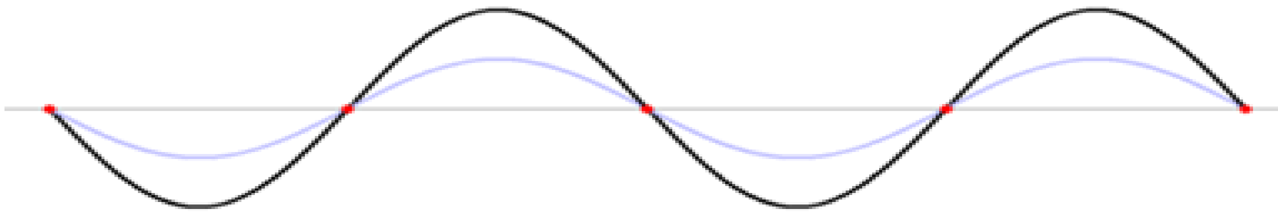


Fig. 6.13. Sloshing Modes of Water in a Trough

Nodes and Antinodes



- node: “anchor point” where something is invariant
- anti-node: point of maximum variation
  - pressure node – where pressure doesn't vary (for instance, approximately at open end of pipe
  - pressure antinode – at stopped end
- velocity node is pressure anti-node, and vice-versa

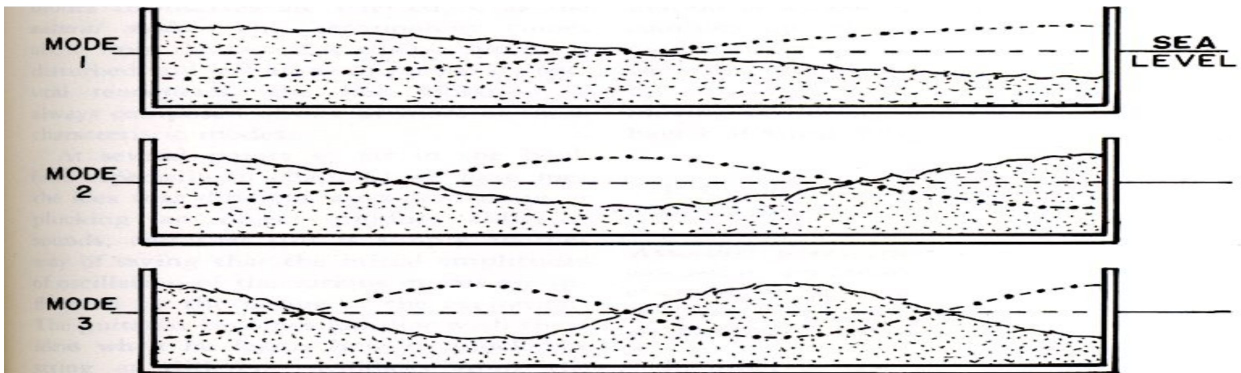
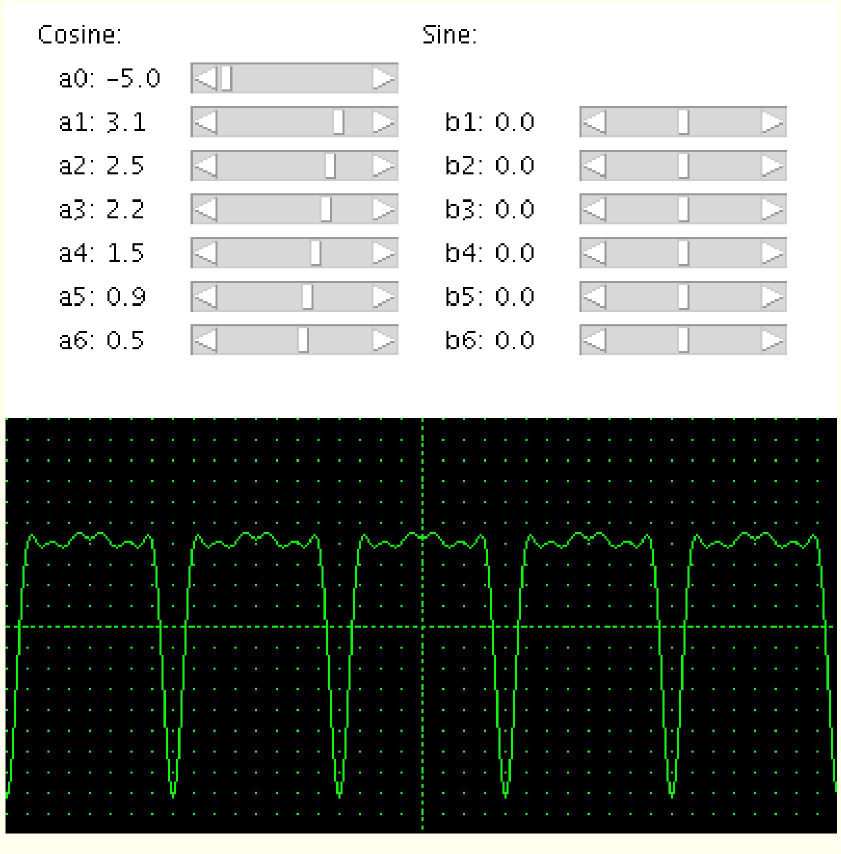
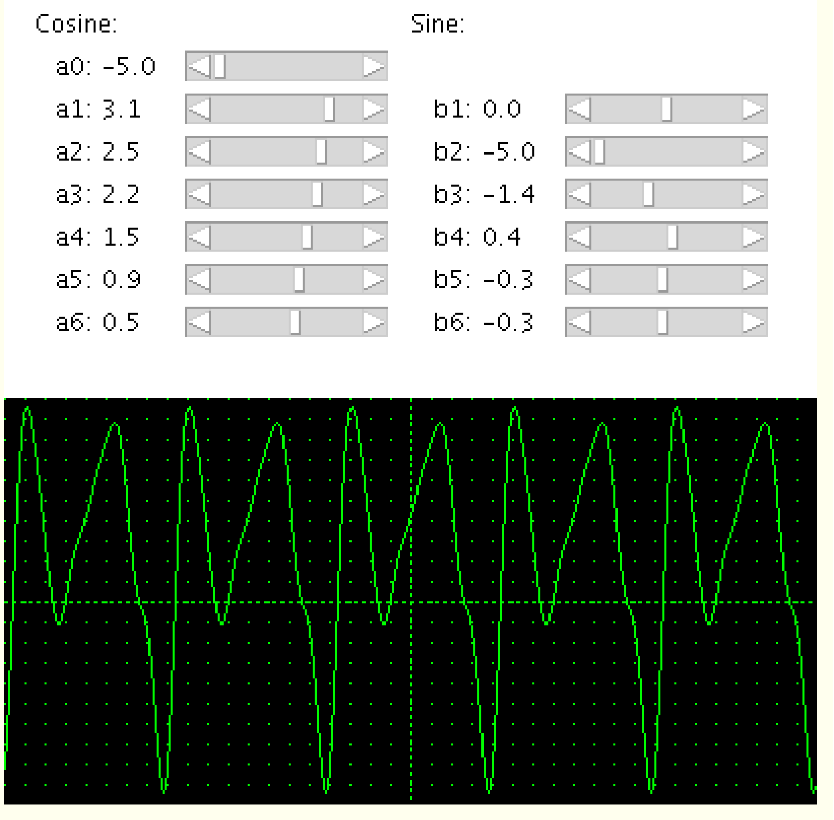


Fig. 6.13. Sloshing Modes of Water in a Trough

superposition of modes

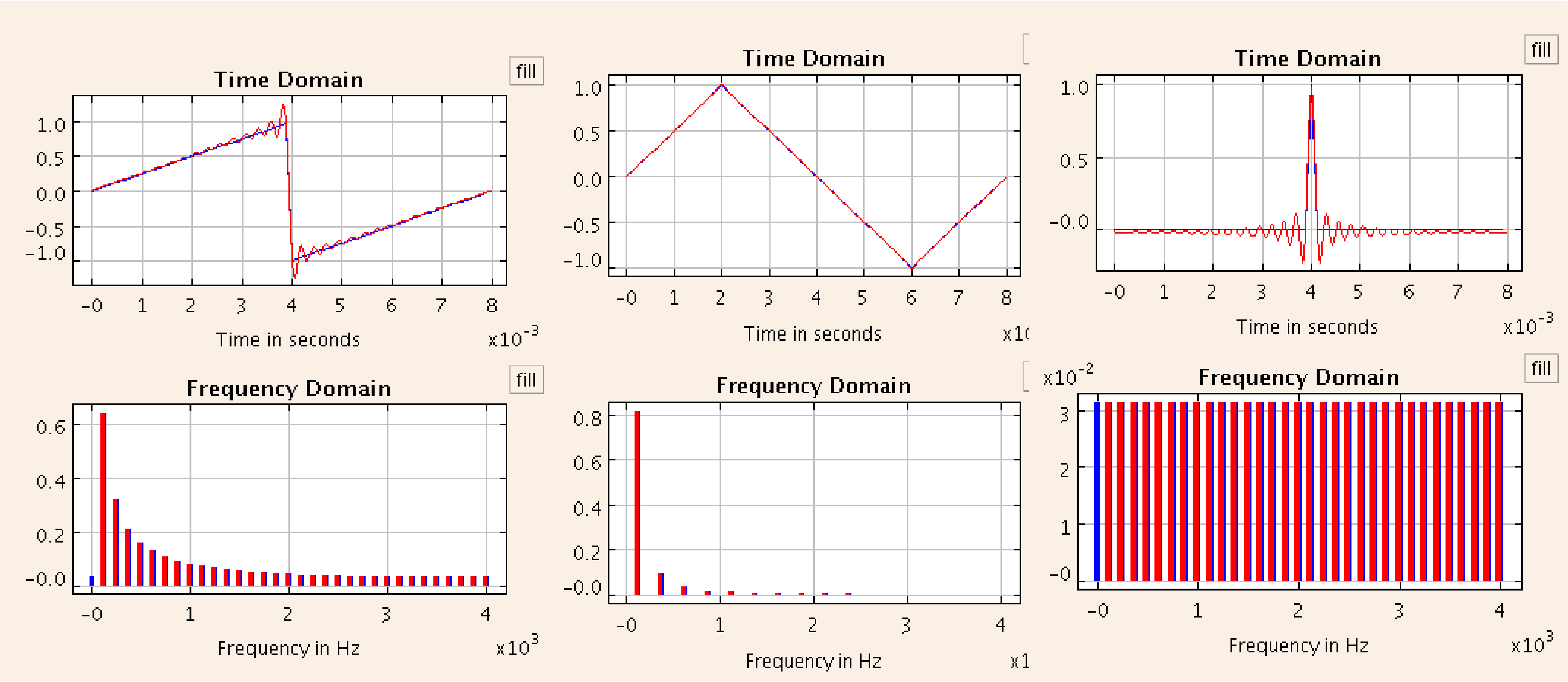
- waves can be superimposed by simple addition
- phase doesn't matter to our ears (at least, in the current context)





sound spectrum

- characteristic waveforms have characteristic harmonic components
  - 'impulse' i.e. spike is about the richest
  - as we've seen, double beating reed is spikelike



harmonics == integer ratios

- harmonics are name for simultaneously active modes
- locked into strictly integer ratios for “steady state”, i.e. sustained notes
  - proven by J. Fourier in 18^{th} century
  - not strictly true of percussion instruments
    - their waveform is not periodic! it decays rapidly with time
  - there is no such thing as a harmonic being “out of tune”, whereas modes in isolation may be

spectra and harmonics

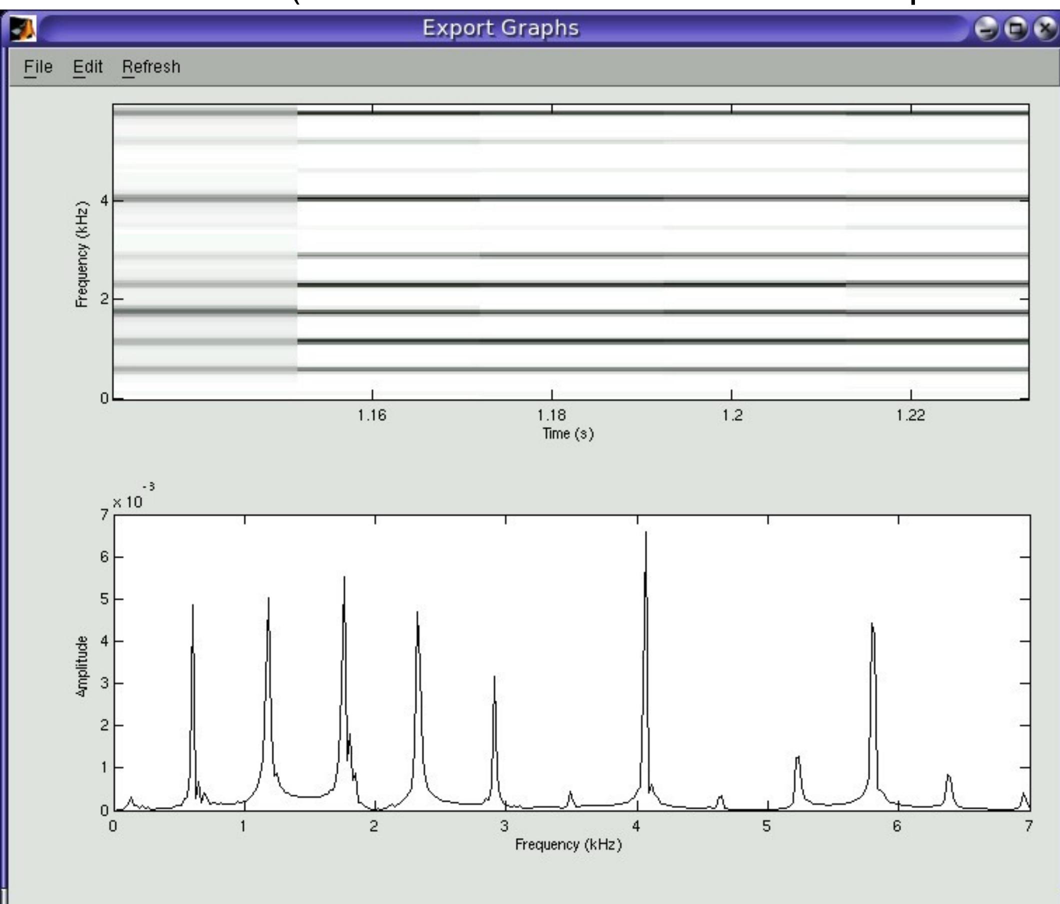
- sound spectrum of steady musical note (from a single generator) consists of perfectly sharp spikes
  - if not, note is wavering in pitch or otherwise changing!
  - also, real mathematical methods of spectral analysis have a limited “resolution”, thus a finite peak width

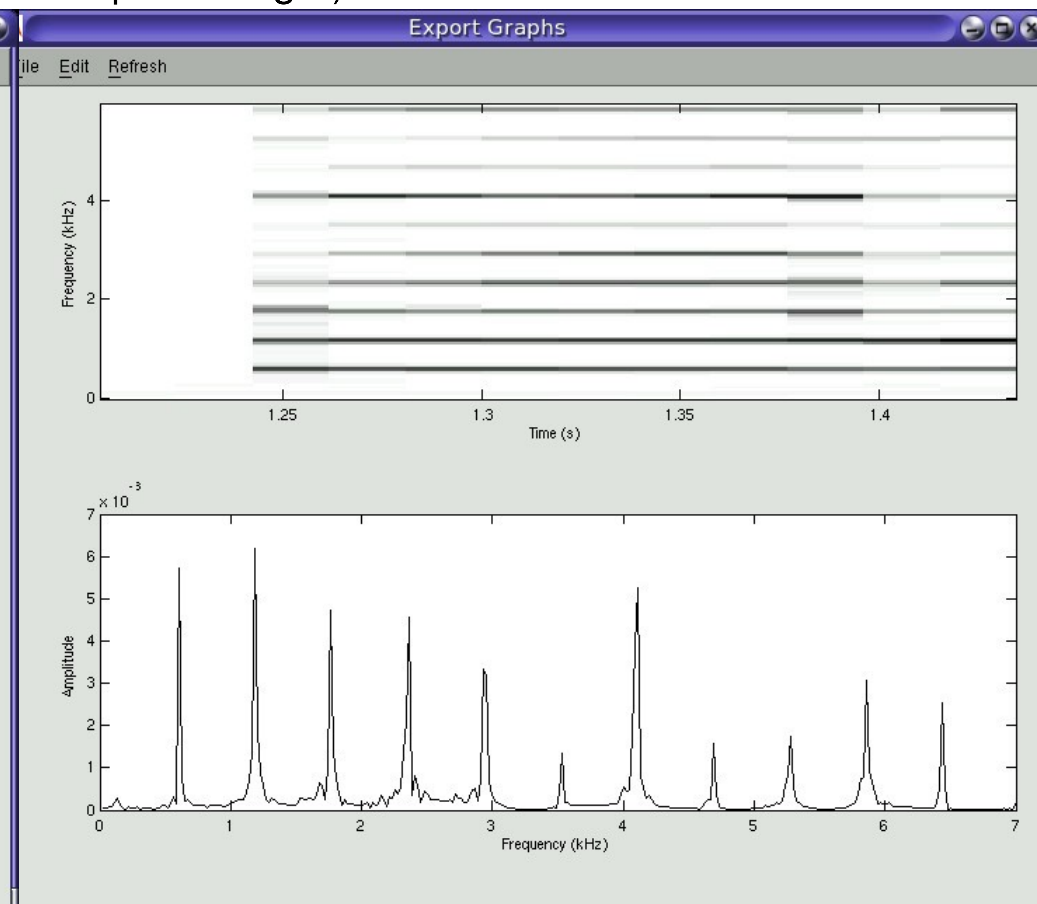
harmonics and tone

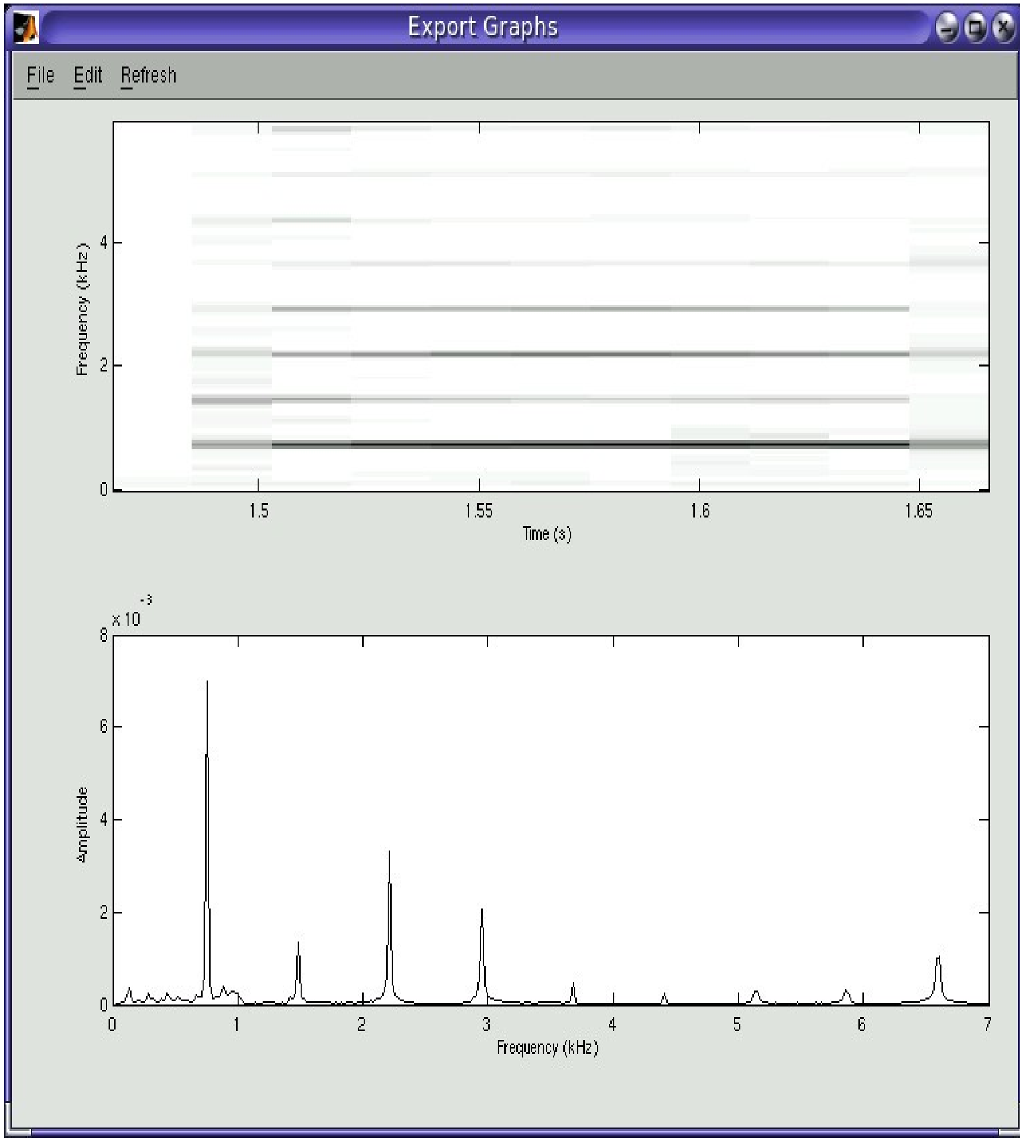
- only way to tell difference between sustained notes on different instruments
- only part of the 'tonal' makeup
- time-evolution of harmonics (or 'partials') also important
- harmonic “spectrum”: which partials, in what proportion?

comparing two similar sound spectra

- similar chanters, same reamers etc.
  - same reed and recording conditions
  - (note two charts not normalized quite to same peak height)







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Time (s)
Amplitude
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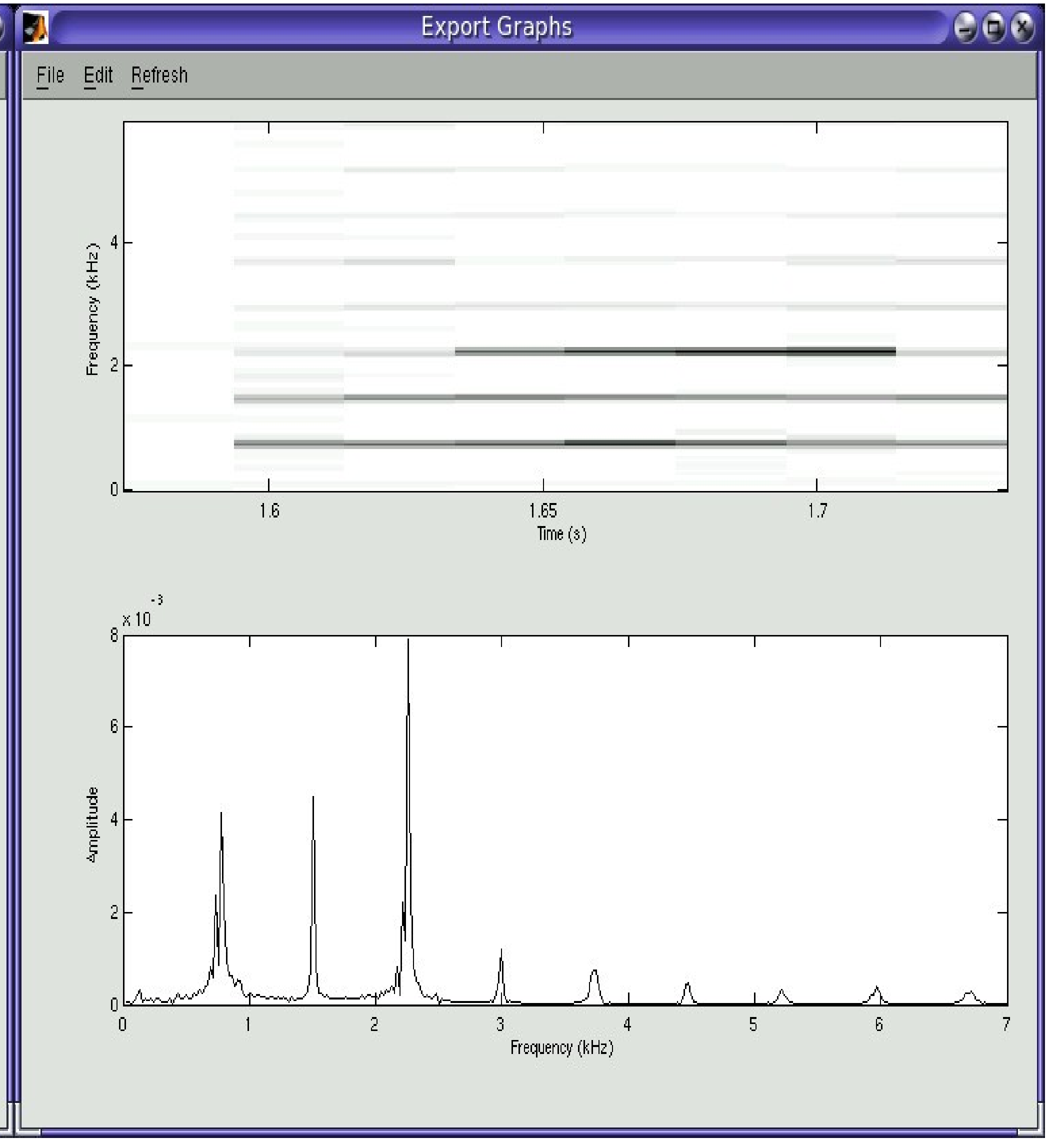
Frequency (kHz)



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Time (s)
Amplitude
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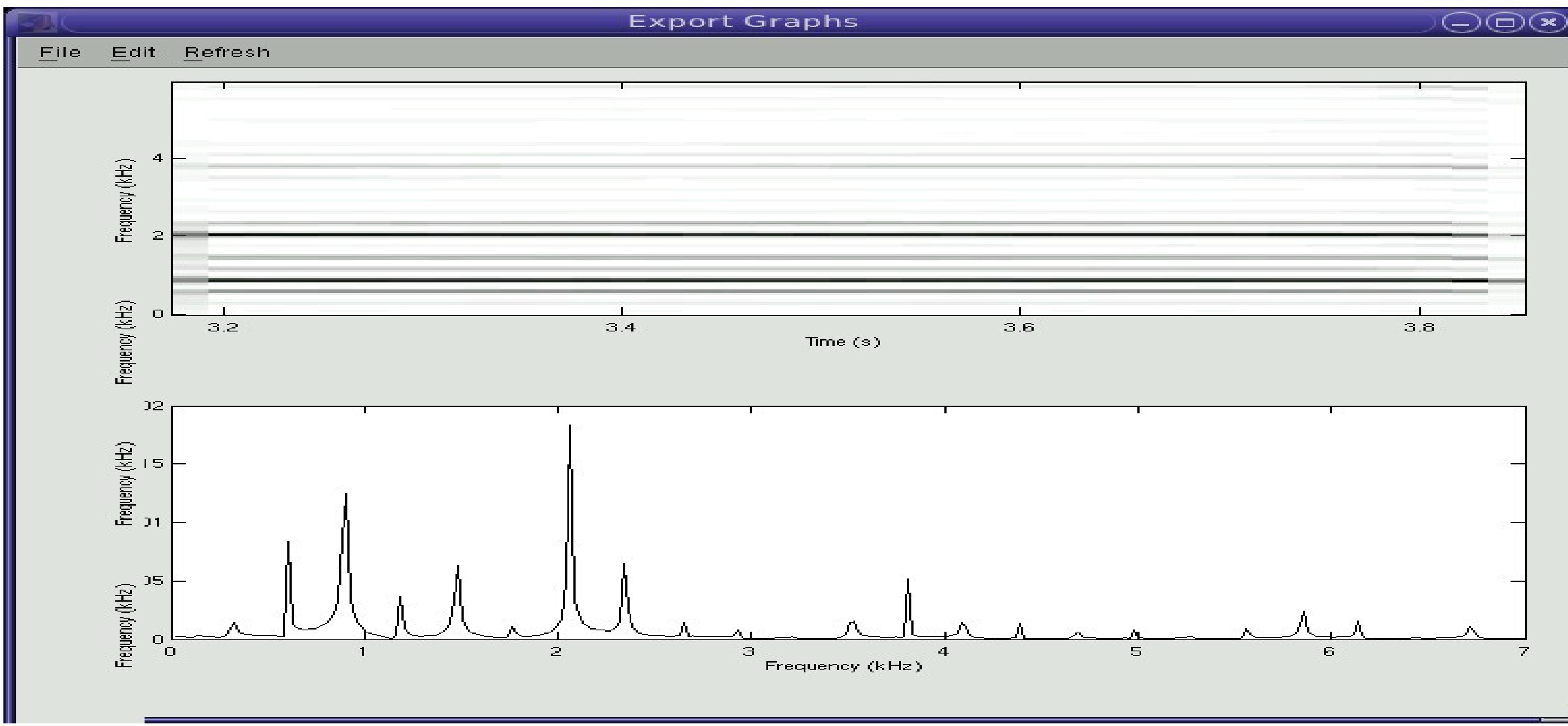
Frequency (kHz)

fundamental not always primary

- this confuses tuning meters
- but human ear is good at detecting “series” of harmonics
  - sometimes “too good” - can be tricked into hearing things in wrong octave!



Impedance, admittance, and resonance

- impedance and admittance tell us about degree to which bore 'supports' a certain frequency of oscillation (when input)
- reed produces entire spectrum of harmonics as input, as a perfectly aligned series (though amplitudes may be unequal)
  - each must find a peak with which to 'align' in order to be supported by air column
- particular 'misaligned' resonance peaks will 'pull' the input spectrum sharp or flat
  - in second octave, the fundamental is missing, which accounts for octave tuning differences

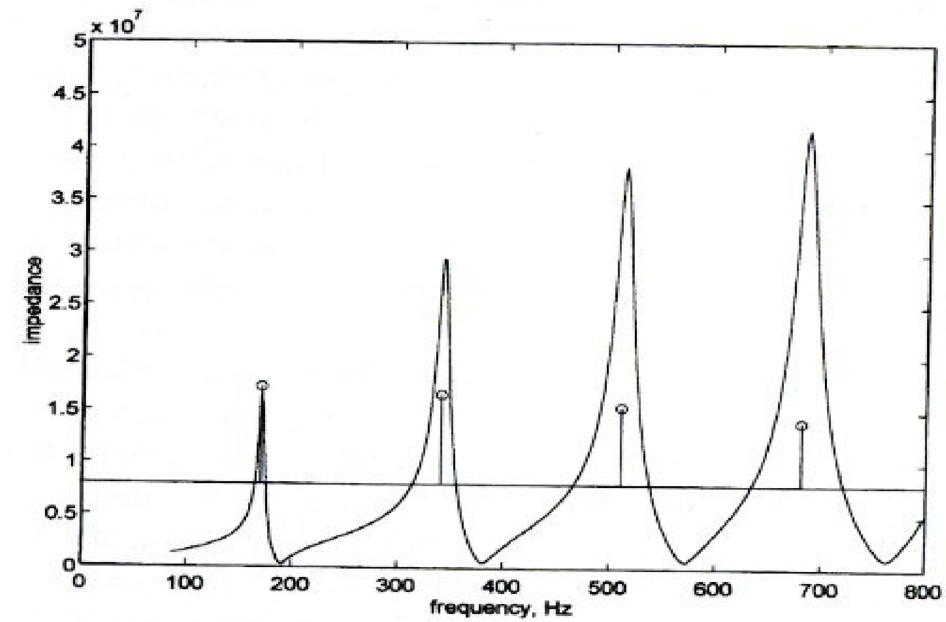
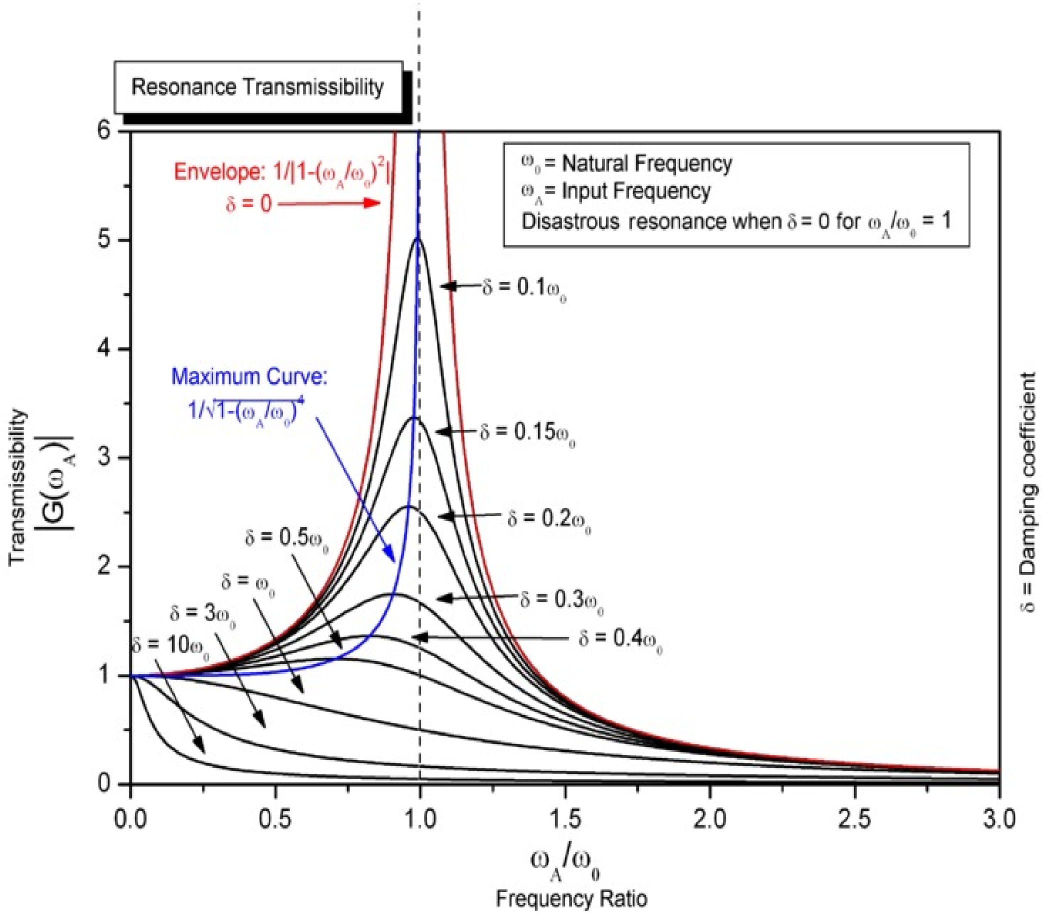


Fig. A6.2. Spectra of the passive impedance of a conical pipe (drawn line) and that of the impedance generated by the reed (circles).

Damping and resonance

- damping affects width and height of peaks
  - too much damping causes excess losses, especially of high harmonics, poor transient behavior (sluggish attach)
  - some damping is useful if peaks are poorly aligned
    - poorly aligned peaks with little damping may feel “unstable”



Damping and resonance

- less damping means more high-frequency transients

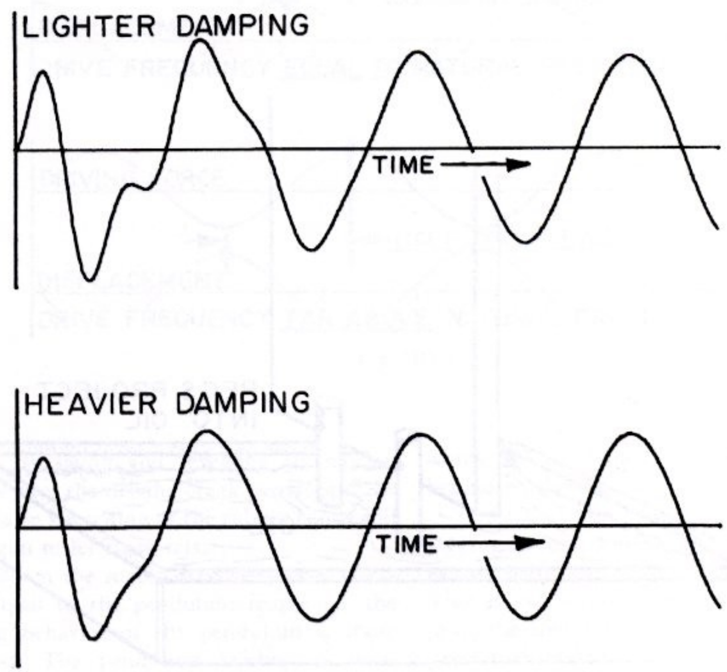


Fig. 10.6. The Influence of Viscous Damping on the Duration of the Initial Transient

Reed/air column interactions: forced oscillations

- fundamental mode is analogous to pushing someone on a swing
- for double reeds, motion is mostly “beating”, short bursts of air flow
  - could consider reed as a pure 'on/off' valve

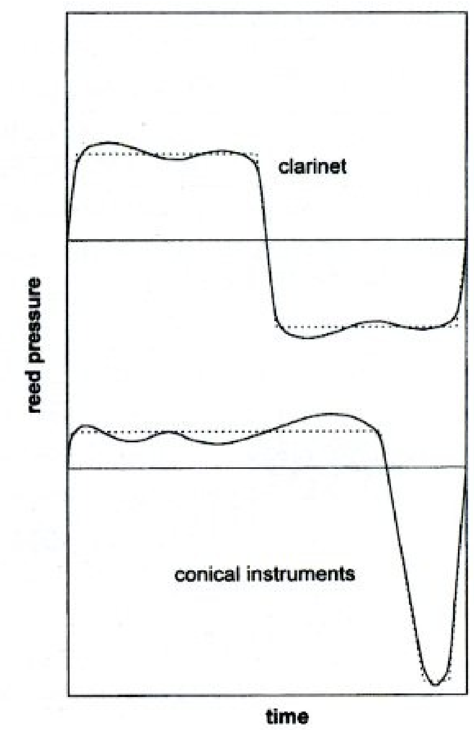


Fig. A5.3. Pressure across the reed for a beating clarinet reed (above) and a reed on conical instruments (below).

characteristics of the reed itself

- cantilever model
- 'beating' reed acts as a valve
- resonance of reed formed by blade compliance and staple dimensions
- compliance affects 'effective volume'
- stiffness vs. inertia determine blade frequency
  - aka 'head speed'
- don't forget, staple/reed forms top of bore

“Musically useful bores”

- admittance peaks more or less aligned in integer ratios
  - support partials for bright tone
  - support for multiple modes critical to starting and sustaining standing waves
    - complicated reasons involving nonlinearity
  - 'idealized' as cylinders, cones, or Bessel Horns
    - real instruments have mouthpieces, reeds, non-ideal behaviors – thus counterbalancing differences from ideal shapes

useful bores (cont.)

- also usually forgotten: “stepped” cylinders
  - drones, for instance
  - potentially very useful, omitting modes n(N+1)
- “perturbations” are required for numerous reasons
- principle of complementary bores may be of interest
- pipe chanters are most similar to oboes or bassoons, except for stopped end

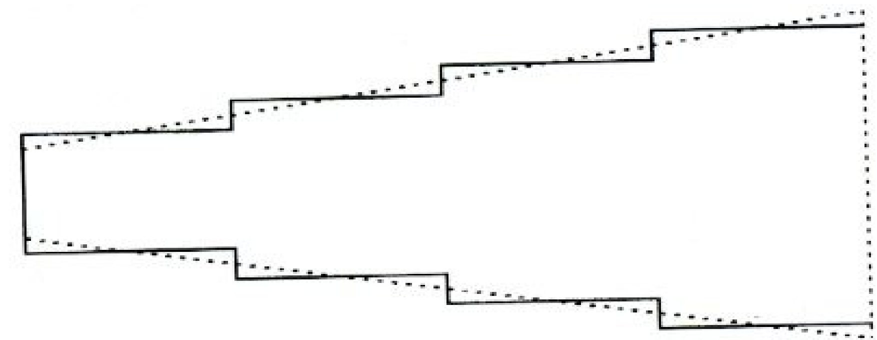


Fig. A3.16. Saxophone made of successive cylinders.

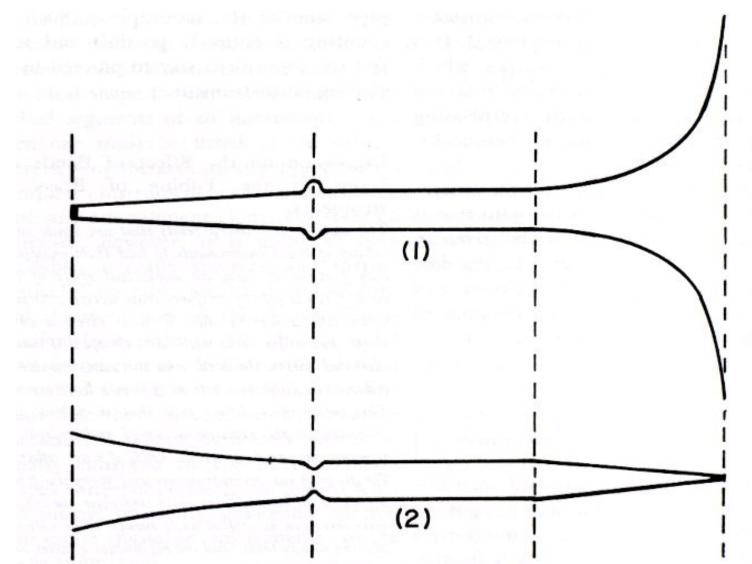


Fig. 20.10. A Horn and Its Dual

effect of diameter to length ratio

- in general, wider bores attenuate higher harmonics
  - but very narrow bores can increase damping, counteracting this effect
  - cone angle of conical bore affects harmonic content

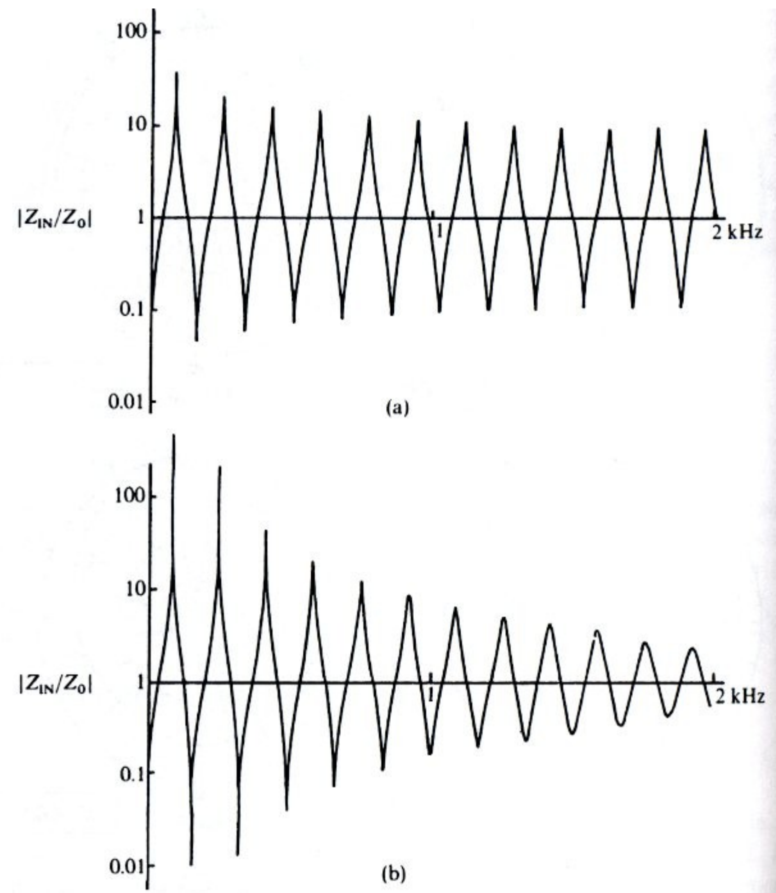


FIGURE 8.11. Magnitude of the acoustic input impedance Z_{IN}, in terms the characteristic impedance Z_0, for open cylindrical pipes of length 1 m a diameters of (a) 2 cm and (b) 10 cm.

modes of a truncated cone

- like cylinder, with 1/r2 attenuation
- stopped end forms pressure antinode

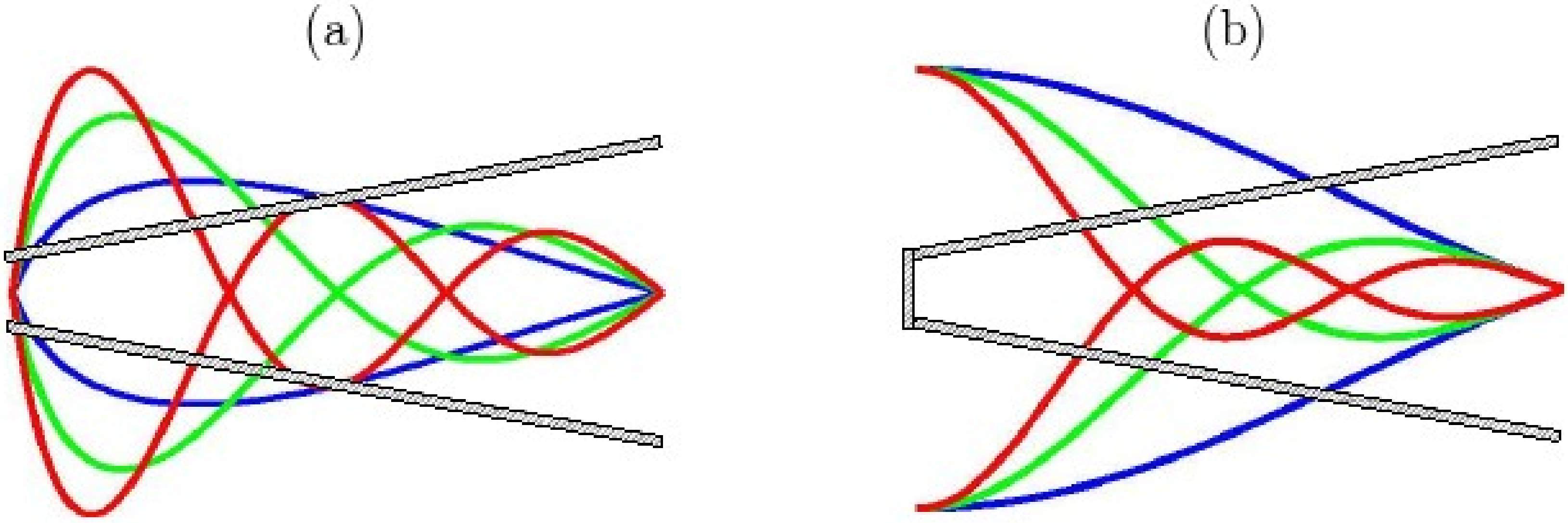


Figure 2.7: First three modes of vibration of pressure for a truncated cone (a) open and (b) closed at the top end

effect of perturbations

- impedance drop (i.e. enlargement) at pressure antinode lowers frequency
- impedance drop at velocity node (i.e. pressure antinode) raises frequency
    - increase at open end tends to raise all, as you move upwards lower modes are selectively affected
    - increase at closed end tends to flatten all, as it's a pressure antinode for all modes and tonehole configurations

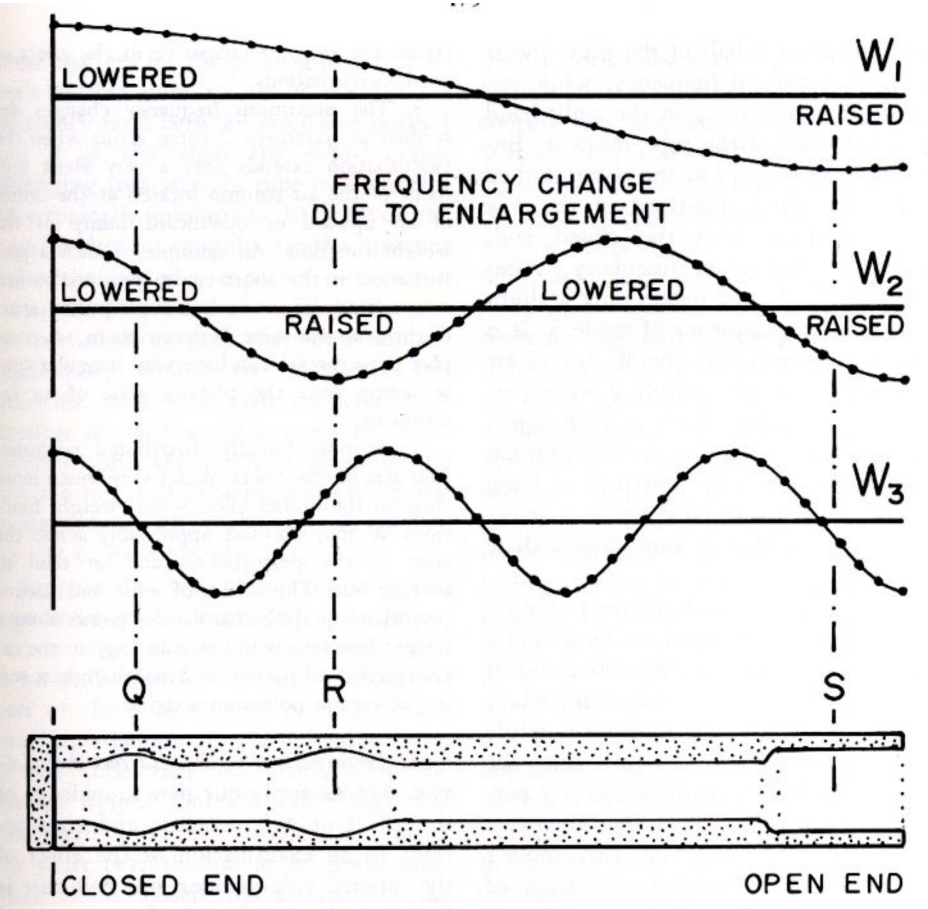


Fig. 22.3. The Use of Perturbation Weight Functions for a Clarinetlike Air Column

effect of perturbations (cont.)

- note effect of reed socket

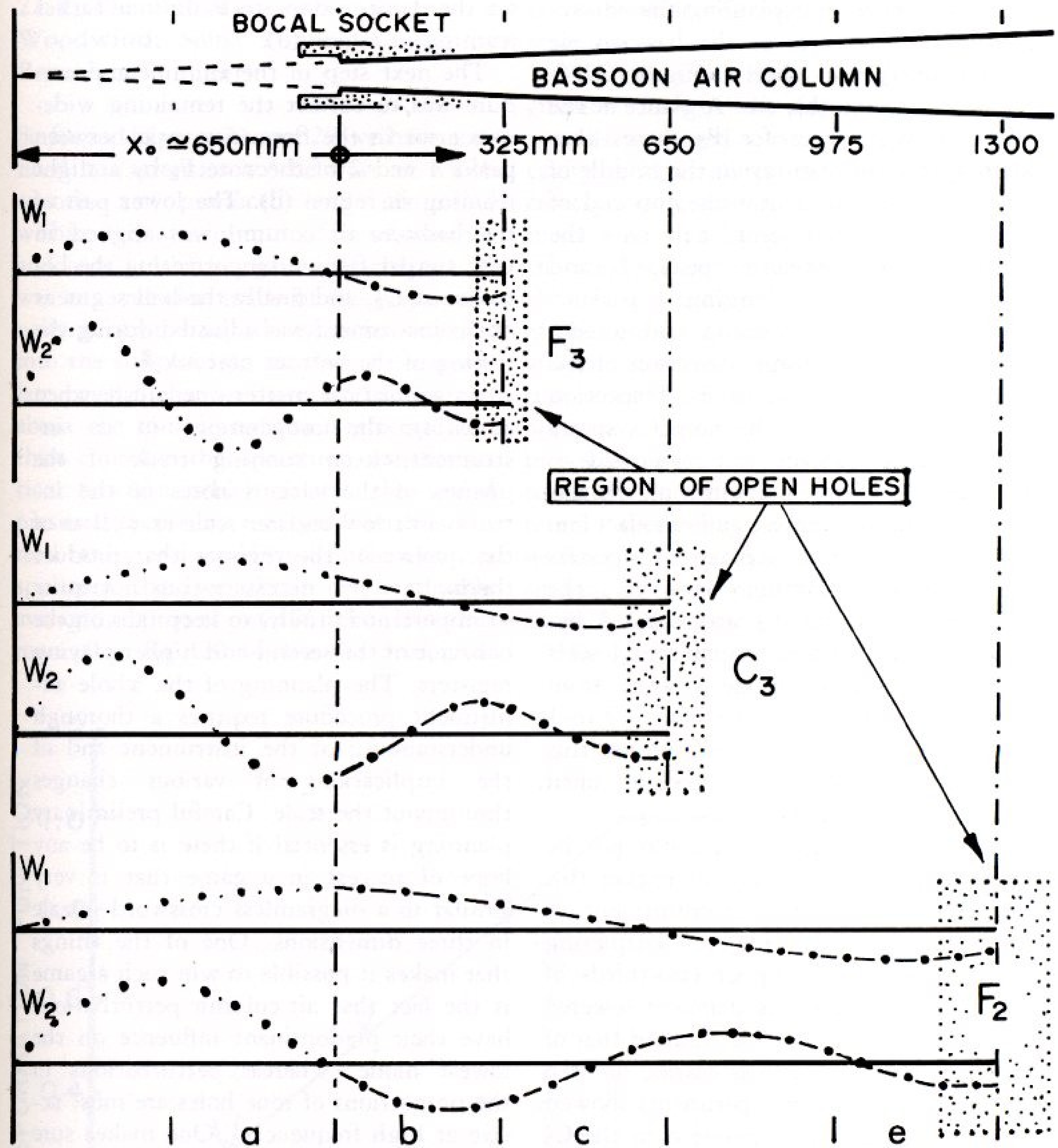


Fig. 22.4. The Use of Conical-Instrument W Curves for the Alignment of Various Notes on the Bassoon

effect of perturbations (cont.)

- case in point, near oboe reed seat
  - note that one change didn't seem to have major effect, but another was disastrous!
  - makes intuitive sense when one considers that the first change 'mostly' cancelled itself out for most modes

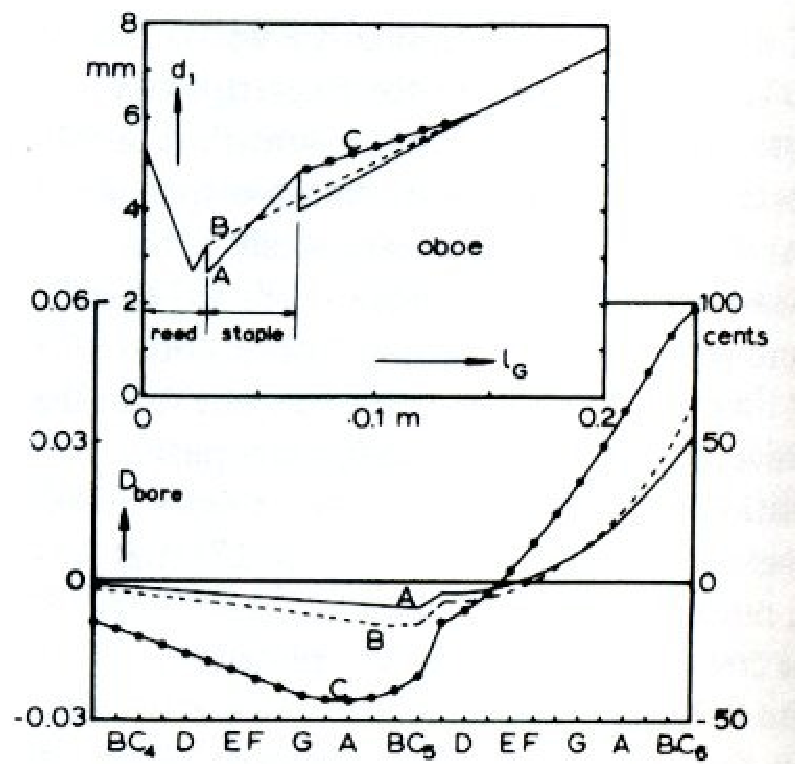


Fig. 45.1. Tuning diagram for an oboe, unchanged (A) and changed in two different ways (B and C) as shown in the diameter plot in the insert.

effect of bore perturbations on harmonic peaks

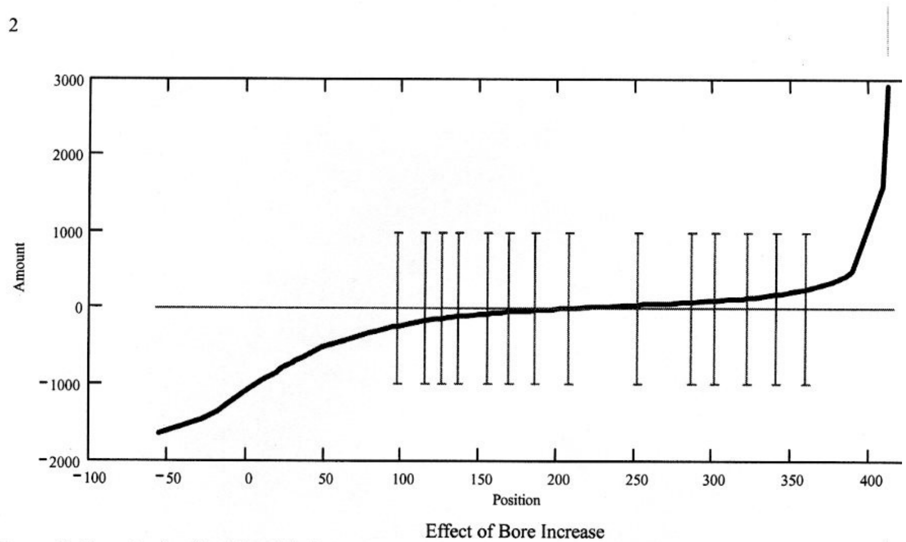
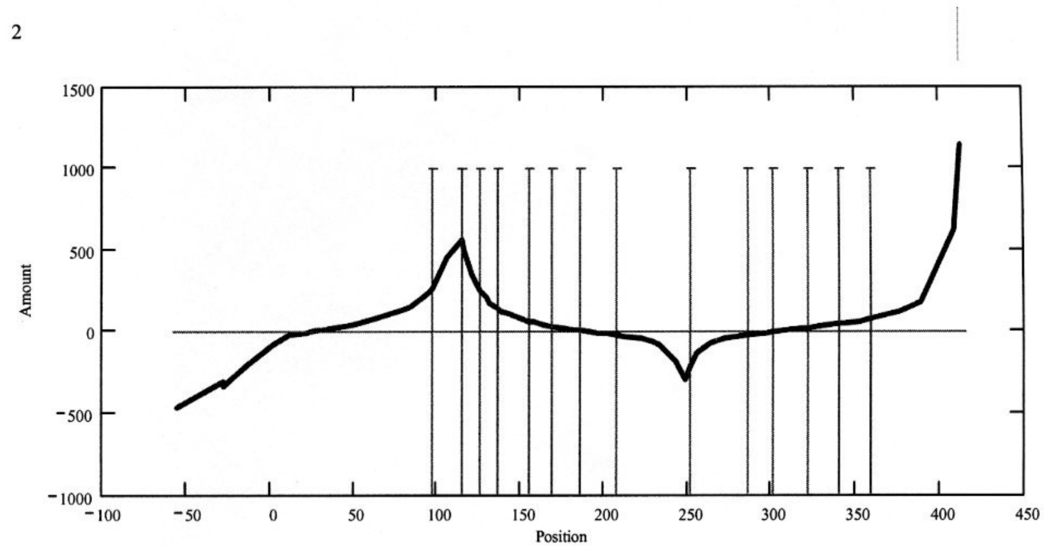


Figure 9 Bore tuning for First Mode.



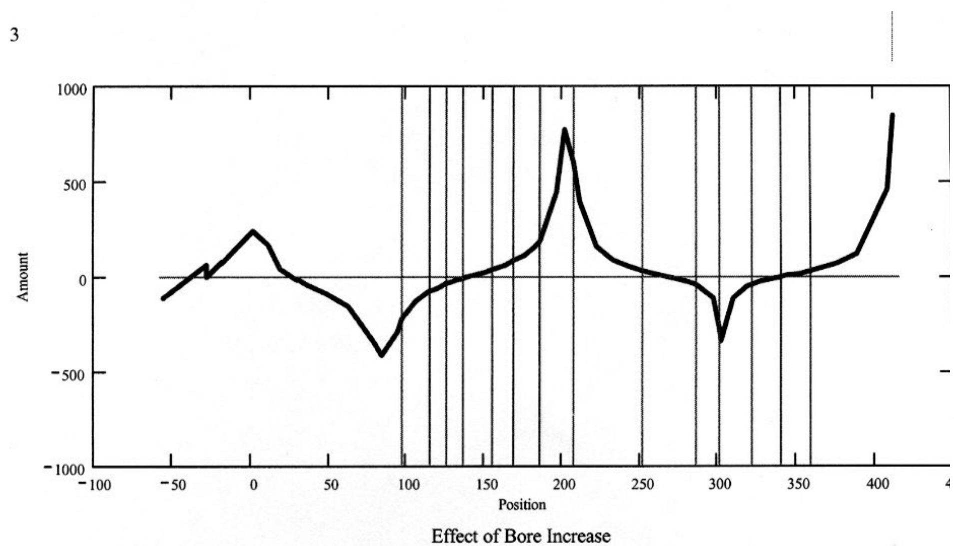


Figure 11 Third Mode

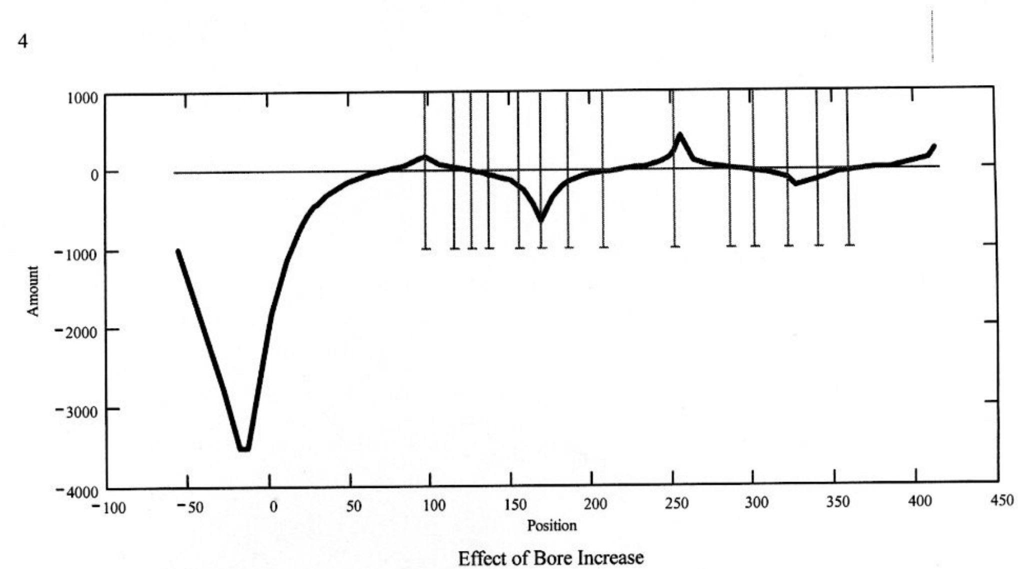
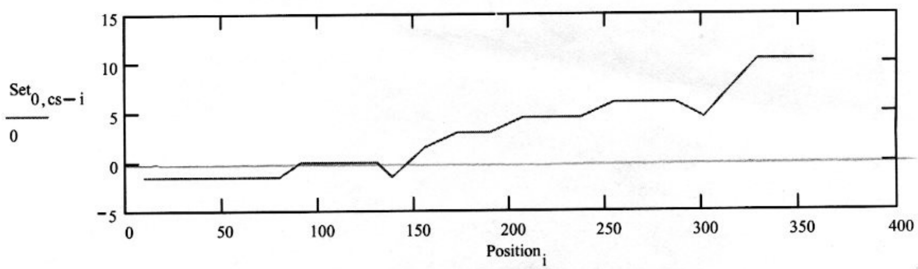
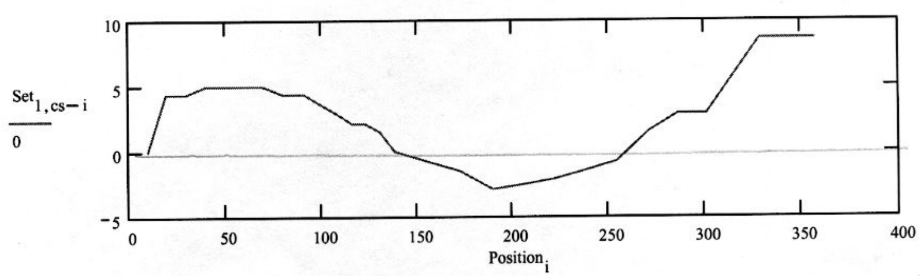


Figure 12 Fourth Mode

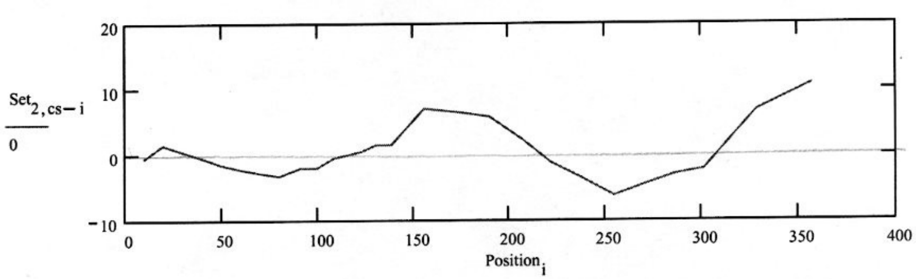
D1



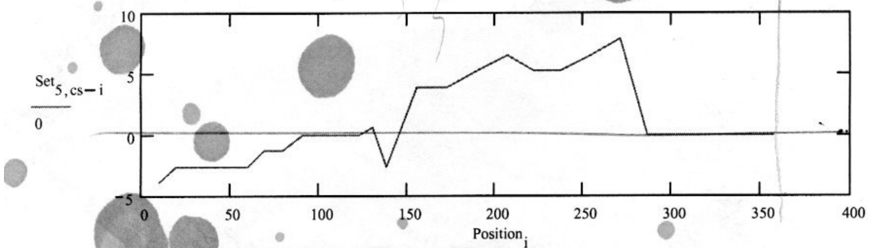
D2



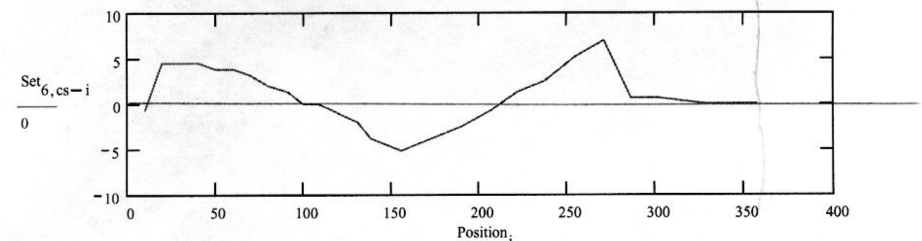
D3



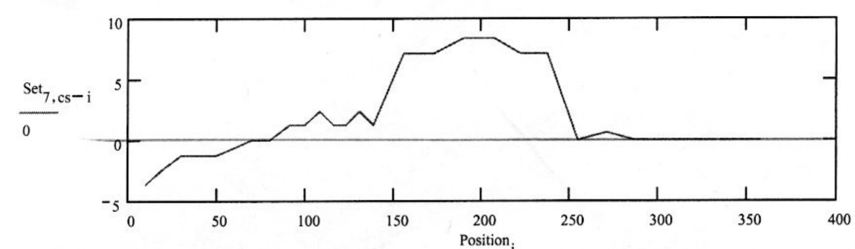
E1



E2



F#1



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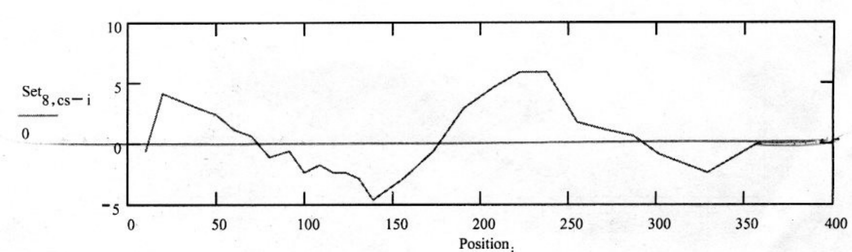
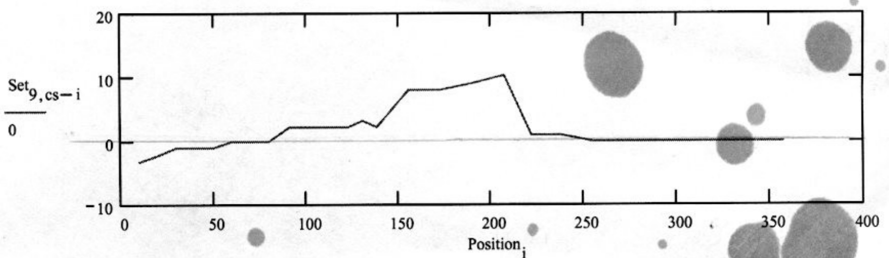
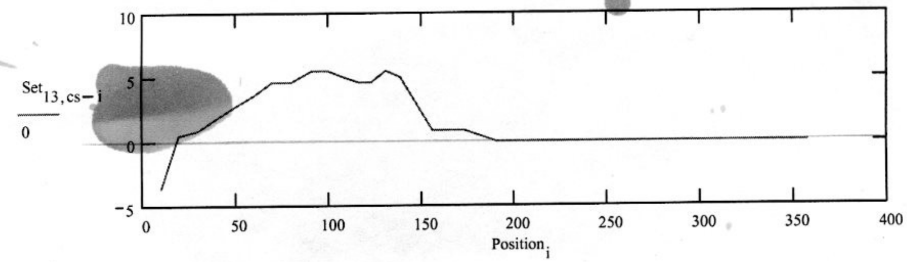


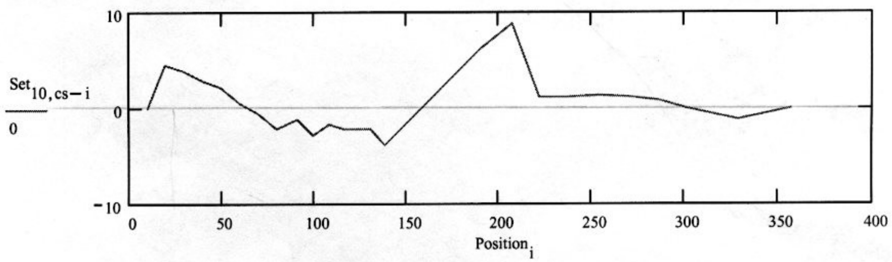
G1



B1



G2



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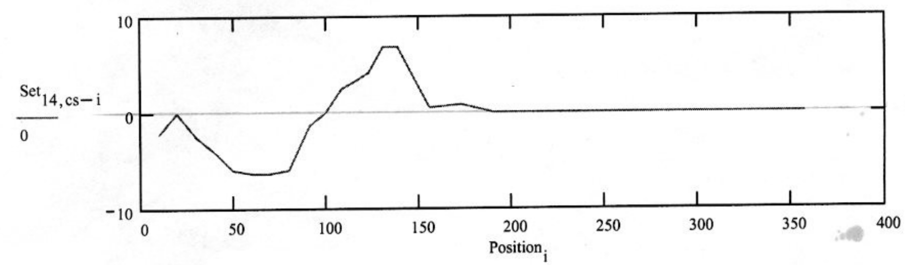
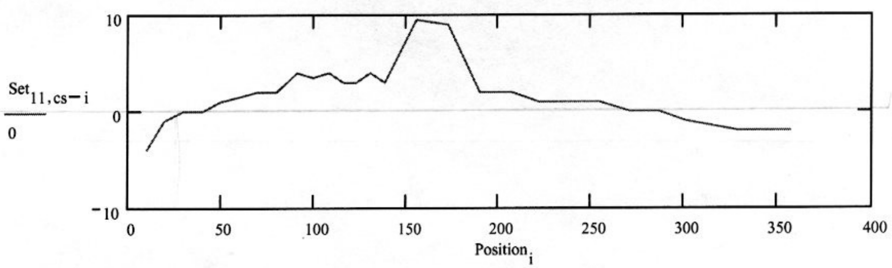
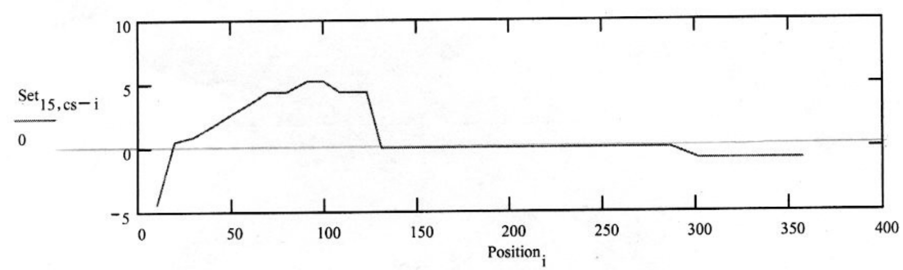


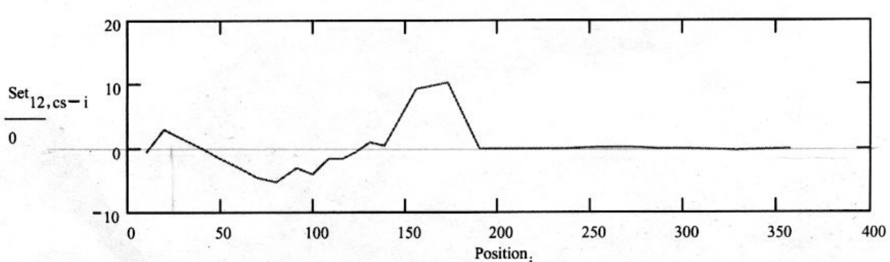
A1



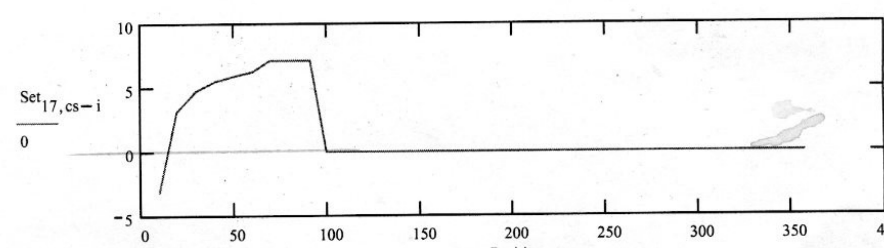
C#



A2



D'



toneholes and equivalent length

- tube with side-hole has, in general, similar resonance behavior to a somewhat longer one w/o hole.
  - 'equivalent' length
  - sometimes called 'tonehole end correction'
  - analogous to end correction of cylinder

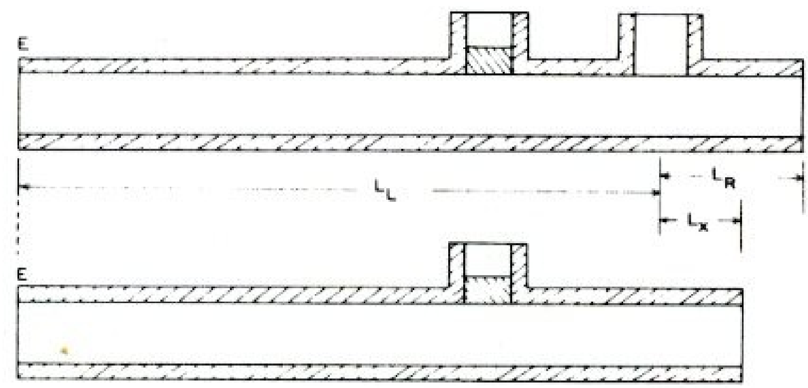


Fig. 15.2. Situation for a tube with two holes, one of which is stopped with a piston. Top: the real tube. Bottom: the substitution tube for the real tube.

side hole in a conical bore

- can be thought of as 'kink' in standing wave profile
  - may affect different modes to different degrees, giving rise to octave tuning issues

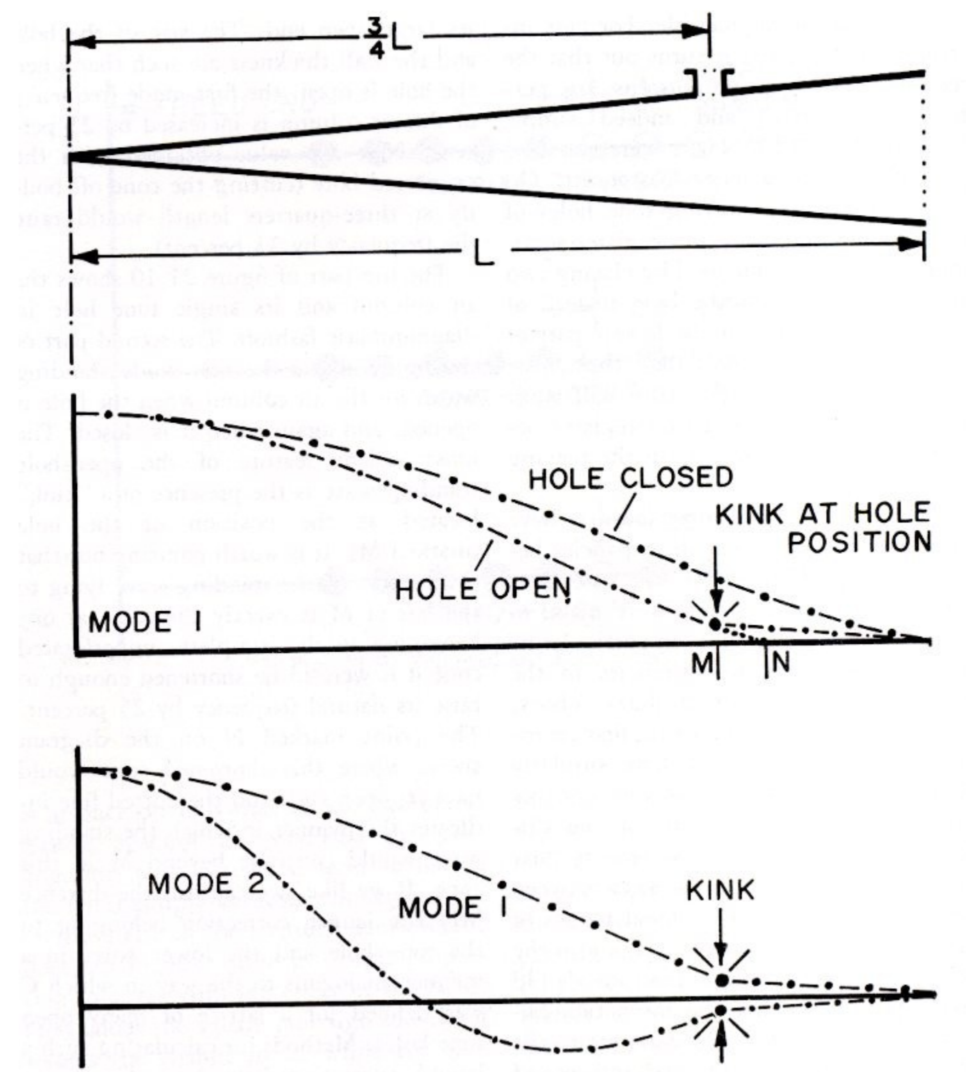


Fig. 21.10. Standing Wave Patterns for a Conical Tube Having One Open Hole near Its Lower End

tonehole effects (cont.)

- toneholes also effect the impedance of the bore even when closed
  - general rule is tha they make bore act 'wider' and 'longer'

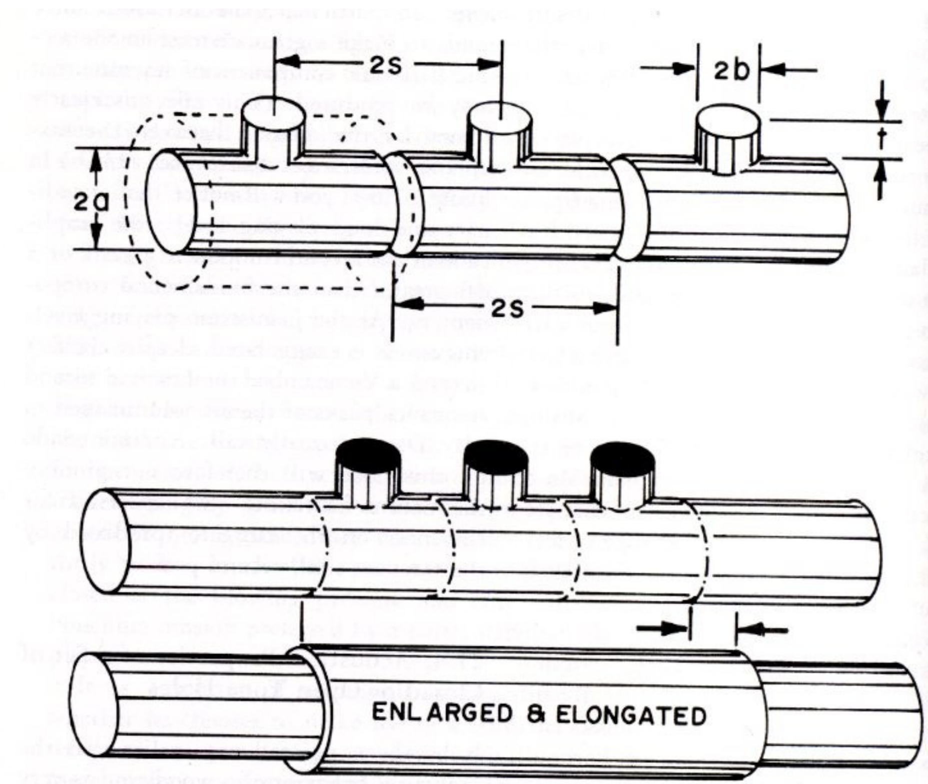


Fig. 21.8. *Top,* representation of woodwind tone holes on their air column as a series of shaped sections; *bottom,* closed tone holes effectively enlarge and lengthen the air column.

tonehole size effects

- effective 'length correction' depends on diameter, 'chimney', shape
- small holes encounter boundary layer conditions, turbulence, etc.
  - mitigated by rounding edges
  - rounding edges generally reduces turbulence and damping

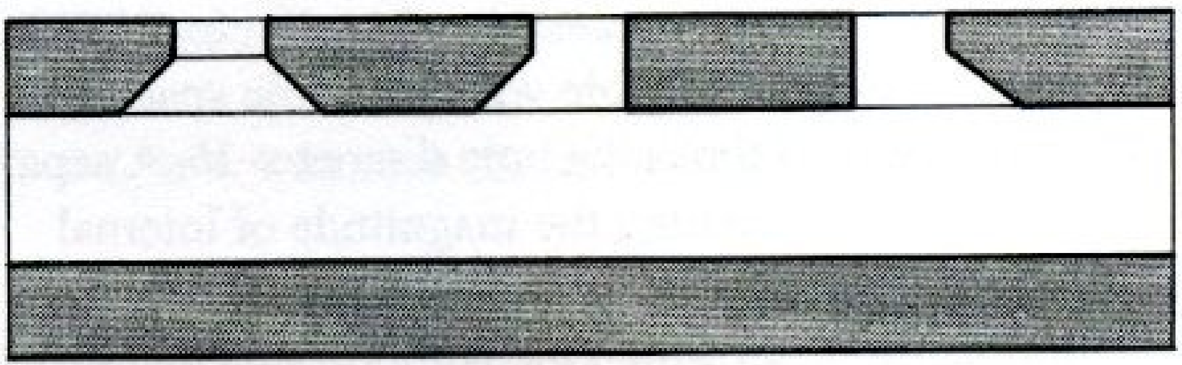


Fig. A3.6. Undercutting of holes, symmetrical (left), upstream (middle) or downstream (right).

tonehole size effect on peak alignment

- in general larger toneholes reduce effect of “counter bore”, maintaining resonance peak alignment
- there are particular values where new alignments appear
- perturbation required in most cases to correct

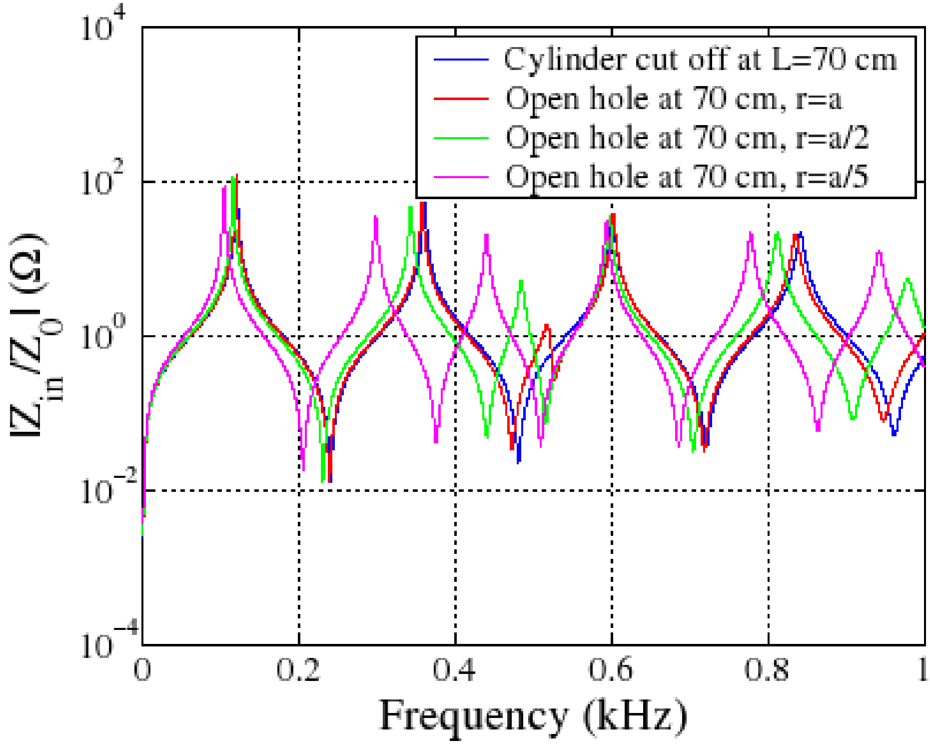


Figure 2.11: Normailsed input impedance magnitude of a cylindrical tube of length $L = 1$ m and $r = 2$ cm with a tone hole placed at $L = 70$ cm of different radius

'foot length' effect on peak alignment

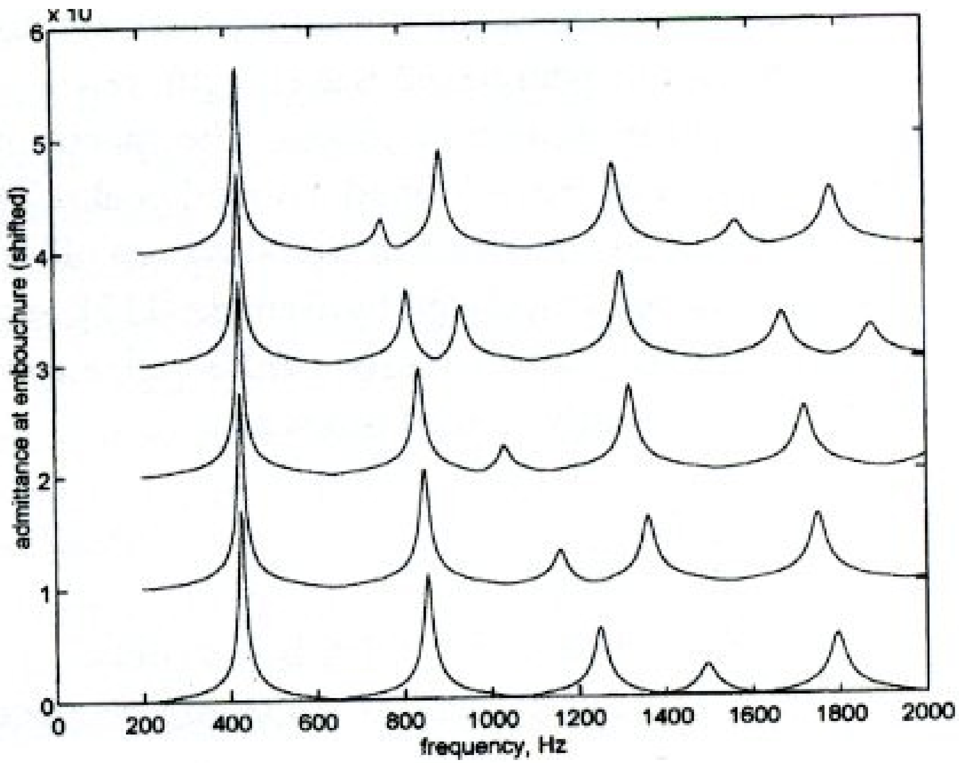
- 

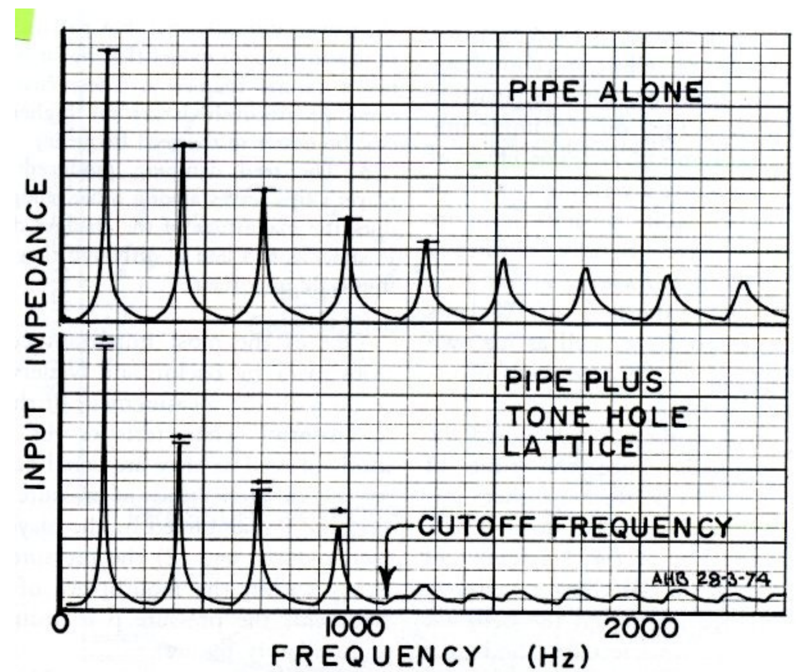
Fig. A6.3. Admittance spectra of a flute with one open hole, where the right-hand tube piece length L_R is stepwise increased in length, starting with 0.1 m and stepping up with 0.025m. Left-hand tube piece length L_L is 0.379 m, hole radius is 9.5 mm, and (transformed) hole length λ_H is 22 mm. The plots are shifted vertically for better visibility.

tonehole dimensions

- undercutting
  - increases effective diameter
  - reduces turbulence
  - increases closed-hole perturbation
  - reduces damping
- enlargement
  - increases closed-hole perturbation
  - increases cutoff frequency
  - reduces damping
- scalloping
  - reduces chimney height
  - increases effective diameter
  - reduces closed-hole perturbation

cutoff frequency

- peaks (and consequent resonance behaviors) mostly disappear above 'cutoff frequency' for open tonehole lattice
  - different when played 'closed'
  - actual effect on harmonic content is complex, since above cutoff, reflection is low but radiation efficiency is high



stopped pipes, cross-fingerings, and other problems

- end correction depends on mode, for long 'foot' sections
- the 'zombie zone'
  - neither dead nor alive

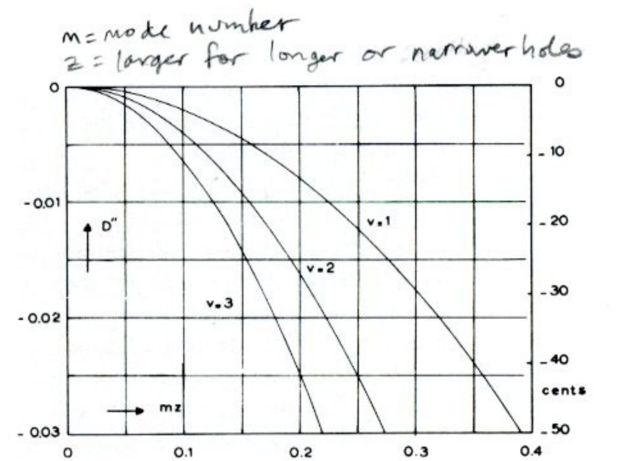


Fig. 32.4. Difference between first and second-order calculation of the resonance frequency as a function of the product *mz*, for various frequency shifts, plotted for three different shifts when opening the hole, expressed in number of semitones *ν*.

boundary layer and materials effects

- wall losses exceed radiation losses 10:1
- these losses are due to air viscosity and drag
  - can't change air viscosity, but can reduce roughness, porosity, etc.
  - also thermal losses – do thermal properties matter?
    - $pV = nRT$
- air column instruments very different from soundbox instruments, so many arguments from soundbox experience/theory do not apply
  - infinitesimal wall movement (though we can feel it at fingerholes)
  - virtually zero transmission to air

damping and end corrections tend to flatten pitch

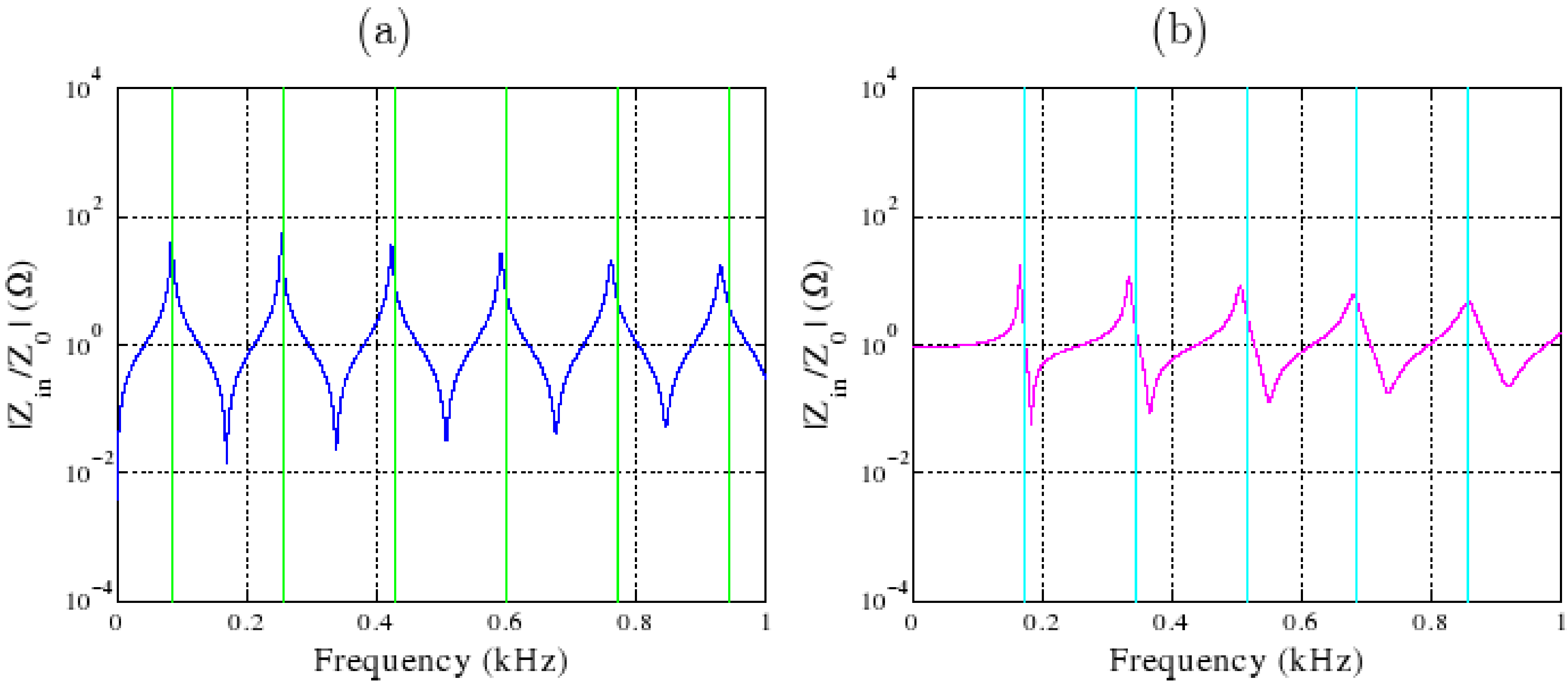


Figure 2.9: Normalised input impedance magnitude of (a) cylinder of $L = 1$ m and $r = 2$ cm open at $x = L$ and (b) truncated cone with $L = 1$ m, $r_0 = 10$ cm and $\theta = 3^o$, open at $r = L^*$, taking into account viscous and thermal drag, as well as end correction effects due to the change of impedance at $x = L$ and $r = L^*$ respectively. The green/cyan lines show where the resonant frequencies would lie, without taking into account wall losses and end correction effects

tuning and temperament

- tuning changes with temperature because speed of sound depends strongly on T
  - causes octave relationship changes between wet-blown and dry-blown conditions
- meters are almost always set to 'equal temperament', which is not ideal for pipes
  - 'ET' divides octave (2:1) into 12 equal ratios (12th root of 2, i.e. about 1.059)
  - also meters tend to look for high amplitude partial, which isn't usually the fundamental

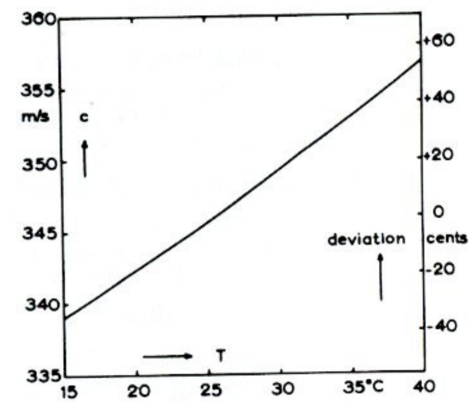


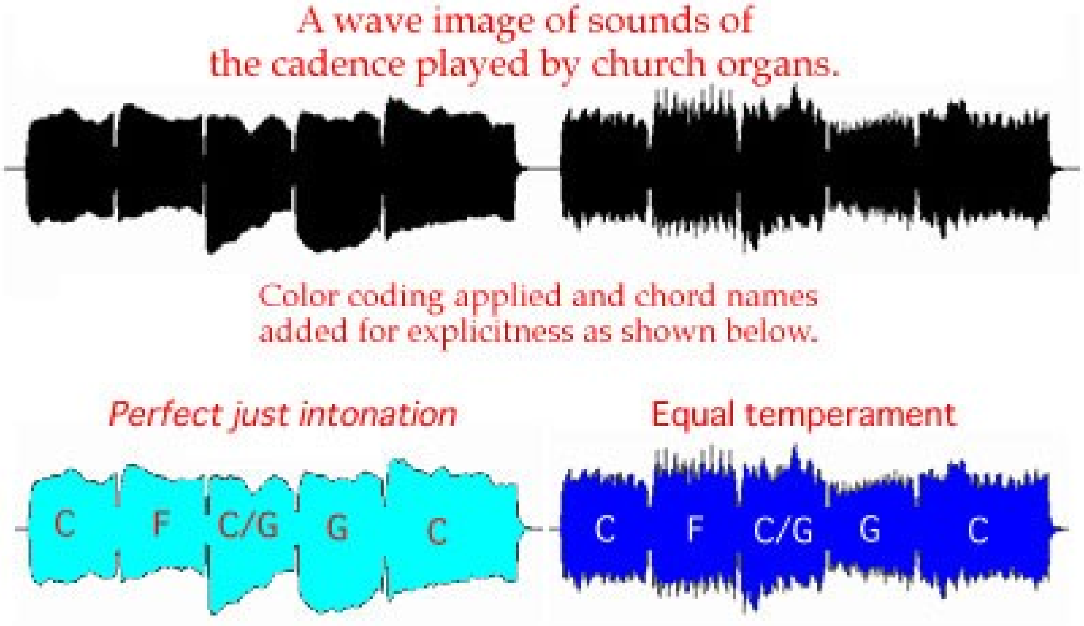
Fig. 22.1. Velocity of sound in free space as a function of temperature for air saturated with water vapour and containing 2.5 % CO_2. On an additional scale the deviation in the tuning with respect to the adopted value at 25.5°C is plotted.

Just Intonation

- equal ratios between intervals, or between drone/tonic and note
  - i.e. 3:2 is “major fifth”, i.e. A/D
  - corresponds to node/mode relationships we've seen before
  - 'partials'/harmonics of a single air column are always JI
  - thus JI means notes are in perfect consonance with drone harmonics
    - a few limits apply: for instance if E and A are both perfect to the drone, they won't be perfect against one another, etc.

Just Intonation (cont.)

- allows particular intervals to sound more pure
- not possible to make all intervals between 12-tone scale pure – thus one must choose preferential keys or reference tone
  - in our case the drone/tonic is the reference



every little thing...

- effect of bends
  - makes tube seem fatter

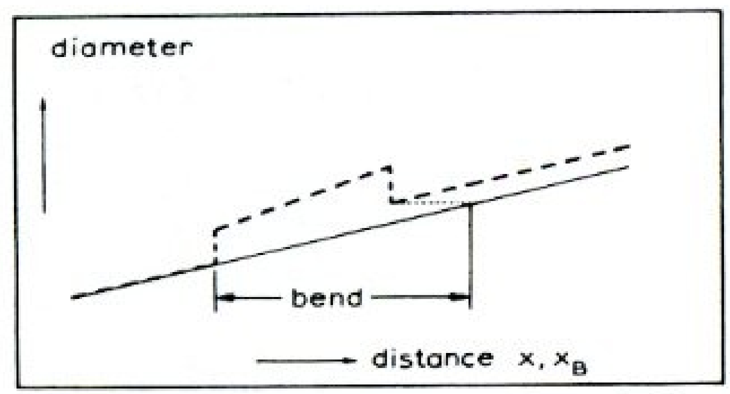


Fig. 37.2. Example of a conical bore before and af
correction for a sharp bend — = measured alo
centre line, – – – = apparent diameter, as a func
of apparent distance x_B

Scaling to different pitches

- sometimes said that narrower bores yield lower pitch; this is generally false
  - of course narrowing certain parts of the bore may lower pitch
  - in extreme cases the increasing viscous losses, damping, and boundary layer effects *do* lower pitch, but not a lot
- simple linear scaling along length fails
  - cone angle differs
  - requires atypical reed

Scaling (cont.)

- Benade concluded that this was a “hard problem”
  - advocated keeping very top of bore unchanged
  - seemed to advocate retention of cone angle
  - requires non-obvious chimney and tonehole size adjustments if similar “tone” and feel are desired
- Coyne seems to have conceptualized it differently
  - lower pitch means “extending” the existing bore
  - ergononics dictated tonehole placement, which was empirically adjusted

demos

- hacksaw blade
- tube (stopped & open)
- balloon pop
- ball-and-paddle

key points

- soundbox instruments very different from air column instruments
- woodwind acoustics is in its infancy; beware of oversimplified formula and/or statements of cause/effect
- our pipes present a particularly difficult case, and many first-order approximations fail
  - be especially wary of borrowing uncritically from flute lore
- acoustics can provide a framework for thinking about some paradoxical phenomena, and for carrying out experiments

Bibliography

- Arthur Benade, *Fundamentals of Musical Acoustics, 2nd Ed.*, 1976.
- Fletcher and Rossing, *The Physics of Musical Instruments*, *2nd Ed.*, 1998.
- C. J. Nederveen, *Acoustical aspects of woodwind instruments, revised edition.* 1998.
- Sandra Carral Robles Leon thesis (*Relationship between the physical parameters of musical wind instruments and the psychoacoustic attributes of the produced sound*), University of Edinburgh 2005
- *wikipedia 'Acoustics' is not bad...*