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Acoustical aspects of the transverse flute from 1700 to present

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The transverse flute is one of the oldest musical instruments and in principle, the acoustics are very simple, being a tube that is open in both ends. However, the modern flute is a very sophisticated instrument and the acoustics are not at all simple. In medieval Europe, a cylindrical flute with six or seven tone-holes was used in folk music and in the military (the fife), but the range of usable musical tones was rather limited, and the harmonics of the tones were in general out of tune. Around 1700, instrument makers in France managed to solve these acoustical problems with the so-called Hotteterre flute, which had a cylindrical head joint combined with a conical body with seven tone-holes, narrowing towards the end. This flute had a pleasant soft tone suitable for indoor playing. However, there were still musical limitations, because some tones were quite weak, and the flute could not play all chromatic tonalities equally well. Thus, the flute continued to develop gradually until 1847, when Theobald Boehm presented a quite revolutionary new design of the flute. This solved the technical problems, but also changed the sound to be stronger and brighter than before. The evolution of the flute is illustrated with instruments from the author's flute collection.

1 Introduction

The flute as we know it today is the result of a long process of development, where acoustical principles are combined with practical and musical needs. The development is also closely connected to a few outstanding flute players and flute makers. This paper explains the most important acoustical principles of the flute, and how the instruments have changed over the centuries in order to meet the increasing musical and technical demands.

The musical acoustics terminology is based on section 13 in ANSI S1.1 [1].

2 Early transverse flutes

Since the late middle Ages, the fife or the Schweitzer-pfeiff (Swiss pipe) was used in the military together with drums. It is a simple flute in one piece with a mouth hole and six or seven tone-holes (see Figure 1).

Figure 1. Examples of Transverse flutes in one piece with cylindrical bore. 1: Military Fife with seven tone-holes (Poland, date unknown, missing one endcap). 2: Military Fife with six tone-holes (USA, 1993).

The fife has a narrow bore and a shrill sound. The six tone-holes are all that is needed to produce a diatonic scale (like a keyboard using only the white keys). Starting with all tone-holes closed, they are uncovered one by one from the bottom end until all are open. This is the first octave. Repeating this while blowing a little harder produces the second octave. However, the partials of the tones are in general out of tune, i.e. they depart from whole multiples of the fundamental frequency, in contrast to harmonic partials that are whole multiples of the fundamental frequency.

The fife #2 in Figure 1 plays the second octave about one-third semitone too low compared to the first octave. Thus, it is only the second octave plus a few tones in the third octave that are usable on the fife. These octaves are also the loudest and most penetrating. The fife was a standard instrument in European infantries by the 16th century, and it was used for signalling on the battlefield, as the trumpet in the cavalry and the artillery.

In the Renaissance, flutes of different sizes were used in art music, often in groups of four or more flutes. Like other musical instruments of the time, they were used in groups from the same family, but not mixed with instruments from other groups. This would be too unpleasant to the ear, because of the partials of different instrument types did not match.

3 Acoustics of open cylindrical pipes with side holes

3.1 A long pipe with one side hole

Like most woodwind instruments, the transverse flute uses side holes to produce tones with different frequencies. The effect of a side hole is to shorten the acoustical length of the pipe. If the hole is small compared to the diameter of the pipe, the effect is small, whereas a large hole is equivalent to cutting the pipe a short distance below the position of the hole, see Figure 2. This means that the flute maker can chose the position of the holes where they fit the fingers of the player, and then make the size of the hole larger or smaller in such a way, that the desired diatonic scale is obtained.

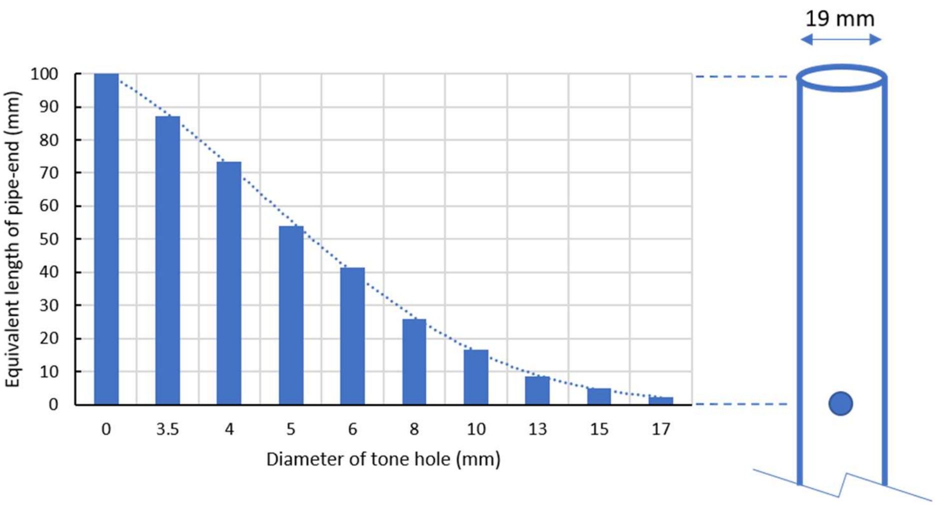

Figure 2. The effect of the size of a side hole on an open cylindrical pipe. The hole is placed 100 mm from the end of the pipe, which has an internal diameter of 19 mm. A 4 mm hole is equivalent to cutting the pipe about 27 mm shorter. A 13 mm hole is equivalent to cutting the pipe 9 mm after the centre of hole.

3.2 A long pipe with multiple side holes

Figure 3 shows a section through a cylindrical flute with side holes, some of which are closed, and others are open. The first three modes are shown in terms of the sound pressure amplitude. A cylindrical pipe will have slightly different acoustical length for each mode. The modes with higher frequencies have a little longer acoustical length that the first mode, because the higher frequencies (with shorter wavelengths) are less affected by the open side holes further down. This is the reason for the inharmonicity of the fife. The distance from the centre of the first open hole to the point where the mode should have a pressure node is the tone-hole correction C_{tone}. Similarly, at the embouchure-hole (blowing hole) there is open access to the air outside the pipe, but the pressure node is shifted a short distance towards the closed end (the cork), and this is the embouchure hole correction C_{emb}. The word embouchure is from French (bouche = mouth) and is also used for the mouth technique of the flutist.

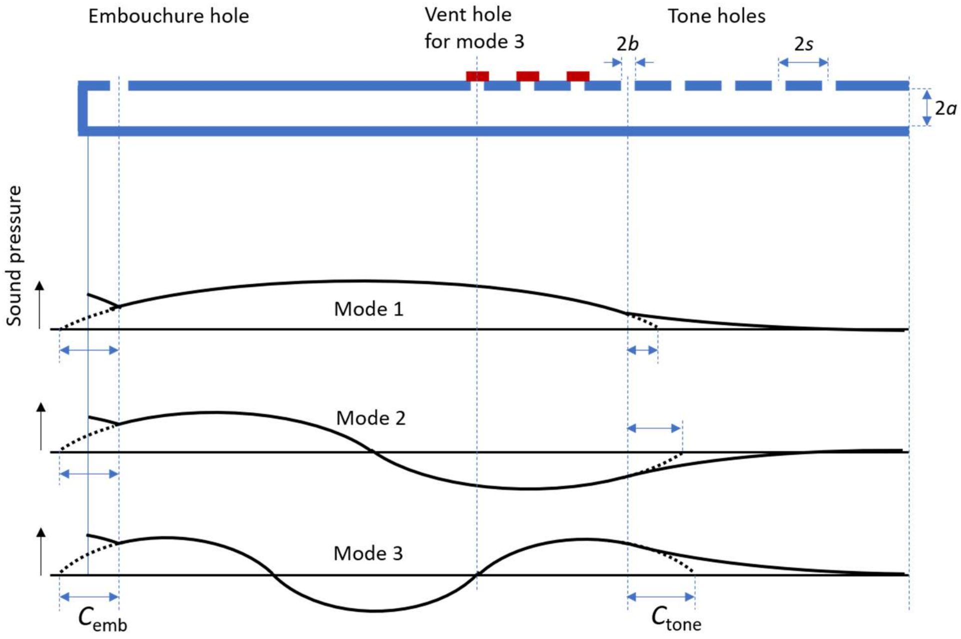

Figure 3. Sketch of the acoustic pressure of the first three modes for a flute with the upper three tone-holes closed. The vent hole will be explained later (After Benade [2] Fig. 22.12).

The frequency dependency of the tone-hole correction can be explained by the vibrating air moving in and out through the hole. Although very small, the air in the hole has a mass m, and the resistance to the movement of the mass increases with frequency as in any vibrating system. The impedance is $j\omega m$, where $\omega = 2\pi f$ is the angular frequency and f is the frequency in Hz. At a higher frequency, the standing wave pressure at the open hole is greater and thus higher modes propagate further into the lattice.

3.3 Tone-holes and the end correction

When a tone-hole is open and sound is produced, the air is moving in and out through the hole. Physically, the mass of the moving air plug includes a small amount of air immediately beyond and above the hole. The effective depth of a tone-hole, t_e is approximately (Benade [2] p. 449):

$$t_e = t + 1.5 \cdot b \tag{1}$$

where t is the physical depth of the hole and b is the radius of the hole. For a wooden flute, the depth is the wall thickness, whereas for a metal flute, the depth of the hole is provided by a chimney, because the wall thickness is very small.

A tube with a series of open holes in the side have different properties for sound propagation at low and high frequencies. At low frequencies, the first open hole will greatly influence the sound propagation, almost as if the tube had been cut off at this place. However, high frequencies are less affected of the holes and propagation continues until the end of the tube. The transition from low-frequency behaviour to high-frequency behaviour is at a cut-off frequency. The open hole lattice cut-off frequency, f_c is approximately (Benade [2] p. 449):

$$f_c = 0.110 \cdot c\, \frac{b}{a} \sqrt{\frac{1}{s\, t_e}} \tag{2}$$

where c is the speed of sound (343 m/s at 20 °C), a is the radius of the tube and s is half the distance between the open tone-holes, see Figure 3. We notice that larger tone-holes lead to higher f_c.

The tone-hole correction C_{tone} increases with frequency up to f_c. At low frequencies, the value can be estimated by (Benade [2] p. 450):

$$C_{\text{tone}} = s\left(\sqrt{1 + 2\frac{t_e\, a^2}{s\, b^2}} - 1\right) \tag{3}$$

The embouchure hole correction C_{emb} also varies with frequency. At low frequencies, the value can be estimated by (Benade [2] p. 495):

$$C_{\text{emb}} = \frac{4\, a^2}{d\, w} \cdot h_e \tag{4}$$

where a is the radius of the bore, d and w are the length and width of the embouchure hole and h_e is the effective height of the chimney of the embouchure hole as it is increased by the nearness of the player's lips. The net height of the chimney is defined by the wall thickness of a wooden flute or the riser of the lip-plate in case of a metal flute.

The under lip of the flutist covers a part of the embouchure hole. By adjustment of the open area of the hole together with the speed and direction of the air current, the flutist can fine-tune the pitch and timbre of each tone. Thus, a tone that is too sharp can be "lipped down" to the correct pitch, and vice versa if the tone is too flat. The mastering of this technique is particularly important for playing in tune on the baroque flute.

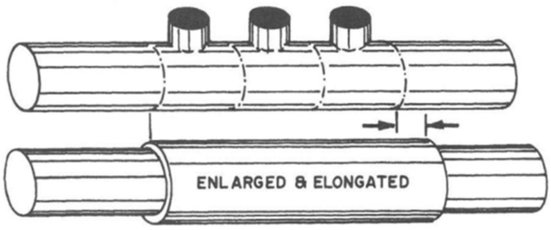

Figure 4. Closed tone-holes effectively enlarge and lengthen the air column (adapted from Benade [2] Fig. 21.8).

When the tone-holes are closed, either by fingertips or padded keys, there are irregularities in the inside tube, which effectively enlarge the length and the cross-sectional area of the air column, see Figure 4. In addition, the irregularities cause increased viscous-thermal losses that tend to attenuate the higher partials of the produced sound (Rossing & Fletcher [3] p. 178-181). The relative enlargement can be estimated by the factor E_c (Benade [2] p. 449):

$$E_{\text{c}} = 1 + \frac{1}{2}\left(\frac{b}{a}\right)^2 \left(\frac{t}{2\, s}\right) \tag{5}$$

The amount of this is typically from 2 to 5 percent, greater with large tone-holes. If we consider n closed holes in a row with the average hole-to-hole distance $2s$, the length correction due to the closed tone-holes is:

$$C_{\text{n}} = \frac{1}{2} n\, t \left(\frac{b}{a}\right)^2 \tag{6}$$

Finally, the total length correction adds up to:

$$C_{\text{total}} = C_{\text{emb}} + C_{\text{tone}} + C_{\text{n}} \tag{7}$$

The above formulas are approximations and certainly not sufficient for the design of a flute. However, the formulas can be helpful for understanding the acoustical principles of the flute and in explaining some empirical observations.

3.4 The effect of a conical pipe

If the inner shape of the pipe is not cylindrical, but conical, the mathematical model for the acoustical behaviour of the pipe becomes very complicated. However, a simple qualitative approach may suffice here.

The baroque and classical flutes have a cylindrical head joint connected to a conical body tapered towards the bottom. The cylindrical part is about one-third of the total length of the flute, and all the tone-holes are on the longer, conical part. We now assume that several tone-holes are open as in Figure 3. The ideal flute would then be a shorter cylindrical pipe, cut a short distance below the first open tone-hole. This would be a pipe that is open in both ends and with a harmonic series of modes. The frequency of the partials would be 1, 2, 3, 4, etc. times the frequency of the fundamental (B in Figure 5). However, as explained above, the cylindrical pipe with some open tone-holes have partials that are a little closer together (A in Figure 5).

When the lower part of the pipe is tapered towards the bottom, it tends to close the lower end of the pipe. A perfectly closed pipe has a length equal to one-quarter wavelength of the lowest mode. The higher order modes of a closed pipe have frequencies proportional to 3, 5, 7, etc. times the frequency of the fundamental (C in Figure 5).

Thus, the effect of the conical bore is to widen the interval between the partials. Precisely how much the tapering of the bore must be to make the partials perfectly harmonic, is a matter of experimentation.

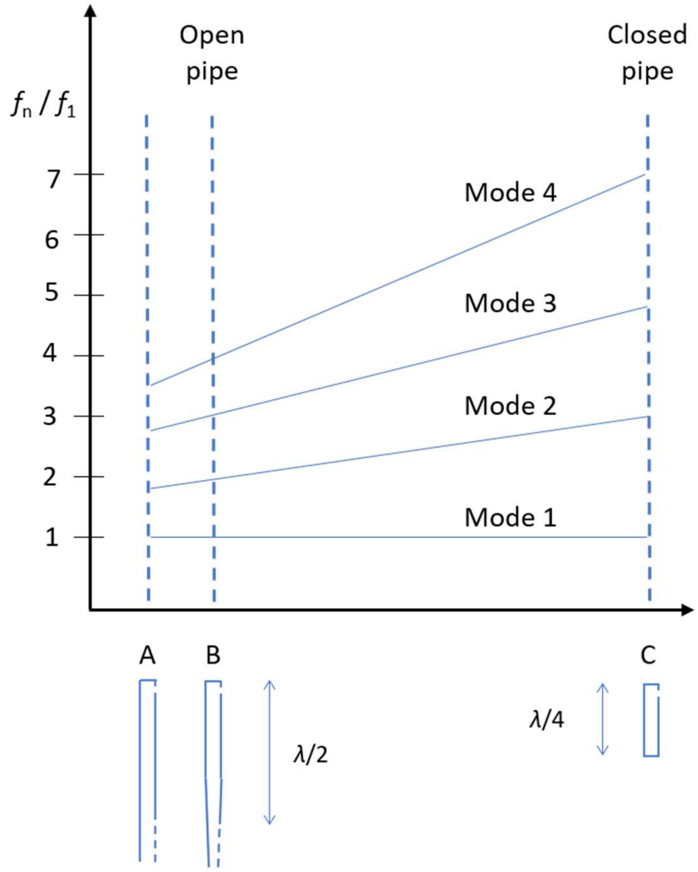

Figure 5. The relative frequency of the partials of a cylindrical pipe with open tone-holes (A), the effect of a slightly tapered conical bore (B) and a closed pipe having the same fundamental frequency (C).

3.5 Sound radiation and directivity

The sound radiation from the flute is different from that of other musical instruments. In principle, the flute is a pipe that is open in both ends, so the sound radiation is basically like that from a dipole. Sound is radiated from the embouchure hole and from one or more of the open tone-holes. When all tone-holes are close, the second pole of radiation is the end of the tube.

For tones in the first octave, the fundamental generates pressure variations in phase at the two radiating openings, see A in Figure 6. However, the second partial comes from the second mode that generates pressure variations in opposite phase, see B in Figure 6. So, the fundamental and all uneven partials radiate as a (+ +) dipole, whereas the even partials radiate as a (+ −) dipole. The fundamental radiates in all directions, approximately like the sound from a point source. The even partials radiate with a notch perpendicular to the axis of the flute, see Figure 7.

Tones in the second octave uses only the even modes, so the fundamental comes from the second mode and the partials are related to the even modes, only. This means that all tones in the second octave radiate with a notch perpendicular to the axis of the flute.

In the third octave the dipole model for sound radiation does not apply. The radiation is more or less like that from mode 5 and 6 with many notches. In practice, omnidirectional radiation can be assumed.

The body of the flute contribute to the sound radiation. Although nearly negligible, it can be recognised by the human ear. The body radiation is strongest with thin-walled metal flutes, and less with thick-walled wooden flutes.

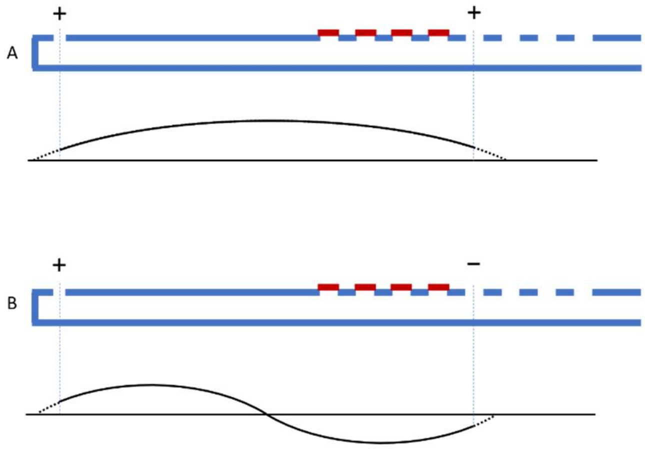

Figure 6. The flute as a dipole. A: the first mode radiates as a (+ +) dipole. B: the second mode radiates as a (+ −) dipole.

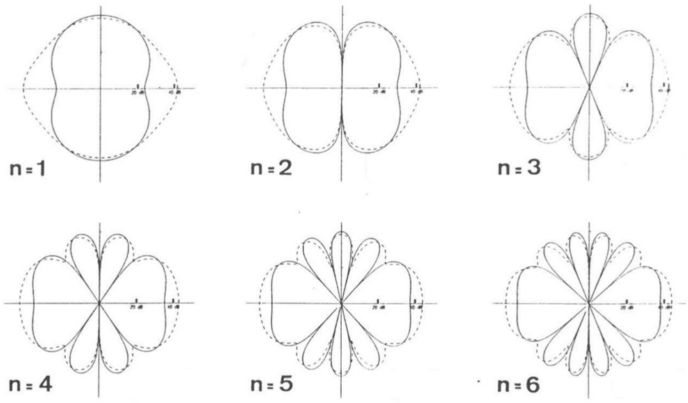

Figure 7. Calculated directivity of the first six modes of a flute playing a tone in the lower octave. The mode number is *n*. Full curves are for the far field, dotted curves are for the near field. (After Bork [4] Fig. 6).

4 The baroque flute

4.1 The Hotteterre flute around 1700

Around 1680 a radical transformation of the Renaissance flute took place in France at the court of Louis XIV by members of the Hotteterre family, who built and practiced woodwind instruments. A separate cylindrical head piece was jointed with a conical body with six finger-holes, and a foot-joint with a closed key, see #3 in Figure 8. While the body was tapered towards the end, the foot-joint could be cylindrical or even expanding slightly towards the end, which made the lowest tone (D4) more powerful. The conical body of the flute was an elegant solution to the problem with the harmonics being out of tune on the cylindrical flute, see section 3.4. During the 18^{th} century the flute was changed and made in four sections instead of three, but without major acoustical changes, see #4 in Figure 8. The introduction of a single closed key had the obvious purpose to allow the semitone D# (Eb) in the first and second octave. However, the key could also solve the problems with some difficult tones in the third octave, so for the first time the flute had become fully chromatic over more than two-and-a half octaves (from D4 to A6).

The flute was quickly adopted in the music ensembles, and around 1750 it had fully replaced the recorder, which had until then been the most important member of the flute family. An example of the new musical possibilities offered by the transverse flute are the 12 fantasies for solo flute by G. Ph. Telemann composed around 1730: They are in the gradually ascending keys A major, A minor, B minor, Bb major, C major, D minor, D major, E minor, E major, F# minor, G major, and G minor. What a homage to the baroque flute!

Figure 8: Baroque flutes. #3: Hotteterre flute, copy by John Hanchet probably around 1965 (A = 392 Hz). Original in Museum of musical instruments, Berlin. #4: Baroque flute in four sections, copy by Grzegorz Tomaszewicz after G. A. Rottenburgh (A = 415 Hz). Original in B. Kuijken collection.

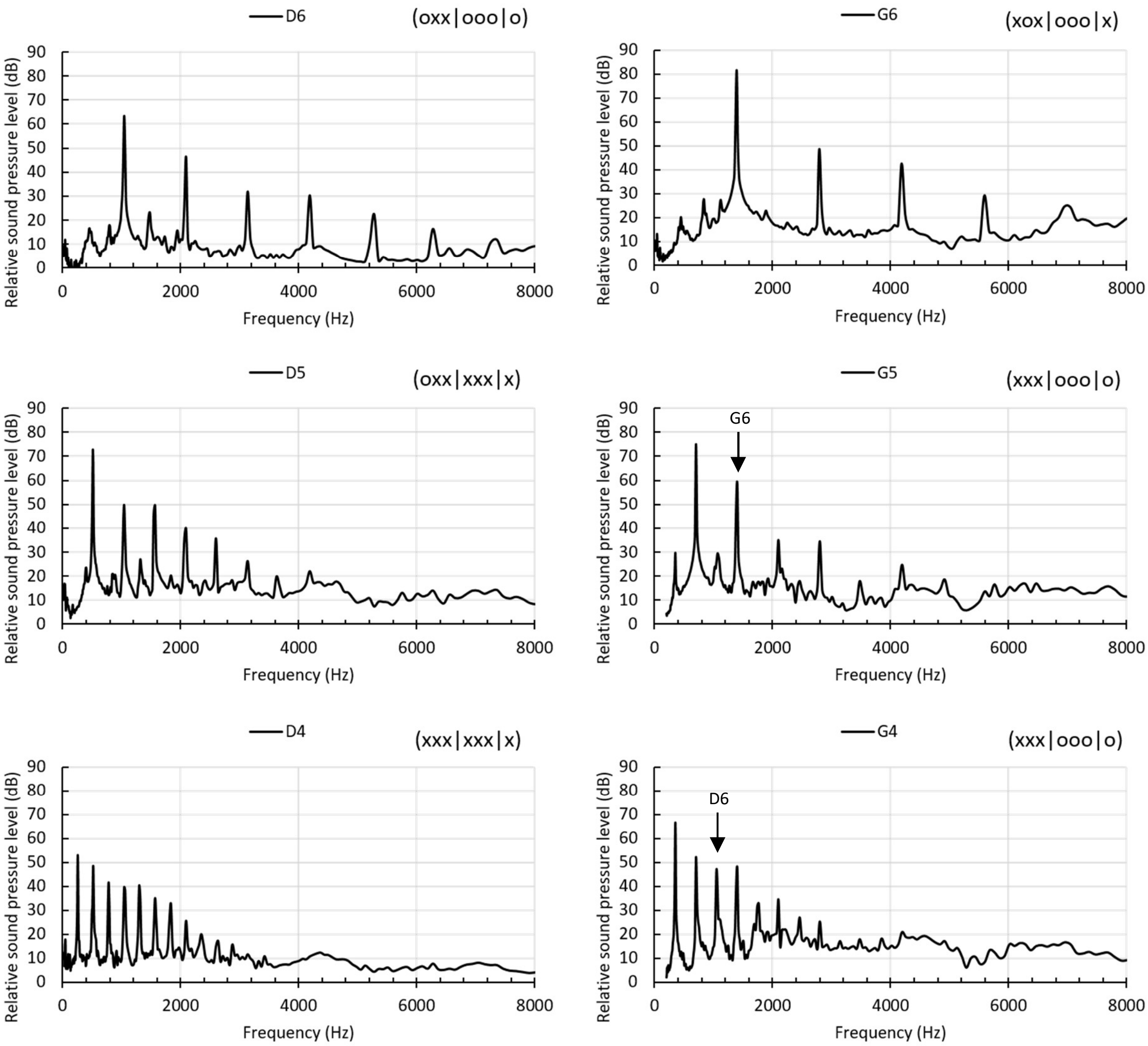

Figure 9. Measured spectrograms for the Hotteterre flute (#3). Left: tones D4, D5 and D6. Right: tones G4, G5 and G6. The fingering is indicated; x is closed tone-hole, o is open tone-hole.

In Figure 9 it is interesting to see, how the tone D6 is derived from the third harmonic of the tone G4. By opening the first tone-hole, the first and second modes are cancelled but the third mode is supported. This is an example of how a tone-hole can serve as a vent hole, see also Figure 3. So, the tone D6 picks only modes 3, 6, 9, etc. from the tone G4. The tone G6 is another example; the second hole is used as a vent hole to secure the fourth harmonic of G4 (or the second harmonic of G5). The technique of using vent holes is very important for all tones in the third octave.

4.2 Forked fingering

The chromatic scale has twelve semitones in each octave. Thus, some tones do not have they own tone-hole on the baroque flute (F, G#, Bb, C). The solution is to use forked fingering (also called cross fingering). The idea is, that a tone can be flattened by leaving one tone-hole open and closing one or more holes further down, see some examples in Figure 10. Further measurements and a theoretical model are presented by Wolfe and Smith [5].

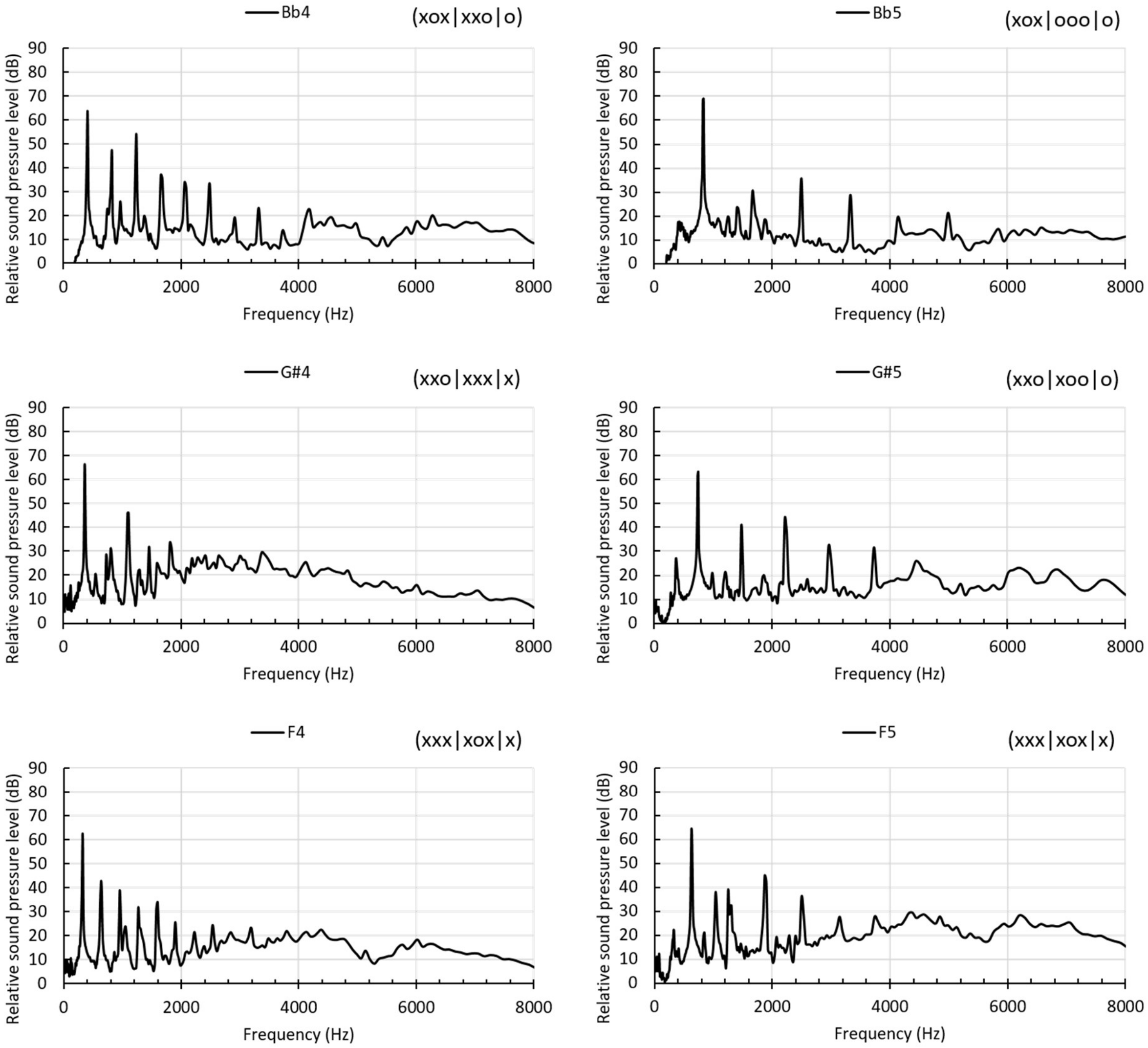

Figure 10. Measured spectrograms of tones with forked fingering played on the Hotteterre flute (#3). The tones are F, G# and Bb in first and second octave. The fingering is indicated; x is closed tone-hole, o is open tone-hole.

The spectrograms of the forked tones are less clean than those of the other tones. When played, the tones sound weak and partly veiled. In the first octave they are also difficult to play in pitch. The second harmonic is particularly weak or missing in the tones F5, G#4, and Bb5. Whether the unequal timbre of the tones is an issue, or a feature is debated by musicians devoted to musical performance on period instruments. Composers like J. S. Bach and G. Ph. Telemann knew perfectly well how to use the strengths and weaknesses of the instrument to support the character of the music.

4.3 The success of the one-keyed baroque flute

While the recorder had been the dominating flute type before 1700, the transverse flute became quickly very popular after 1700. Some composers made music for both instruments, sometimes together. For example, there is a double concerto by Telemann with a recorder and a transverse flute as equal solo instruments. But after a few decades the scene had changed, and after 1750 the recorder was no longer in use. Together with the oboe, the clarinet and the bassoon, the transverse flute joined the wood wind group in the orchestras.

The reasons for this development may be due to the difference in the blowing technique of the recorder and the flute. While the recorder is easy to blow, it is more difficult to create a good sound on the flute. But with enough training, the flute player can adjust the sound in ways that are impossible on the recorder. This includes the proper intonation of every single tone, a wider dynamic range, and a wider tonal range.

5 The development of the classical flute

To solve the problem with unequal timbre of tones with forked fingerings, flutes with extra keys for F, G# and Bb started to appear in England and Germany from around 1750, see #5 in Figure 11. Gradually, more keys were introduced, as on the six-keyed flute #7 in Figure 11. The extra keys are for the C and a duplicate long key for F, operated by the left-hand little finger when the right hand is too busy to use the original short F key. A by-product of the new keys was fingering problems. To access the keys, the fingers must leave their position over the tone-holes, so that some rapid fingering combinations become impossible. In virtuosic passages the solution is to use the baroque cross fingerings, which are still valid, and leave the keys for slower parts of the music, only. A flute without any keys are often preferred in Irish music, se #6 in Figure 11.

Figure 11: Classical wooden flutes with conical bore. #5: Flute in F with four keys (possible late 18th century). #6: Flute in F, stripped for the originally six keys and the corresponding holes stopped with vax. Used in Irish folk music round 1970-1980. #7: Classical flute with six keys (A = 440 Hz), around 1920. #8: Classical flute with nine keys (A = 435 Hz), the lower range extended down to C4, around 1900.

Towards the end of the 18th century, further keys were added to the flute to extend the lower range from D4 to C4 or even lower. An example is flute #8 in Figure 11 that includes the tones C#4 and C4. It also has an unusual E-key at the upper part. However, the six keyed flute (#7) continued to be a popular instrument until around 1920.

6 The Boehm flutes

6.1 Theobald Boehm

Theobald Boehm (1794 – 1881) was born in Munich as son of a goldsmith. He learned the craftmanship from his father, but he was also a gifted flute player. His first flute was a one-keyed boxwood flute. At the age of sixteen he made a flute of his own, as a copy of a six-keyed flute. Already in 1812, he was first flutist in the Royal Isarthor Theater in Munich, and in 1818 he decided to give up the business as goldsmith and devote himself entirely to flute playing.

However, Boehm continued to build flutes, and in 1828 he set up his own workshop. The flutes were of the classical design made from boxwood, grenadillo or other kinds of wood with 6 or 8 keys. In 1831 Boehm performed in London as a soloist on a classical flute of his own make. There he met the English flute player Charles Nicholson (1795-1837), who used a flute with unusual wide bore and very large tone-holes. In a letter much later (1871) Boehm writes about this episode: "I could not match Nicholson in my power of tone, wherefore I set to work to remodel my flute. Had I not heard him, probably the Boehm flute would not have been made." (Boehm [6] p. 8).

6.2 The new key system 1832

Boehm's idea of the new flute was to make the tone-holes of equal size and place them acoustically correct; then a ring-mechanism was developed, which allowed each finger to have just one key to press, but some keys being operated together. In other words, Boehm made it possible to play the twelve semitones in each octave using only nine fingers and keeping all fingers in one position, see flute #9 in Figure 13. This was a significant improvement and it completely changed the playing technique. Later, the system has been adopted to the other woodwind instruments, except the bassoon.

However, many established flute players of the time hesitated to change to flutes with the new key system, simply because the difference from the old system was significant, and it was a matter of security in playing.

Figure 13: Boehm flutes. #9: Conical ring-key flute made by V. Kohlert Sons, Graslitz, Austria around 1910 (A = 440 Hz). #10: Wooden flute with covered keys and C-foot made by E. Rittershausen, Berlin around 1920 (A = 435 Hz, grenadilla and silver keys), #11: Silver flute with perforated keys and B-foot (Jupiter SFL-711 RB) made by K.H.S. Musical Instrument Co., LTD. Taiwan around 1982 (A = 440 Hz). Head joint with lip-plate in gold by Ian McLaughlan, England 2016. #12: Alto flute (Jupiter di Medici 1100) made by K.H.S. Musical Instrument Co., LTD. Taiwan around 2010 (A = 440 Hz)

6.3 The cylindrical Boehm flute 1847

Professor Dr. Carl von Schaffhäutl at the Technical University of Munich was a friend of Boehm. In 1845-1846 he helped Boehm studying acoustics, and in particular musical acoustics. As part of the studies, Boehm made experiments with a great number of conical and cylindrical tubes. These experiments showed (quotation from Boehm [6] p. 16):

1. That the strength, as well as the full, clear quality of the fundamental tone, is proportional to the volume of the ait set in vibration.
2. That a more or less important contraction in the bore of the upper part of the flute tube, and a shortening or lengthening of this contraction, have an important influence upon the production of the tones and upon the tuning of the octaves.
3. That this contraction must be made in a certain geometrical proportion, which is closely approached by the curve of the parabola.
4. That the formation of the nodes and segments of the sound waves takes place most easily and perfectly in a cylindrical flute tube, the length of which is thirty times its diameter, and in which the contraction begins in the upper fourth part of the length of the tube, continuing to the cork where the diameter is reduced one tenth part.

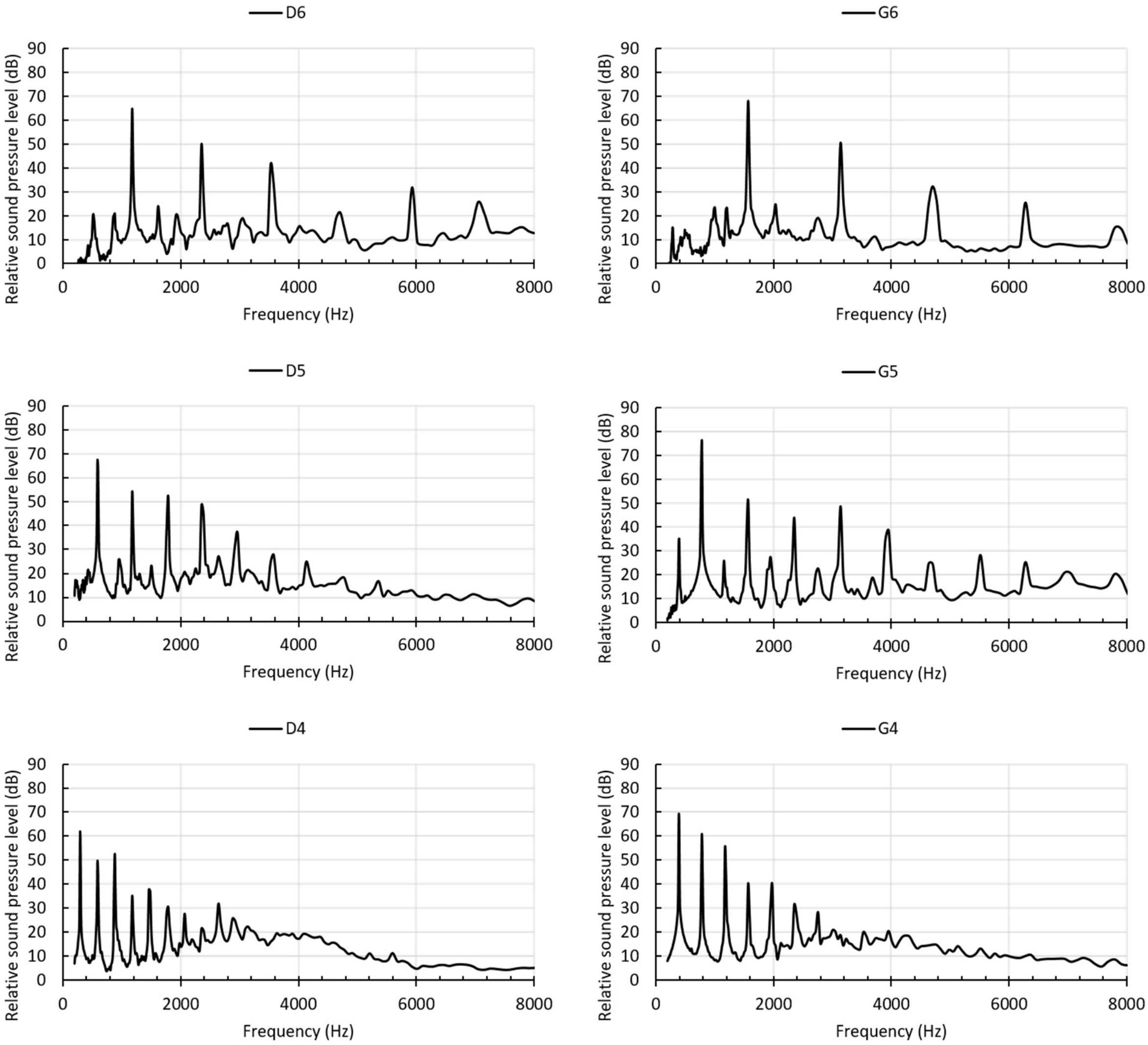

Figure 14. Measured spectrograms for the silver Boehm flute with B-foot and open keys (#11).

The new flute was made of silver instead of wood, see #11 in Figure 13. The wall was very thin, and it was necessary to make the tone-holes with raised edges to have the depth as in a wooden flute. Also, the embouchure-hole should have the correct depth and therefore it was necessary to add a lip-plate on top of a riser. The contraction in the bore of the head joint was determined by experiment. The important thing was, that the correct tuning of the harmonics as in the baroque and classical flutes, could also be obtained with a cylindrical shape of the body, if the bore of the head had an appropriate contraction towards the cork.

The cylindrical flute tube made it possible to use very large tone-holes of equal size. This made the instrument louder and brighter in timbre. Another consequence was that forked fingering would not work. The position of the tone-holes was calculated precisely to obtain an equal tempered scale, i.e. the distance from one hole to the next increased by a factor $2^{(1/12)} = 1.059$ descending from the top to the foot. The only exception is the first tone-hole for C# because this has an important double role as a vent hole. If this hole were made larger and moved downwards as the other holes, it would no longer be in the right position to act as a vent hole for D6, see section 4.1.

Figure 14 shows measured spectrograms of selected tones with the cylindrical silver Boehm flute. By comparison with the spectrograms for the Hotteterre flute, Figure 9, several differences can be noted. In general, the higher harmonics are stronger with the Boehm flute. The high notes D6 and G6 have larger bandwidth of the harmonics, which is a clear indication of higher viscous-thermal attenuation as could be expected because of larger and more numerous tone-holes. The D4 is very strong on the Hotteterre flute because all holes are closed for this tone, whereas the D4 on the Boehm flute is negatively influenced by the longer tube with three more open holes.

The cylindrical silver flute was presented at the London World Exhibition of 1851, and at the Paris World Exhibition of 1855. In both cases Boehm received Medals and the highest recognition. The composer Hector Berlioz was in the jury in 1851, and he declared: “We do not doubt that the Boehm system will triumph within a short time”. But he was not entirely right on this; only in France the cylindrical silver Boehm flute was quickly accepted. In other countries and especially in Germany there was strong resistance to the new instrument. Nearly one hundred years should pass before the cylindrical silver Boehm flute was in general use worldwide.

There were two different kinds of resistance against the new flute. One was from the flutists; the fingering system (from 1832) was radically different from that of the classical flute, and for an established flutist it would be risky to change to the new system. It was also a problem that Boehm insisted on an open G# key instead of the closed G# as on the classical flute. This meant that the left-hand little finger should press the key for most of the tones and thus the left hand was in a locked position. Today, a modified version is used with two duplicate G# holes, one closing together with the A key, and one to open as on the classical flute. But Boehm was stubborn and denied delivering this solution from his workshop. The other resistance was because of the sound of the cylindrical silver flute (1847), which was stronger, brighter and more penetrating than the sound of the conical wooden flutes. It is known that in 1882 Richard Wagner prompted the principal flautist at Bayreuth Opera House, Rudolf Tilmetz, to give up his silver Boehm flute for a wooden, conical 1832 model.

However, in France the cylindrical silver flute was quickly adopted both in the orchestras and at the Paris music conservatory. The bright timbre was ideal for the impressionistic music stile in France, initiated by Claude Debussy around the end of the 19^{th} century.

Boehm’s preferred material for flutes was silver, but from 1854 he began to make cylindrical flutes also of wood, see #10 in Figure 13. They were thick-walled as the classical flutes, and a little heavy to play, but the difference in sound compared to the silver flute is negligible.

6.4 The alto flute

In 1858 (at the age of 64) Boehm developed a new flute at a deeper pitch. The aim was to create a deeper, stronger, and at the same time more sonorous flute tone, and the result was the alto-flute in G, tuned a major fourth below the normal flute in C, see flute #12 in Figure 13. He was very satisfied with this instrument and thought that this was his very best invention. In a letter much later he said, “I only regret that I did not make this flute forty years ago.” In his old days he played his alto flute every morning. The construction of the flute is like an up-scale of the normal cylindrical Boehm flute, but with a slightly wider bore-to-length ratio. This makes the high tones in the third register more difficult to play, but more importantly, favours the lower tones in the first register.

7 Discussion

Table 1 presents some physical data of four different flutes that represent the evolution from c 1700 to the modern cylindrical Boehm flute. The size of the tone-holes are about the same on the baroque and the classical flutes, increases a little on the Boehm 1832 version (Kohlert) and suddenly becomes much larger on the Boehm 1847 version (Jupiter), except for the three upper holes that also serve as vent holes. From the position of the tone-holes it is straight forward to calculate the effective total length correction. This is the difference between a half wavelength of the fundamental of the tone in first octave and the distance from the centre of embouchure hole to the centre of tone-hole as given in Table 1. The calculations are based on the equal tempered tuning and the speed of sound at 20 °C. The results are displayed in Figure 15 as function of the tone-hole diameter. The small tone-holes on the baroque and classical flutes yield long effective length corrections, whereas the large tone-holes on the cylindrical Boehm flutes yield effective length corrections around 60 mm for the silver flute and a little more for the wooden flute.

Table 1. Data for four flutes; size of embouchure hole and diameter of tone-holes, bore diameter, and position of holes measured from centre of the embouchure hole. The unit is mm.

	Hotteterre (A = 392 Hz)			Classical 6 keys (A = 440 Hz)			Kohlert (A = 440 Hz)			Jupiter (A = 440 Hz)		
Hole	Size	Bore	Position	Size	Bore	Position	Size	Bore	Position	Size	Bore	Position
cork		19.6	-26		17.8	-17		19.3	-17		16.65	-17
emb	10,3*9,4		0	12,4*10,5		0	12,4*10,6		0	11,6*10,3		0
D#5		19.6			17.8	125	6.6	19.3	180	6.5	18.85	202
D5		17.3					6.6		201	6.5		218
C#5	6.6		247	6.4		225.5	6.6		221	6.5		236
C5				6.4		244	6.6		248/262	13		267
B4	6.2		287	6.4		261	6.6		267	13		286
Bb4				4.8		279	6.9		289	13		309
A4	5.3		326	6.3		299	8.2		312	13		331
G#4				4.6	13.7	317	8.2		338	13		354
G4	6.6		390	6.4		367	8.2		363	13		378
F#4	6		430	6.6		392	7.7		389	13		404
F4				6.4		411	7.7		416	13		430
E4	5.3	12.5	468	5.6		435	7.7	11.4	444	13		460
D#4	5.7		525	8.4		485	10.6		485	15		490
D4		13.7	591		13.4	541	10.6		518	15		524
C#4							10.6		549	15		558
C4								10	592	15		594
B3											18.85	638

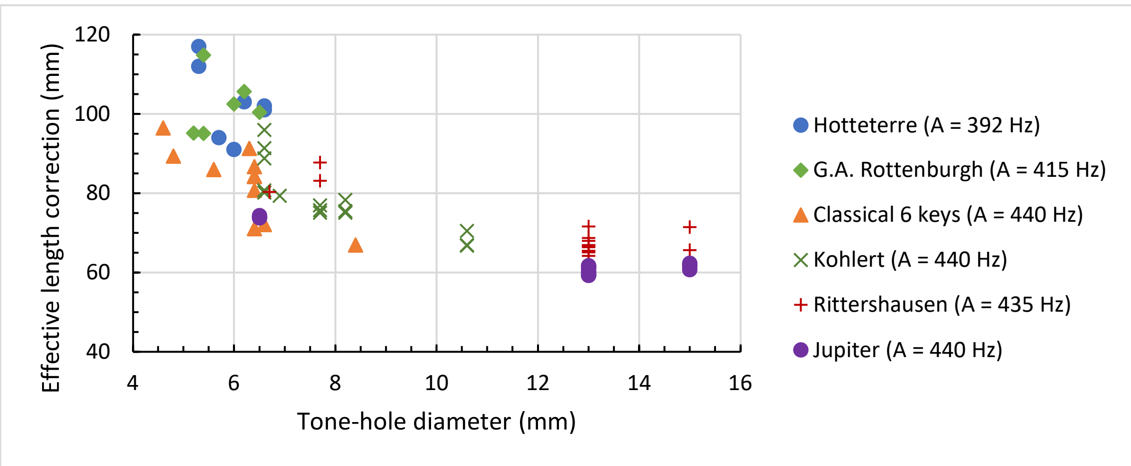

Figure 15. Effective length correction as function of the tone-hole diameter for six flutes.

By experiment Boehm found that the total length correction was 68.5 mm, namely 51.5 mm measured from the cork plus 17 mm to the embouchure hole ([6] p. 34). In Figure 15, the results from the Rittershausen flute are in reasonable agreement with Boehm's finding, whereas the Jupiter flute has somewhat shorter length corrections. A possible explanation could be that this flute has perforated keys, and thus the end corrections are smaller than with covered keys.

8 Piccolo flutes

The piccolo flute (*flautino* or *ottavino* in Italian) sounds one octave higher than the normal flute. It is a transposing instrument sounding one octave higher than the written music. The development from mid-18th century to piccolos with Boehm system was like that of the normal flute, although with some delay. The only difference is that there was no need for a foot joint to extend the range below D5, which is normally the lowest note.

Figure 16: Piccolo flutes. #13: One-keyed Eb piccolo. England, probably around 1800. #14: Eb Piccolo with five keys. #15: Classical piccolo, six keys, probably around 1900. #16: Conical wooden piccolo with Boehm system, Yamaha YPC 61, around 1970. #17: Cylindrical metal piccolo with Boehm system, Royal, around 1965.

Some examples are shown in Figure 16, and the oldest one, #13, is in principle like a baroque flute with six tone-holes and one key. The instruments #13 and #14 are Eb piccolos, whereas the others are orchestral piccolos. Flutes of different size are usually named after the 'six-finger' note, i.e. the note produced with the six tone-holes closed. Thus, the Eb piccolos are tuned a semitone higher than the normal piccolos, which are D flutes. In England and Ireland, there is an old tradition for flute bands with flutes in different sizes, analogue to a brass band with brass instruments. As an example, a flute band with 26 players can have one Eb piccolo, nine Bb flutes, three F flutes, three Eb flutes, three Bb bass flutes, two F bass flutes, one Eb bass flute and four percussion (Bate [9] p. 6).

During the 18th century, the piccolo occurred occasionally in opera music, e.g. by J.-P. Rameau and W.A. Mozart (Nursey [10]). One of the first appearances of the piccolo in the symphony orchestra was 1808 in Beethoven's fifth and sixth symphonies (first performed at the same concert). For this occasion, the traditional Viennese orchestra was expanded not only with the piccolo but also with the contra bassoon and trombones, and Beethoven was excited: "He could not wait for the moment when three trombones and flautine [piccolo] would erupt from the orchestra with a joyful noise – more noise than six kettledrums and better noise at that". (Morris [11] p. 125). From then on, the piccolo was a standard instrument in the symphony orchestra. Rossini used the piccolo in his operas, first in *Il barbiere de Siviglia* from 1816, and the piccolo also became a standard instrument in the opera orchestra. Examples of remarkable soloistic parts for the piccolo are found in music by Tchaikovsky (fourth symphony) and Shostakovich (ninth symphony).

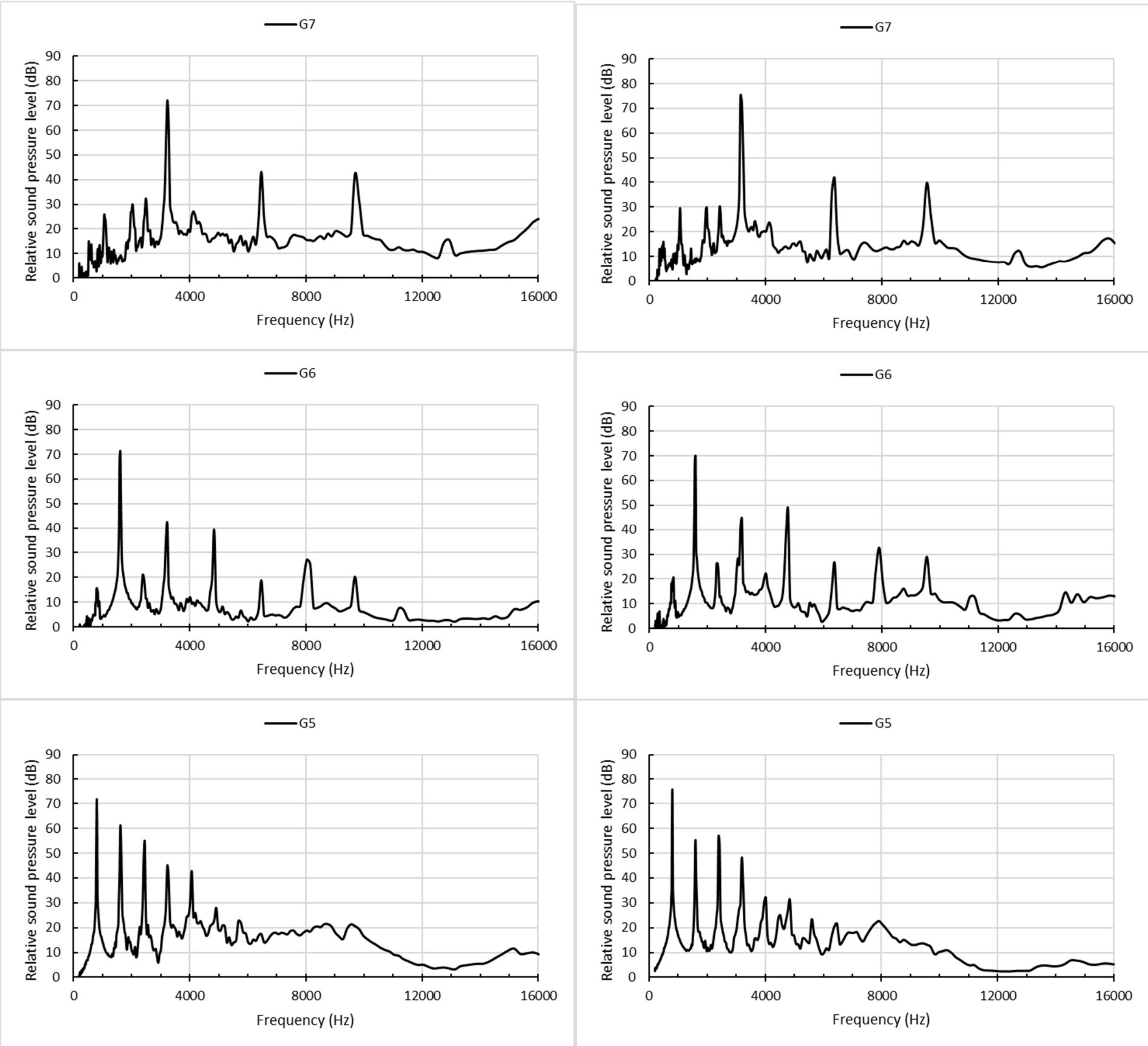

Figure 17. Measured spectrograms for two piccolo flutes. Left: Conical wooden piccolo (#16). Right: Cylindrical metal piccolo (#17).

The instrument #15 in Figure 16 was bought together with the classical flute #8 in Figure 11, and they may have been made by the same (anonymous) flute maker. The conical wooden piccolo #16 in Figure 16 is typical for the preferred instrument in most modern symphony orchestras. Although a cylindrical metal piccolo like #17 is also used by some flutists, the softer and less shrill sound of the conical wooden piccolo is preferred by most flutists today. As late as the 1920s it was not uncommon that the orchestra flutist switched between a cylindrical Boehm flute and a classical, simple system piccolo like #15 (Bate [9] p. 13).

Figure 17 shows the measured spectrograms for the tone G in three octaves for the two modern piccolos, #16 and #17. The differences are small, but there is a tendency to stronger higher partials in the cylindrical piccolo, especially the third partial in G5 and G6. Also, the second partial is weaker in these tones on the cylindrical piccolo. Together this may explain the sound to be shriller than in the conical piccolo. However, these examples also show that the spectrograms are not fully reliable, because the ear will find the sound of the two piccolos very different, but it is hard to see the difference in the spectrograms.

9 Further reading and listening

The evolution of the flute and playing technique has been described in depth by some experienced musicians [7, 8, 9]. A good description of the performance practice of the flute, and how the paying technique has developed from Baroque to modern times is found in Chapter 4.4 of the book by Campbell et al. [12].

For those interested in listening to the sound of different flutes, the two CD’s [13, 14] are highly recommended. The first one presents 19 flutes covering a span of 450 years. The second one presents five flutes from Boehm’s workshop ranging from a classical 8-keyed flute to an alto flute.

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