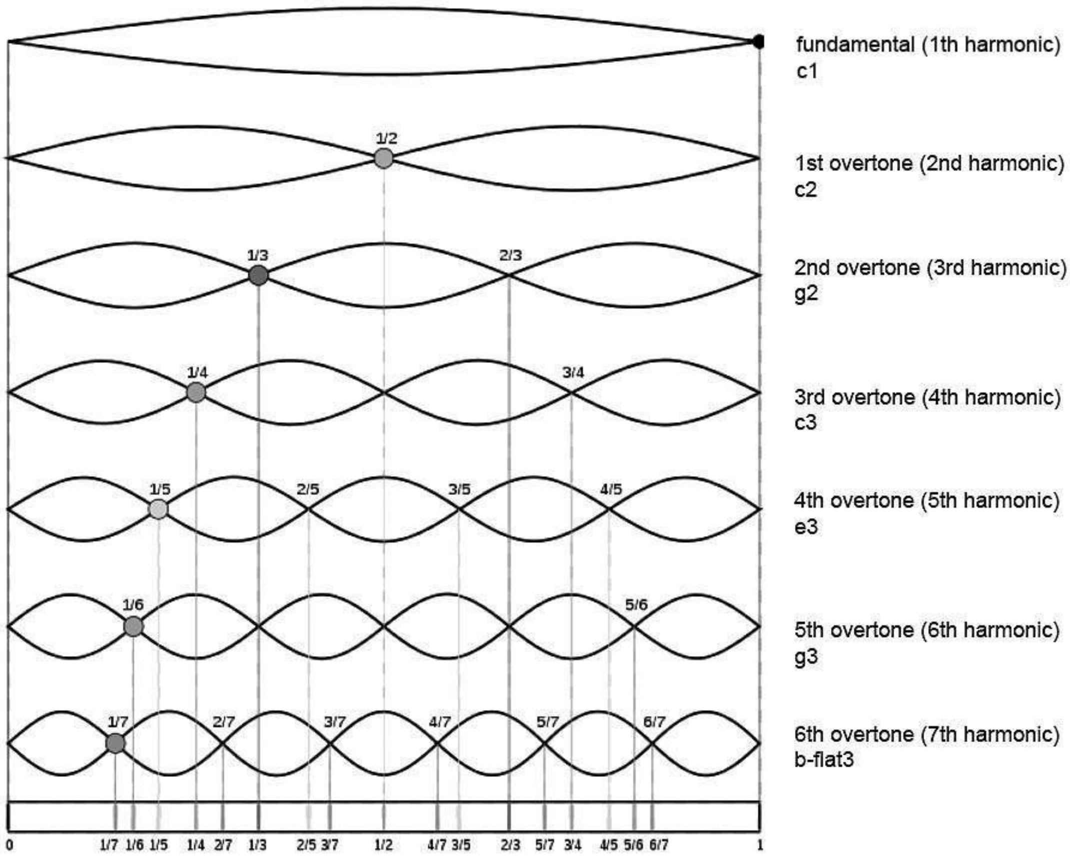
FoMRHI Comm. 2041 **Jan Bouterse**

Making woodwind instruments

3b- Practical acoustics for woodwinds: sound research and pitch measurements

Pure tones, fundamentals, overtones and harmonics

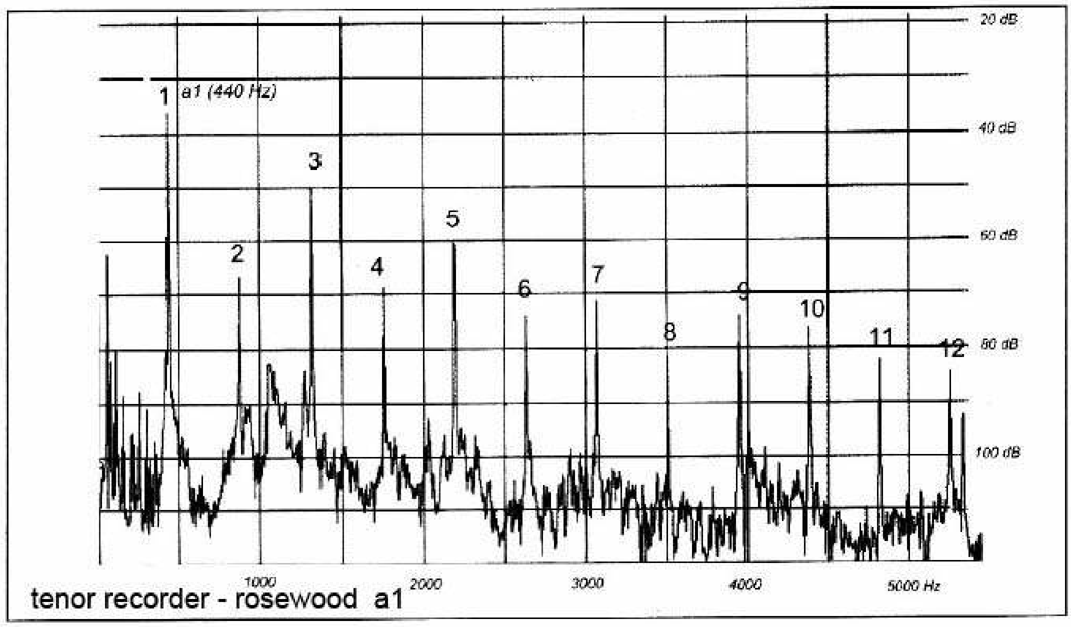
A so-called pure or simple tone has only one single frequency. But most acoustic instruments emit complex tones containing many individual partials (component simple tones), but the untrained human ear typically does not perceive those partials as separate phenomena. Rather, a musical note is perceived as one sound, the quality or timbre of that sound being a result of the relative strengths of the individual partials.
Many instruments and also the human voice produce complex tones that are more or less periodic, and thus are composed of partials that are near matches to integer multiples of the fundamental frequency and therefore resemble the ideal harmonics and are called 'harmonic partials' or simply 'harmonics' for convenience. Partials whose frequencies are not integer multiples of the fundamental are referred to as inharmonic partials.

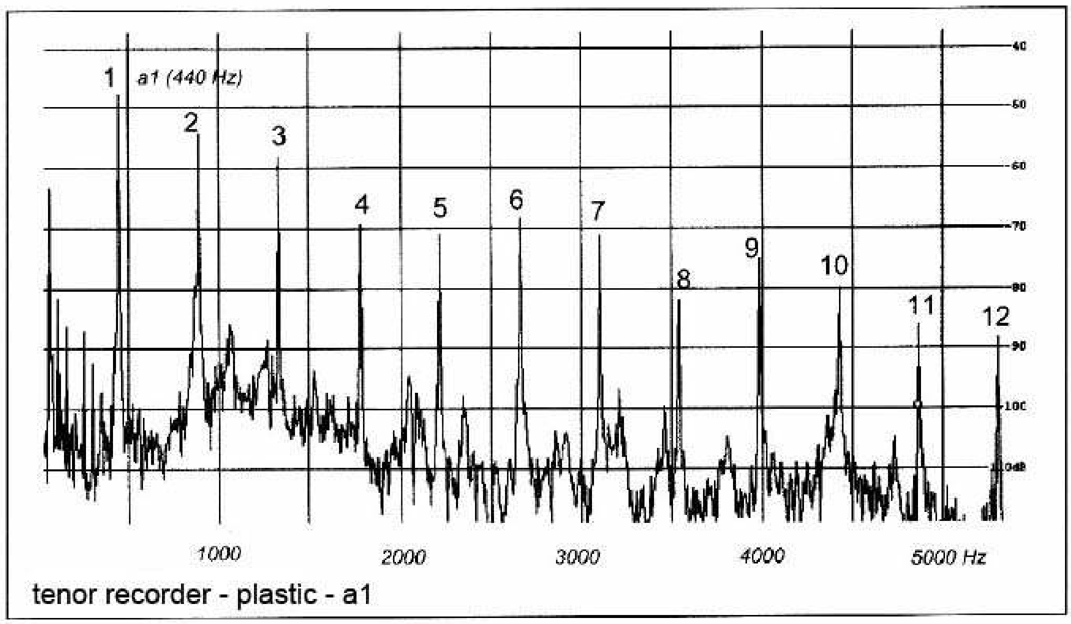


This picture shows the overtones on a vibrating string. Important to know: the fundamental is the 1st harmonic, the first overtone is the 2nd harmonic, et cetera.

It is nowadays possible to analyse the sound of your instrument and measure all those partials at home: you just need a computer or smart phone with a microphone and the right

software (which is free available on internet). Doing so, you will see that between the partials there is also ‘noise’, which is elements of the sound which have no frequency of their own. Noise is often described as ‘unwanted sound’, but that is not always true. A certain level of noise carries the harmonic components of the sound and blend them perhaps also better.
Without that noise the sound has a rather artificial character, such as can be heard on first-generation electronic organs.





Fourier graphs of two tenor recorders, showing the harmonics in the sound of the tone a1 (440 Hz). At point 2 is a2 (880 Hz), at point e3 (3 x 440 = 1320 Hz), point 4 is a3 (4 x 440 = 1760 Hz), point 5: c#4 (5 x 2200 Hz), etc. Visible between the peaks of the harmonics: the level of noise.

The graphs on the previous page were published in 'De Bouwbrief' (August 2004): Floor van Rijn, a 16-year old school girl had written an article for her physics lessons on the sound analysis of her recorders. What she discovered was that there were only very small differences between the Fourier-graphs of the instruments when she played them in the normal way. But by using a wind machine, the differences became much clearer. Conclusion: when we play woodwind instruments, there is always the tendency to manipulate the sound (that is possible even on recorders!) into a specific direction.

The odd harmonics (1, 3, 5, etc.) are on the rosewood recorder stronger than the even ones. On the plastic recorder we see a more gradual decline in intensity. What does that mean for the sound character? On a clarinet are the even harmonics largely absent, what causes (part of) the 'warm' or 'dark' sound of that instrument compared to the 'bright' sound of a saxophone.* See www.phy.mtu. edu/~suits/clarinet.html for more information about the sound of these instruments.

*: *the clarinet is a tube which has a (motion) node at the mouth end (with reed) and an antinode at the open lower end of the bore. This situation applies for all overtones of the instrument, which means that only the odd harmonics can be heard. The saxophone, however, which has the same type of reed, behaves like an instrument with two open ends, which means that the even harmonics too are present in the sound of the instrument.*

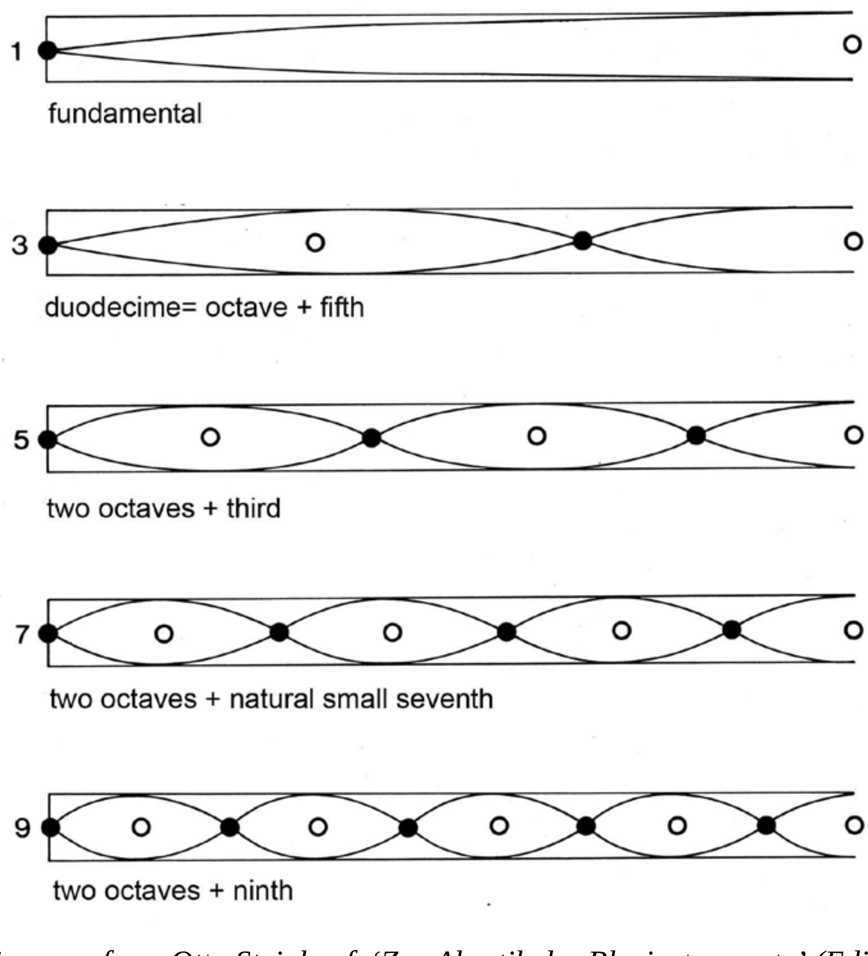
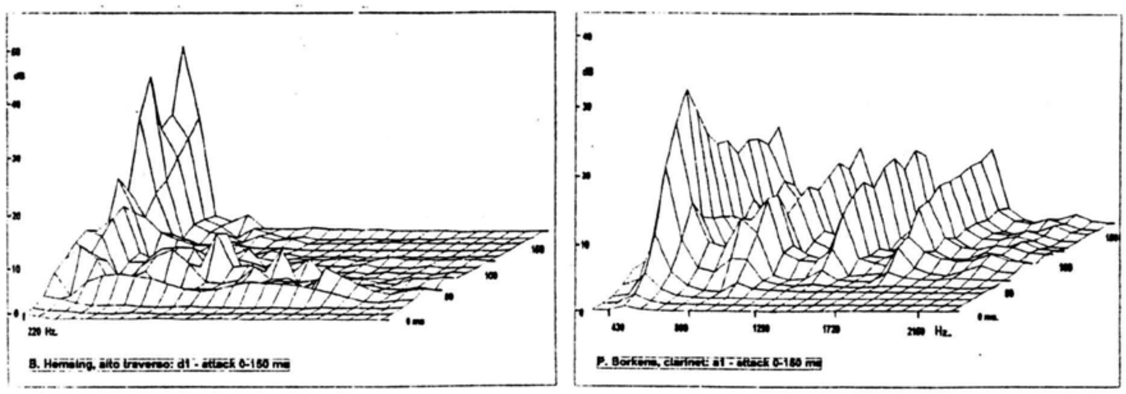


Diagram from Otto Steinkopf, 'Zur Akustik der Blasinstrumente' (Edition Moeck, 1983).



On the left picture the development of the sound of flûte d'amour by Bernard Hemsing, and on the right one a clarinet by Philip Borkens. The frequencies are depicted on the X-axis (from left to right), the intensity of the sound on the Y-axis (upwards) and the time (in milli-seconds) on the Z-axis (backwards). From Rob van Acht: 'The sound quality of Dutch wind instruments from the baroque period: the project (1)', Proceedings of the Institute of Acoustics, Isma '97 Conference, p. 533-540. Edinburgh 1997.

What also has to be considered is that it takes some time for the sound to develop. The attack, what happens in the first milliseconds of the sound wave, is very important in recognising the instrument: when leaving out the attack it is often surprisingly difficult to hear the difference between a violin or a trumpet, for instance. The flute by Hemsing has a rather soft attack, the lower frequencies develop after some time, and the upper harmonics - so characteristic for the attack - soon fade out. On the clarinet it is all different: the first harmonic (fundamental) appears rather soon, directly followed by the upper harmonics which stay strong.
As I mentioned before: it is possible to carry out sound measurements at home. But it is not so simple to do that in a really professional way. You need to make the room very silent, using isolation materials which absorb all reflections. The microphones must be of a very good quality (much better than on your smart phone), and the whole system (microphones, software) must also be able to handle high frequencies.

The other question is what to do with the results of a Fourier analysis. Why does the rosewood recorder sound so different from the plastic one, and how can we change the sound of a woodwind instrument, for instance when we will enhance the odd harmonics in favour of the even ones? There is no simple answer to that question. Several variables play a role, for instance the type of wood or other stuff of which the instrument is made, the finishing of the inner walls of the instrument (very smooth or a bit rough), and on a recorder the thickness of the labium edge, the dimensions of the window, and so on.
What a recorder maker must learn is to discern the several types of noise, and what are the possible causes of that noise. This will be discussed later on.

Pitch measurements

The first instrument I ever made (1980) was a tenor fourth flute, a 'copy' of an instrument by Stanesby Junior. I didn't know exactly the pitch of that recorder (which is about a1=407 Hz) and tuned my copy at a1=415 Hz, supposing that was the standard for baroque record- ers. But the result was reasonable good, even without the help of modern tuning aids, only using my ears. Now, 35 years later, I can hardly understand how I had managed this. However, tuning an instrument with only the help of a tuning fork is not such a bad idea. In Holland it is even a task for piano tuners when they have their final examination.

Measuring: some tips and rules

- Comparing the pitch of tones with another instrument is an option, but be careful. Pianos generally have stretched octaves, this because each tone has to be tuned with the second harmonic of the lower octave (of which the second harmonic is generally a bit too wide). Harpsichords or organs may be tuned in a mean tone or other historic temperament. Devices for pitch measurements (tuners) are now cheaply available (Korg is a well-known brand), there are even free tuner apps on smartphones.
- It is not good to measure the pitch of a cold instrument in a cold room. That means play the instrument before, at least for 10 minutes, and/or make it warm (by keeping it close to your body); the temperature of the room should be 20 degrees Celsius.
- The most common way is to measure the pitch of a tone as its difference in cents from the pitch of that tone in a common standard, for instance a1= 415 or 440 Hz, in the equal tempered temperament. If possible give also the frequency of the tone in Hz.
- Never measure a tone on its own (in isolation), but play a few notes and finish on the one you want to assess: you will then have a better idea of the best wind pressure for that tone.
- Some tones are more flexible than others: it is good to measure (especially on recorders) the pitch at normal as well as maximum wind pressure, just before the tone overblows into a higher register.
- On historical instruments you can never be sure of the original fingerings. It is therefore good to measure the pitch of one tone with different (also unusual) fingerings.
- It is good to know the pitch of a head joint only, or of an instrument without its foot or bell (I have never seen such measurements for historical woodwind instruments); it is very useful when I make after a prototype.

Interpreting

Measuring of the pitch of individual tones of a historical woodwind instrument (if you have permission to play it, and the condition of the instrument allows it as well) is not too difficult, but interpreting the results is a different matter. This is mainly because we do not always know which tuning system (temperament) in combination with which fingerings were used by the maker. The problem is well-known: it is not possible in our western system of twelve tones in an octave to tune all intervals within the octave pure (or just), using simple ratios as 2/3 for a fifth, 3/4 for a fourth, etc. A pure fifth with a pure fourth give a perfect octave, but 12 fifths do not add up as 7 octaves (adding up means: multiplying the ratios); three pure great thirds (5/4) do not result in a pure octave: going down from 250 Hz (multi- plying by 4/5) we get 200 Hz, 160 Hz and 128 Hz: that is 3 Hz higher than the 125 Hz of a pure octave to 250 Hz: it is a simple mathematical problem.

Several systems are invented in the history of western music to deal with the problem. That means that choices had been made which intervals had to be better in tune than others.
In the modern equal tempered system all octaves are pure (1:2 ratio), and all other intervals more or less out of tune. All the smallest intervals, (semitones or half steps) have the same ratio: 1.05946 (which is the 12th root of 2). In the system where each equally tempered semitone has 100 cents (and an octave 1200) is the result that fifths are 2 cents too wide, and fourths 2 cents too narrow. But the differences are much greater for the thirds: 14 and 16 cents.

	equally tempered	*pure interval*	*difference*
octave:	1200 cents	1200 cents	0
fifth:	702 cents	700 cents	2
fourth:	498 cents	500 cents	2
major third:	386 cents	400 cents	14
minor third:	316 cents	300 cents	16

Many articles are written about those historic tuning systems. A problem is that most of these publications don't deal with woodwinds, but are about tuning keyboard instruments. Tuning aurally (by ear) means: counting the number of the beats per second when two tones in an interval are played at the same time. When some of their partials approximate each other in pitch, they create 'beats'. Beats can be heard when the sound waves that are close to, but not at the same pitch, reinforce and cancel each other.

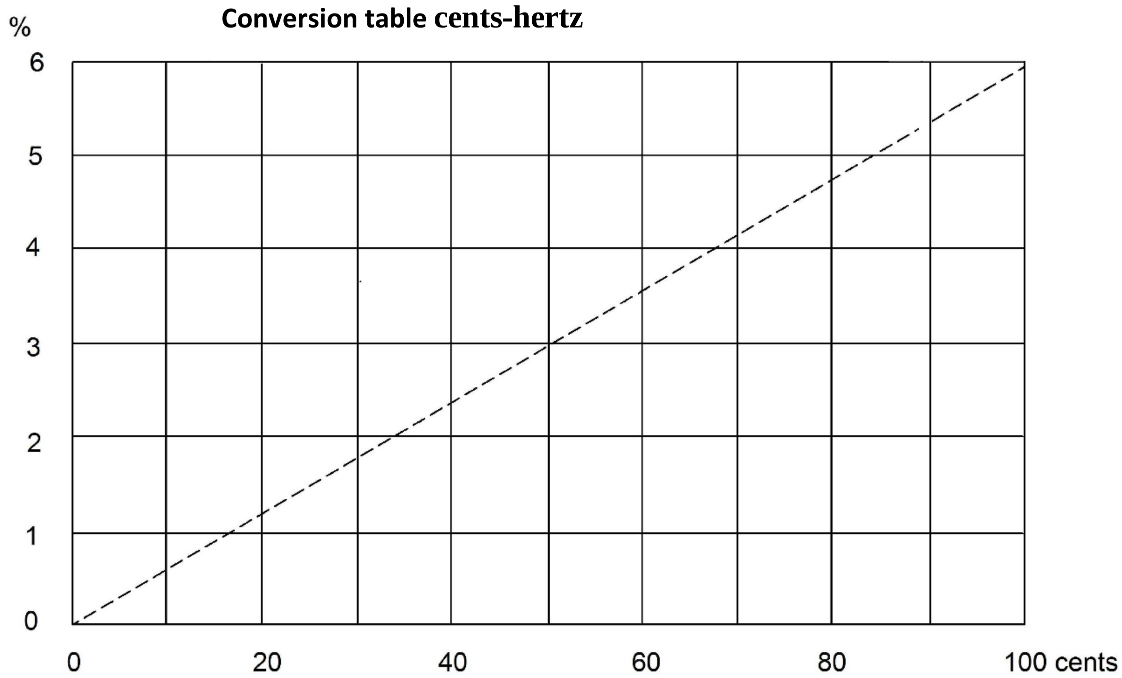
I give here a survey of the some widely used temperaments, with deviations in cents compared with well-tempered tuning.

	I	II	III	IV	V
c	0	-6	+5	+10	+6
c#/d-flat	0	+8	-8/+14	-3 (c#)	0
d	0	-2	+1	+3	+2
d#/e-flat	0	-12	-11/+10	+8 (e-flat)	+4
e	0	+2	-2	-3.5	-2
f	0	-8	+7	+13	+8
f#	0	+6	-6/+16	-5 (f#)	-2
g	0	-4	+3	+6.5	+4
g#/a-flat	0	+10	-10/+12	-1	+2
a	0	0	0	0	0
a#/b-flat	0	-10	-13/+9	+17 (b-flat)	+6
b	0	+4	-4	-7	-4

I: well tempered II: Pythagorean (for keyboard) III: 1/6 comma meantone
IV: Rameau V: Valotti (for keyboard)

How to use this table: the equally tempered semitone is equal to 100 cents. An octave is then 1200 cents and the other equal tempered intervals can be obtained by adding semi-tones. However: a pure fifth has 702 cents and a pure fourth 498 cents; both only 2 cents different from equally tempered intervals. But a pure major third has 386 and a pure minor third 316 cents: much bigger differences with equally tempered thirds (400 and 300 cents).

The Pythagorean temperament has eleven pure fifths (and one very false fifth), and all major thirds are very wide. That means that musicians working with Pythagorean tuning can't play regular chords, but have to stick to simpler music using mainly fifths instead. The 1/6 comma meantone favours much more the minor and major thirds. For instance: the minor third from g to b-flat is (in 1/6 comma meantone) 300 + 6 = 306 cents, not quite 316, but better than the equally tempered 300. The major third from c to e is 400 - 7 = 393, which is also better (closer to pure) than the equally tempered interval.



1 cent:	1.00058	25 cent:	1.01455	50 cent:	1.02930	75 cent:	1.04227
5 cent:	1.00289	30 cent:	1.01748	55 cent:	1.03228	80 cent:	1.04729
10 cent:	1.00579	35 cent:	1.02042	60 cent:	1.03626	85 cent:	1.05032
15 cent:	1.00870	40 cent:	1.02337	65 cent:	1.03826	90 cent:	1.05336
20 cent:	1.01162	45 cent:	1.02633	70 cent:	1.04126	100 cent:	1.05946

How to use this table: when the pitch of in instrument is 25 cents above a-440 Hz, you must multiply 440 x 1.01455 = 446.4 Hz. This table can also be used for scaling instruments. Scaling a traverso in a-440 Hz to a-415 Hz means that it have to sound a semitone (= 100 cents) lower: multiply all length dimensions by a factor 1.05946. Rounded to 1.06 means that the new instrument will be 6% longer. The bore of that instrument becomes also wider, but not so much. Organ makers know about scaling pipes and use often a system discovered by Johann Gottlob Töpfer (1791-1870). His scale (*normalmensur*) provides for a reduction in diameter of the pipes by half at every succeeding 17th pipe (instead of every 12th pipe) to obtain the same sound character in an organ register. The scaling factor for a semitone is then about 4%.

Much more can be said about acoustics. I have already mentioned some websites, but those who prefer books can read for instance *The acoustics of the recorder* by John Martin (Moeck Edition 4054, Celle 1994), or *Acoustical aspects of woodwind instruments* by Cees Neder- veen (Delft 1969). But these publications very much deal with theory (John Martin also with some history). The big name in musical acoustics was Arthur H. Benade (1925-1987), professor at Case Institute of Technology/Case Western Reserve University, Cleveland, Ohio, from 1952 to 1987. One of his books: Fundamentals of Musical Acoustics: Second, Revised Edition (Dover Books on Music).

Example of pitch measurements


TUNING
TUNER SET TO A415. TEMPERATURE CA. 15°C.

f' 01234567 —40
g' 0123456 —40
a' 012345 —60 —40
b♭' 01234-67 —50
01234-6- —30
b♮' 0123-456- —20
0123-567 —60
—40 EASY WITH ½7, ACCEPTABLE WITH -56-
c'' 0123 —40
c#'' 012-456 —55 —60
012-456 —40
d'' 012 —40
e♭'' 01-34-6 —40
e'' 01 —40 —20
VERY WELL IN TUNE. SOME WAX IN HOLES I, IV, & V.

f'' 0-2 —40 —20
f#'' -12 —40
g'' --2- —40
g# --23456- —30 —50 VERY GOOD, FLEXIBLE PITCH FOR G# OR Ab.
a'' Ø12345 —35
b♭'' Ø1234-6 —50
b♭'' Ø1234--7 —20
b♮'' Ø123-5-- —30
c''' Ø123 —40
c#''' Ø12-4 —55
d''' Ø12 —40
e♭''' Ø12-456 —20 —30
Ø12-45-7 —40 VERY GOOD.
e''' Ø12-45 —40 —50
f''' Ø1--45 —40 TENDING FLAT.
g''' Ø1-34-6 —30
Ø1-34-67 —50
—40 EASILY POSSIBLE WITH EITHER FINGERING, OR Ø1-34-6X.

This is the tuning table of one of the two alto recorders by Bressan in the Frans Brüggen collection (from the set of drawings by Fred Morgan, published by Zen On in 1981). Morgan gives for each note the fingerings (also alternative fingerings). The upper notes in the first register (e2, f2, g2) are generally more flexible than the notes which have more closed fingerholes, and react also more strongly on tenon contraction above hole 0. Some other notes can be played a bit higher or lower, for instance a1 that goes from -60 to -40 cents below 415 Hz. This means that the major third f1-a1 can be played as an equally tempered as well as a pure interval. Morgan gives, however, no conclusion as to which temperament (or which fingering system) was intended by Bressan.