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Making woodwind instruments

3a- Practical acoustics for woodwinds: sound waves and tuning

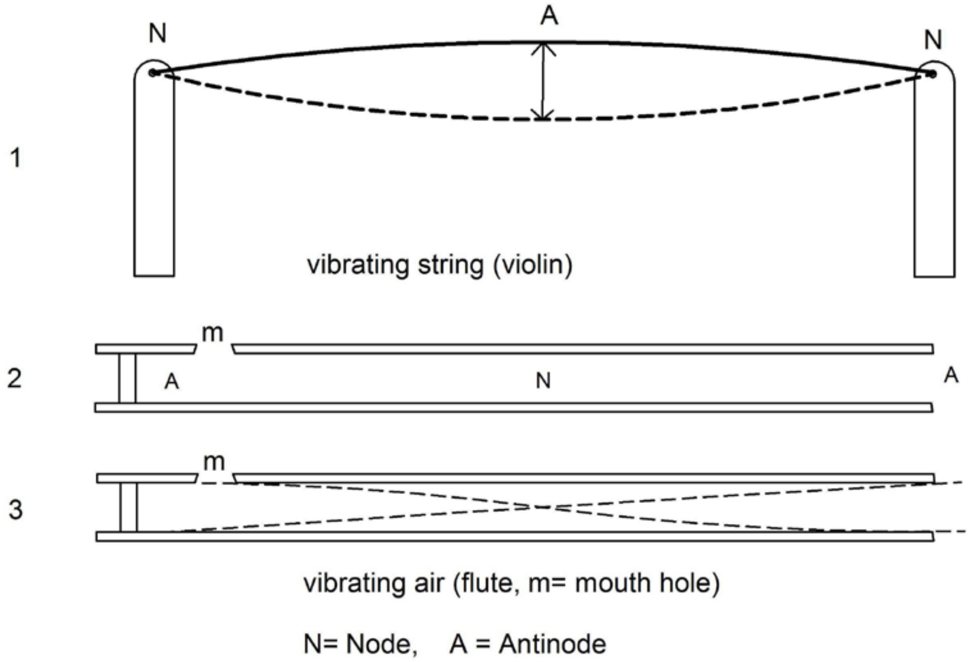
Acoustics of music and musical instruments is a very old science: according to the legend Pythagoras (*c*.569-507 BC) discovered the relation between harmonic intervals and mathematical equations: simple ratios such as 1:2 for octaves, 2:3 for fifths, etc.
But this branch of acoustics is by no way a simple science: delving further into questions about pitch and sound you will find complex problems and formulas which can only be understood when you have a reasonable knowledge of physics and mathematics.

What did the instrument makers in the 17th and 18th centuries know about the physical and mathematical aspects of sound? They must have had a lot of practical experience and knowledge, for instance that a sound produced by an instrument always (or almost always) exists of a complex of several harmonic components: a fundamental and its overtones. Jacob van Eyck, the blind flute and bells player from Utrecht, discovered in the 17th century how to change the profile of church bells to achieve a better relation between those harmonics; as a result of his research the Hemony brothers could forge bells which were much better in tune. Woodwind makers must have made similar discoveries, but they (or other people) didn't write about them. And I believe that the makers who developed new types of instruments (for instance during the introduction of baroque types of woodwinds at the end of the 17th century) must have learned a lot of their experiments. And this is a guide for modern makers: do not put all your efforts in only making exact copies of historical instruments, but give also some time for carrying out experiments. A simple start is scaling a flute or recorder into a different pitch (for instance in a=440 Hz, where the original is a=400 Hz).

Generator and resonator

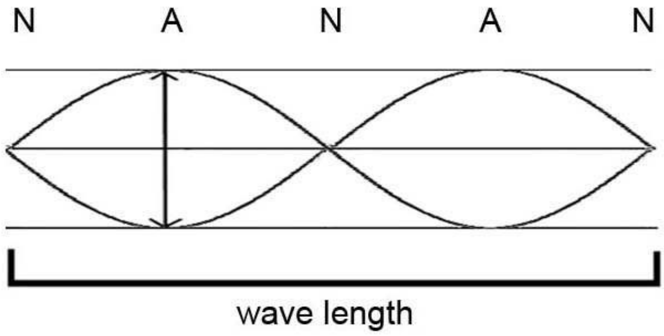
Sound waves exist as variations of pressure in a medium such as air. They are created by the vibration of an object, which causes the air surrounding it to vibrate.
All woodwind instruments have a generator where the vibrations are produced: that is for recorders the edge of a labium, for traversos the edge of the mouth hole, for oboes the (tip of the) reed. The behaviour of the vibrations is largely determined by the properties of the resonator behind that generator and which amplifies the vibrations and modifies them to create the sound of the instrument.
The resonator is for woodwinds the bore of the instrument and the pitch of the sound depends on the length and shape of the bore and how many tone holes are opened (some other factors play also a role, which will be discussed later). Part of the energy of the sound wave escapes through the holes of the instrument and arrives in our ears. The vibrating air then causes the human eardrum to vibrate, which the brain interprets as sound.

This section about acoustics deals mainly with the behaviour and properties of sound waves in the resonators and how to measure this. My aim is to present the information with a minimum of theory and formulas. But some basic principles must be known, for instance concerning the nodes and antinodes of sound waves. For more information there are many websites on the internet which provide explanations on all levels, with videos of vibrating strings and sound waves in woodwind instruments.



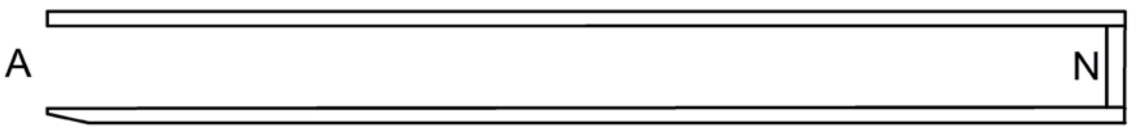
A vibrating string on a violin (1 in the figure above) makes clear that sound has indeed to do with vibrations. Exactly in the middle between two fixed points where the string can't move (the nodes, N) is the point were the motion is at is maximum: the motion antinode (A).

On woodwind instruments there are no strings, but just the (invisible) air molecules that vibrate. The figure above shows (2, 3) a flute in cross section (all fingerholes closed). But here we find two motion antinodes (A) where the air can move freely: at the mouth hole and at the lower end of the tube. As I will discuss later: the vibrating air column protrudes at both ends, and how far depends of the size of the mouth hole and the diameter of the bore. In between, in the middle of the tube, is a motion node (N). The distances between the nodes and antinodes define the length of the sound wave, which is inversely proportional to the frequency, the number of vibrations per second which is measured in hertz (Hz).



The distance between three nodes (covering two antinodes) is by definition the wavelength, see figure.

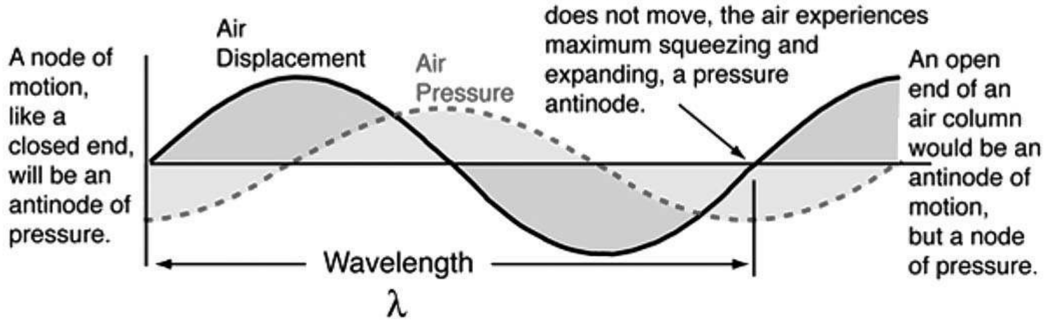
That means that in the example of the flute we see only the half of the wavelength. On a pan pipe it is even only the quarter of the wavelength, as the lower end (right on the drawing, see below) is closed on that instrument.



Air motion, pressure and impedance

In all handbooks about acoustics of musical instruments much attention is given to ‘impe-dance’, an important concept for understanding the physics of sound waves.
The definition in Wikipedia: *Acoustic impedance and specific acoustic impedance are measures of the opposition that a system presents to the acoustic flow resulting of an acoustic pressure applied to the system.*
From http://newt.phys.unsw.edu.au/jw/z.html: *We discuss acoustic impedance on this music acoustics site because, for musical wind instruments, acoustic impedance has the advanta-ge of being a physical property of the instrument alone – it can be measured (or calculated) for the instrument without a player. It is a spectrum, because it has different values for different frequencies – one can think of it as the acoustic response of the instrument for all possible frequencies. For instance, we measure it at the embouchure of an instrument because it tells us a lot about the way the player's lips, reed or the air jet from the mouth will interact with the instrument itself. So it tells us about the acoustic performance of the instrument, in an objective way that is independent of who might play it, and it allows us to compare subtle differences between instruments. ...*
The acoustic impedance of musical wind instruments varies spectacularly with frequency because these instruments are designed to produce one or several frequencies only in a particular configuration. For example, the flute is played with the embouchure hole (at least partly) open to the atmosphere, so the pressure at the embouchure hole is very near to atmospheric pressure. Thus the acoustic pressure (the varying part) is nearly zero. The flow is provided by a jet of air from between the player's lips. Oscillations of air flow in the flute can cause this jet to deflect upwards (outside the flute) or downwards (inside) so that the acoustic flow can be large. Thus the flute operates at minima of Z (the unit of impedance): a small pressure and a large flow. Most other wind instruments have a reed which is sealed by the player's mouth and they operate at maxima of Z: the varying part of the pressure is large, but the oscillating part of the air flow is small at the reed.

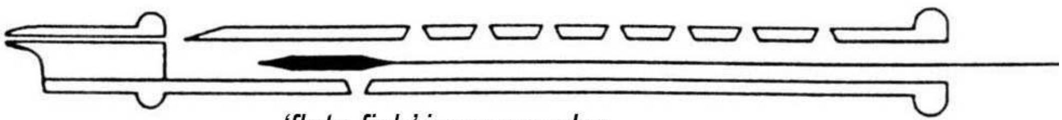
Do we really need to know all aspects of impedance? For me it is much more helpful (and much easier to visualize) what happens with nodes and antinodes of the sound waves in the instruments. It is important for woodwind makers is to know the positions of the nodes and antinodes for all tones. But first we need to know about the difference between motion and pressure nodes and antinodes. See the picture below:



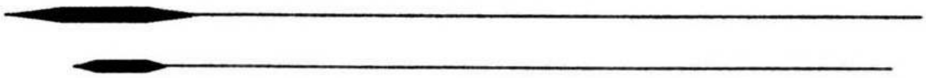
Picture from http://hyperphysics.phy-astr.gsu.edu/hbase/waves/standw.html#c3

The term motion antinode is used for the point of maximum motion (displacement) of the air, and node for the point of minimum motion. But for the air pressure at those points, it is just the opposite: where the air doesn't move (a motion node), is a pressure maximum, anti-node: a pressure antinode. These pressure maximums are important are important places in musical instruments because the transport of the energy of the sound takes place there: for instance the stem of a tuning fork placed on a resonator, or the bridge and the sound post to the plates (front and back) of a violin.

What can we do with the knowledge of both motion and pressure nodes and antinodes? For instance: changing the diameter of the bore at those points has direct influence on the pitch of those tones. Widening the bore at a motion node makes the pitch sharper, widening at a motion antinode just flatter. Making the bore narrower at both points gives the opposite result.
How do you find the nodes and antinodes in your instrument? The way most woodwind makers do that is by moving a 'flute fish' through the bore and listen what happens. The flute fish narrows the bore, and when it passes a motion node of the sound wave, the pitch of the tone will rise; when it passes an motion antinode, the tone will become flatter. Shorter wavelengths have shorter sections of nodes and antinodes, and for a more accurate measurement you must use a shorter flute fish. It makes no difference that with the flute fish the narrowing is in the centre of the bore, or somewhat offset, or close to the walls. You can get the same results by rolling up a piece of paper and put that in the bore: it unfolds itself against the wall (avoid covering of the tone holes).



'flute fish' in a recorder



two sizes of a flute fish

As you can see on the diagram on the next page, there are many 'conflicts' between nodes and antinodes of different tones. Be careful: making a bore wider in a section makes one tone sharper, and perhaps another flatter. But that is sometimes just what you want!
For instance: in the upper section of the upper middle joint are the (motion) nodes of several tones of the first register, and at the same places antinodes of the same tones in the second register. Widening the bore at these sections results in the first register tones beco-ming flatter, and those of the second register sharper: the octave intervals will become wider. In the upper part of the lower middle joint are the motion nodes of d2 and d#2/e-flat2, and no nodes or antinode of d1 and d#1/e-flat1. Widening the bore here will result that d2 and d#2/e-flat2 will become flatter, thus making the octave intervals smaller.
However: the first thing to check when the octave intervals on a traverso are false, is the position of the cork in the head of the instrument. I will discuss that in a later article, but whoever wants to know more may read my article 'Tuning the traverso' in FoMRhI-Q. 41 (1985), p. 25-31.

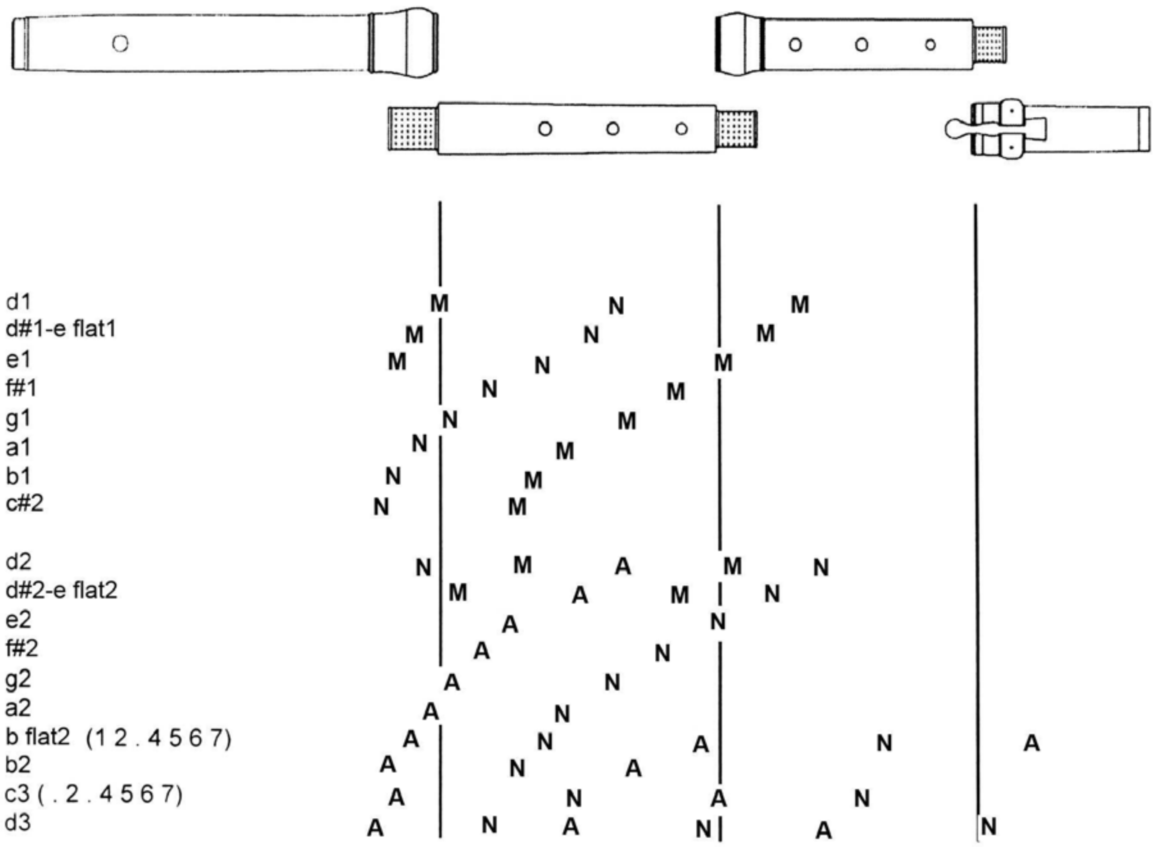


Chart of the approximate position for a selection of tones of the motion nodes (N) and antinodes (A) on the middle joints on a baroque traverso (with d1 as lowest tone). Not depicted: the nodes and antinodes of these tones in (or just outside) the head and the foot of the traverso. M means: narrowing (or widening) the bore has no effect of the pitch of the tone.

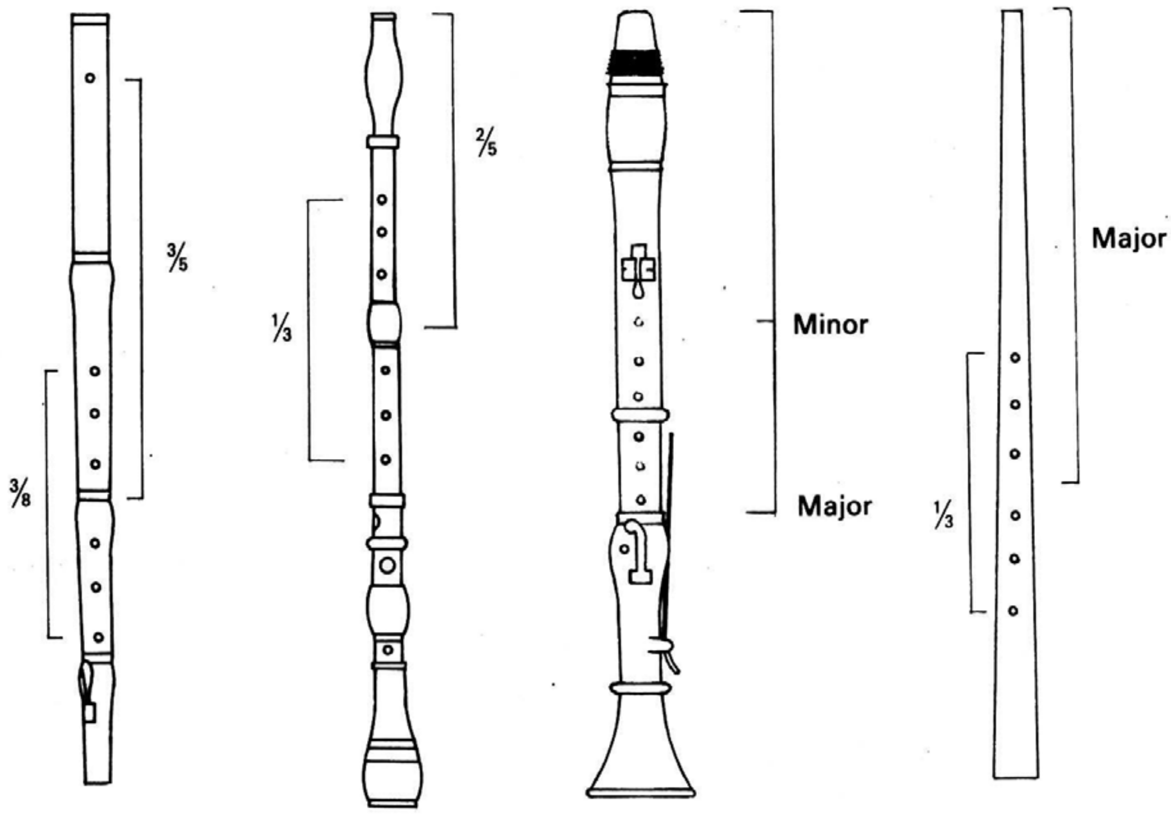
Sounding length

Can we predict or calculate the length of instrument, for instance when we want to make a traverso or recorder? The simplest example is the renaissance traverso with a cylindrical bore. For instance: the tone d2 has a frequency of 587 Hz and a wavelength (in free air) of 582 mm. For a picolo renaissance flute with d2 as its fundamental, half of the wavelength is 291 mm. But that is not the sounding length of the instrument: the distance between the centre of the mouth hole and the lower end on my picolo is only 253 mm. This difference of 38 mm from the acoustical length indicates that the sound wave indeed sticks out at the mouth hole and the end of the bore. But how far at each end? I found in publications (see below) that the correction for the end of the bore varies from 30 to 40% (or even more) of its diameter: for a bore of 12 mm gives that between 3.5 to over 5 mm. That means that wider bores have a longer end correction, which is a reason that of two flutes with the same length the wider one will have a lower pitch. The mouth hole correction is much greater; it can be calculated, but the formula is complicated and includes factors for the size of the hole, wall thickness and the diameter of the bore. It is enough to know that smaller holes have longer corrections (the hole on my little flute is very small, about 7.5 mm). The correction for a renaissance traverso in d1 with a (rather wide) round mouth hole of 10 mm is about 40 mm and for a modern Böhm-flute 30 mm.

For those who can read German: the small book *Zur Akustik der Blasinstrumente* by Otto Steinkopf (Edition Moeck, No. 4029, first published in 1983) gives interesting information, including tables and formulas. See also on internet the article by Paul of Krae Glas about some acoustical aspects of medieval and renaissance wind instruments: http://www.logarithmic.net/pfh-files/design/Medieval_Wind_Instruments.pdf

General rules for tuning woodwind instruments

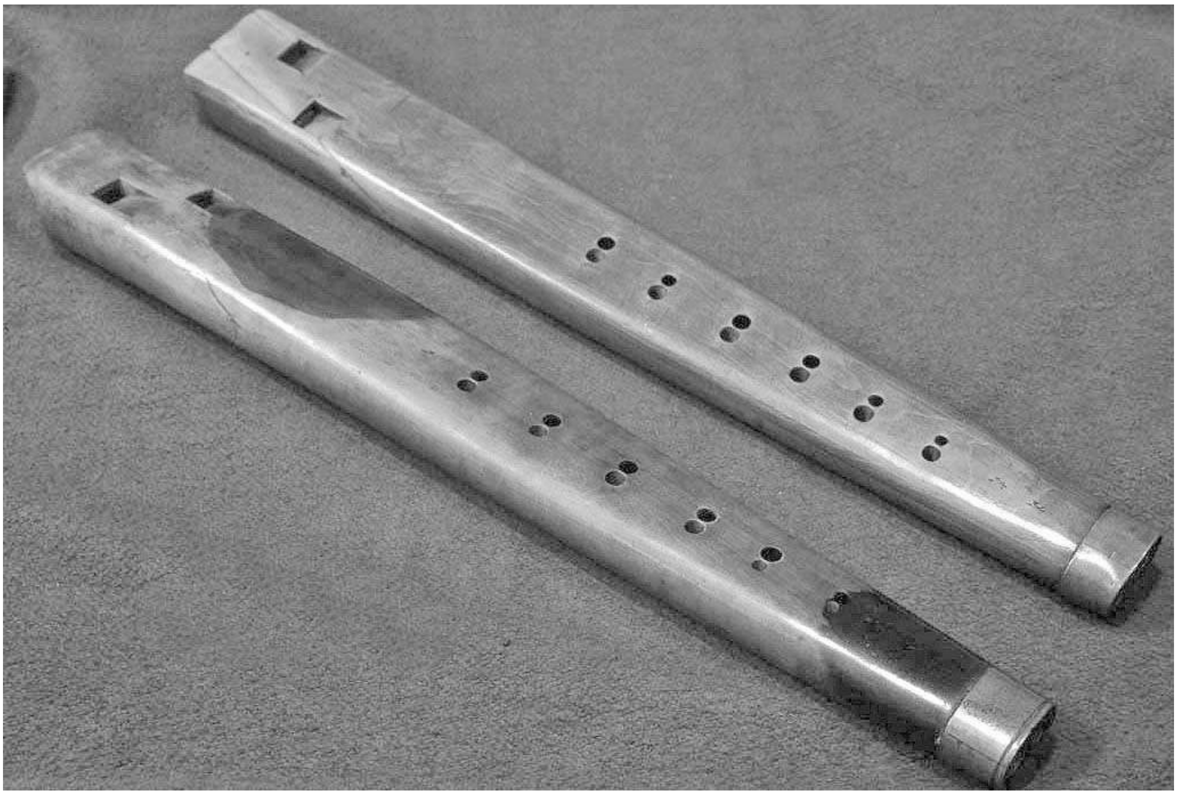
How do you know the position and size of the tone holes? I am often asked this question, and the answer is not simple. It makes a difference whether you are designing a new instrument, or making an exact copy after an existing one.

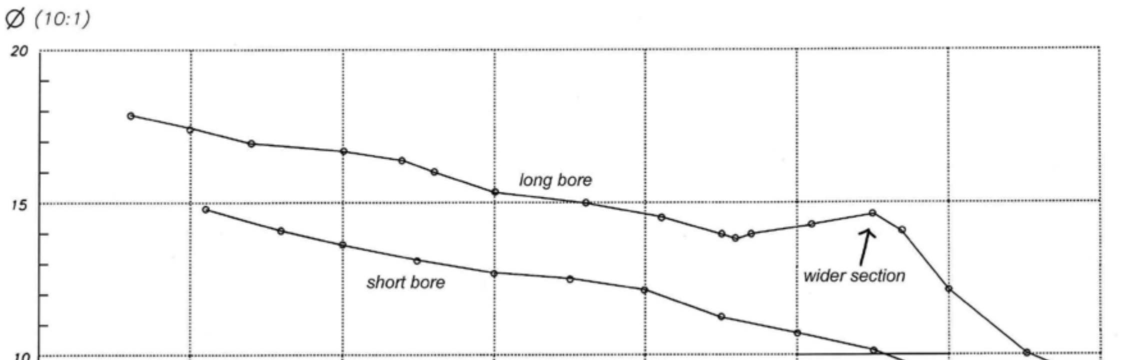


From: Herbert Heyde, *Musikinstrumentenbau, 15. - 19. Jahrhundert, Kunst- Handwerk Entwurf* (Leipzig 1986). Proportions of a traverso, oboe, clarinet and cornetto ('stiller Zink'), p. 183.

It is likely that woodwind makers have used proportional schemes when they designed new types of instruments. But they had also to consider the stretch of the fingers of the players and acoustical aspects: the tone holes should not differ too much in size, this for the uniformity of sound. And it is quite normal to find differences between what are supposed to be the 'ideal proportions' and the real dimensions of the instruments.

As a rule it can be said that for a given bore profile, the position of the tone holes of instruments which play over more than one register is very well established. But also it is to a certain extent possible to design a bore profile for a given positioning of the finger holes. This is especially the case with a double recorder: two sets of finger holes must have the same positions, but they belong to parts of the instrument which differ a third in pitch. The bore profile of both parts are completely different, and so do the sizes of the holes. See the photo and the graph below.





Two double recorders by Michiel Parent (Amsterdam, 1663-1710), in the collection of the Musikinstrumentenmuseum, Berlin, Germany. Inventory number: 2832 and 2833.
The graph of the bore is of the left instrument on the photo. Parent has made a correction (between L 225 and L300), for adjusting the pitch of some tones; but how had achieved this wider section of the bore?

Making a copy is easier than designing an instrument; it is essentially drilling the tone holes in the same place and with the same size and shape as on the original instrument. But that is not what I normally do: I drill the holes always a little (for instance 10%) smaller, which allows me to make some corrections or adaptations when I tune the instrument. It might be wise for the same reason to leave the bore at some critical places initially a bit too narrow, e.g. middle joint of a (baroque) recorder. Tuning implies:
enlarging and undercutting the holes (which raises the pitch of the tones),
and sometimes also making bore corrections (which raises or flattens the tone, depending of the nodes and antinodes involved in the sound wave of the tones). All this will change the position of the nodes and antinodes of the soundwaves, resulting in a change of the wave length and the pitch of the tone.
The thickness of the wall at the tone holes plays also a role. This mainly because a thicker wall results in a bigger inner space of the tone hole; and as we only cover the top of the tone holes with our fingers (or a key) and do not fill them in, these hole spaces add up to the volume of the bore of the instrument, making it effectively wider or longer. One of the consequences is that the pitch of a recorder or flute without finger holes is clearly sharper than of the same instrument on which the holes are drilled and covered. For an alto recorder the difference might be about 20 cents.

Tuning recorders and traversos begins at the lowest tone hole. As the fundamental has no tone hole, we can only make a bore correction in the lower end of the foot. The other solution for raising the pitch of the fundamental is shortening the foot or one of the other joints. Or on a traverso you can make the mouth hole a little larger, and for a recorder the window (or reduce the thickness of the wall around the window). So, what to do?
My advice is: leave the pitch of the fundamental as it is, for the time being, certainly when you are making a copy after a historical instrument and you are not sure of its original pitch. Do not force the pitch of your copy into what you think what it should be, give your copy the chance 'to be itself'.
Go further with the next step (on a recorder hole 7 on the foot, then hole 6), and see (or hear) what happens there. You will then get a better idea of the appropriate pitch of your copy. Small adaptations are possible, but it is not a good idea to raise the pitch too much by enlarging the finger holes: the balance between the tones will become more difficult.

Several holes are involved in more than one tone that must be tuned (also: the pitch and sound of one tone sometimes depends on several holes); that means that we must exactly know what happens when we enlarge or undercut a hole in a specific direction. The main rules are (for flutes and recorders):

1- enlarging a hole rises the pitch of the tones which are tuned on that hole, but does that as a rule more with the tones of the second than the corresponding tones of the first register; the size of the hole has also more influence upon the fork-fingered tones than on the plain (non fork-fingered) tones;

2- enlargement and/or undercutting of a hole downwards ('south') will raise the pitch of the tones of the second register even more than the corresponding tones of the first register;

3- when an octave interval is too wide, you must fill in the lower ('south') end of the hole, and enlarge it at the other ('north') side; another solution is to change the bore profile, which aspect will be discussed later in the articles about the instruments;

4- for an octave interval which is too small, it is generally enough to enlarge the hole at the south side;
5- undercutting a hole (a common practice on historical flutes and recorders, and which is done for a smoother sound and speaking of the tones) has often some more effect on the pitch of fork-fingered than on the plain tones;
6- the position in the bore is acoustically more important than that on the exterior of the instrument; but it is difficult to predict what exactly happens when a hole is drilled at an angle, fork-fingered tones seem to be more affected (depending on the direction of the angle) than the plain tones;
7- it makes no difference at all if a hole is moved to the side (left or right, thus not in a straight line with the other holes);
8- on key holes there is the effect of the key cover shadowing the hole, also here there seems to be an effect on fork-fingered tones, which tend to be too low (for instance on some modern bass recorders).

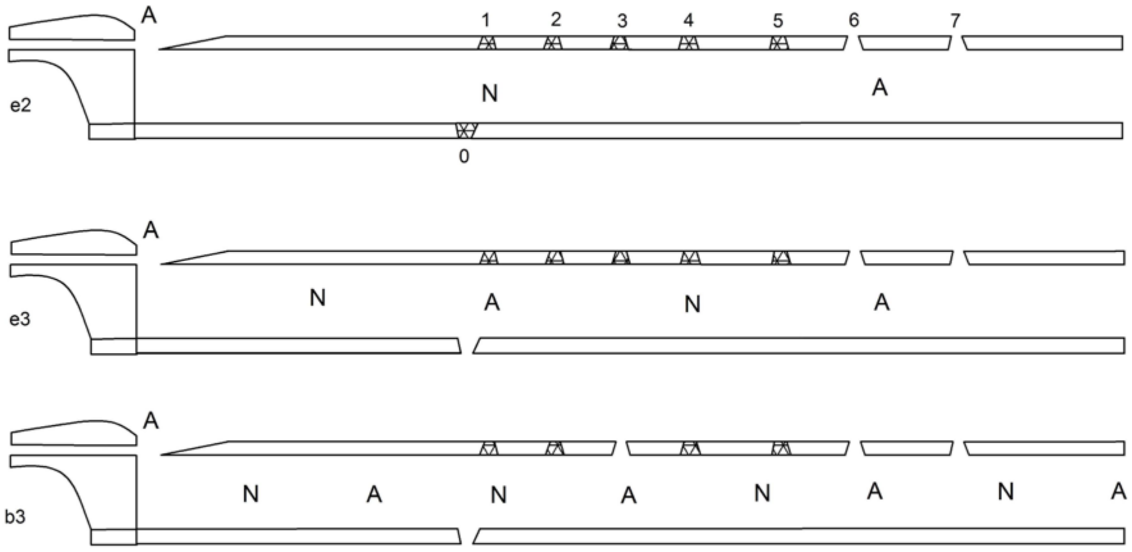
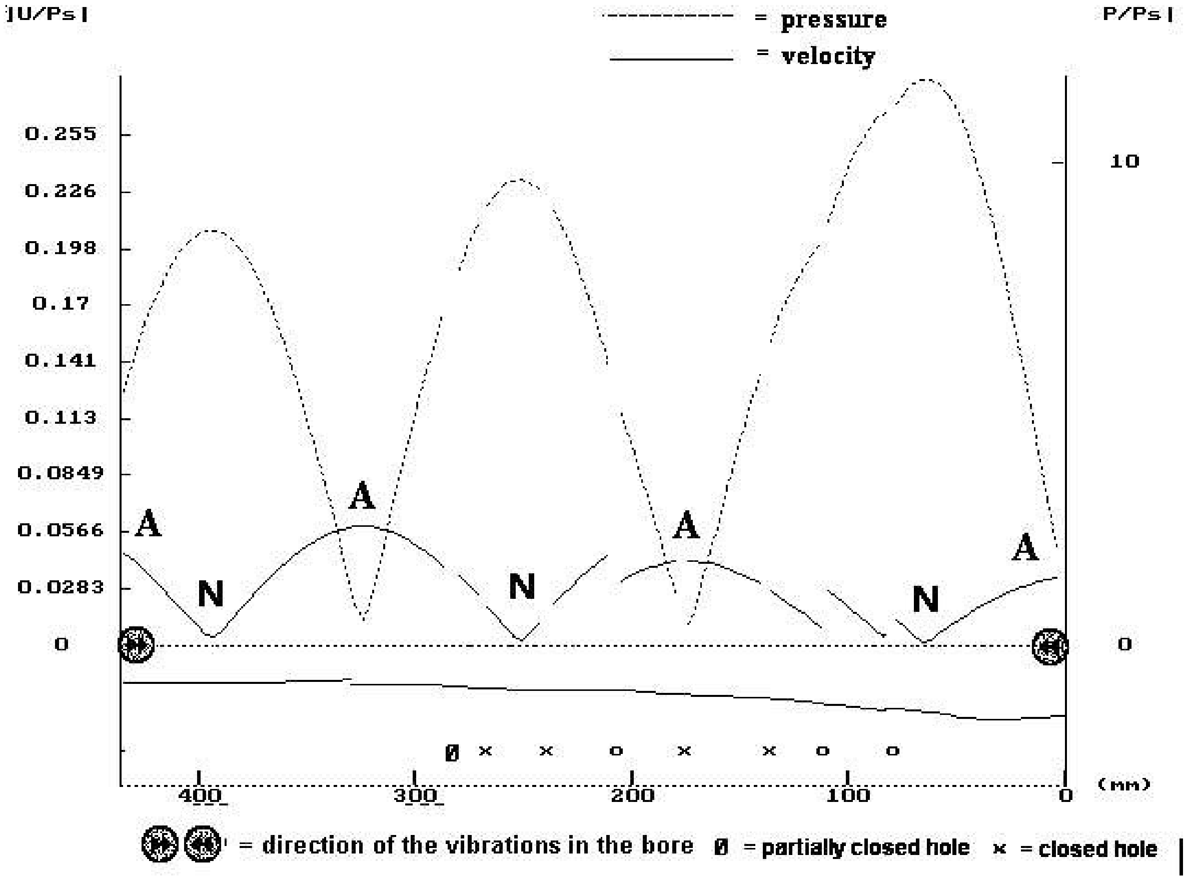
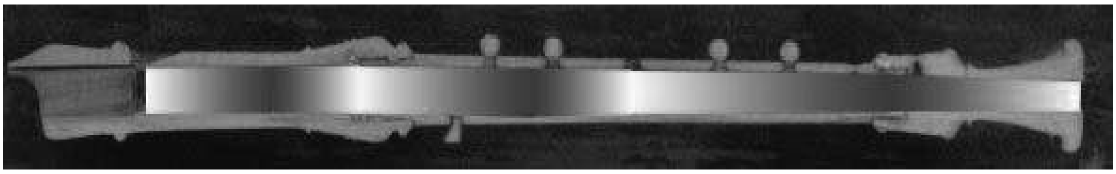


Diagram of a soprano recorder in c2, with a cylindrical bore.

Some holes on flutes and recorders have a double function: as a tuning hole and as an over-blowing hole. The size of the overblowing hole has no, or hardly any, influence on the pitch of the tone which is triggered by opening of that hole. In the diagram of the soprano recorder I have given the position of the motion nodes and antinodes for the first harmonic e2 (fingerings 0 1 2 3 4 5), the second harmonic e3 (same fingering, but hole 0 half opened as an overblowing hole, resulting in an antinode close to this hole) and for the the third harmonic b3 where hole 3 must be opened as second overblowing hole. This triggers in combination with increased wind pressurea new antinode close to hole 3 and overblowing in the duodecime (octave + fifth).
It is important to know that there are no nodes or antinodes for the first and second register notes e2 and e3 in the bore of the lower part of the instrument (from hole 7 to the end), but they are clearly present for the tones of the third and higher registers (from b-flat 3 onwards). One of my observations is tht making the foot of a recorder longer makes the fundamental lower, but does that much more with the tones of the third register.

The French recorder maker Philippe Bolton has an interesting website (bilingual, in French and English): http://www.flute-a-bec.com/. He explains in detail the sound of a recorder. The graphs on this page come from the section ‘The recorder's air column’.





This chart shows velocity (or motion) antinodes (A) and nodes (N) for the e3 of an alto recorder, which corresponds with the b3 of a soprano recorder (see previous page). There is one graph for velocity and one for pressure variations along the air column. This note belongs to the third register. The leaking thumb hole, combined with another open hole in the correct place inhibits the nodes of the first two registers and thus causes the air column to divide into three parts, giving a note a twelfth above the first register. There are three nodes here. Not only do the vibrations go up and down from the ends of the air column to the nodes, but also between the nodes, with maximum velocity at the antinodes.
The recorder's bore profile, and the open (o), closed (x), and partially closed (ø) holes are shown underneath: antinode sections are bright, node sections dark. In the high registers the air column uses the whole length of the instrument's bore.