FoMRHI Comm. 2131 **Adam St. John**

Acoustics for Flutemaking

Preface

This text is mostly applicable to keyless, wooden flutes of western European style, such as Renaissance or Irish flutes. It will primarily set out to investigate the acoustics of simple transverse flutes, summarizing the most important aspects for flutemakers and translating them into practical and simple guidelines. Much of this information is otherwise scattered and buried in technical discourses which make it somewhat inaccessible to the aspiring flutemaker. Often where there are texts which cover most of the details, the key points are somewhat hidden from those less technically inclined to be able to sift them out. The aim is to rationalize and summarize a list of non-mathematical guidelines for the design of transverse wooden flutes in general. I really wrote it as a gift to the flutemaking community and an effort to keep wooden flutemaking alive.

This leads us to the second emphasis of this writing-- that a totalizing, theoretical conception of flute design is unnecessary for the practicing maker, has never been relied upon by the masters, to this day does not yet exist, and is likely impossible. However, this is not to deny that the detailed investigations and calculations of mathematical acoustics have not practically contributed to contemporary flute design-- this essay itself is indebted to them. Nevertheless, for the practicing maker and player of wooden flutes, the literally unending development of applied calculus becomes increasingly superfluous for the craft of an extremely (tonally) flexible instrument which will ultimately be filed, tuned, and played by the hands, mouth, and breath of a human. This is not an excuse for mine or any maker's lack of craft, but a recentering from the theoretical to the practical, from the mathematically justified to the hand made.

A Personal Introduction

When I first set out to make wooden flutes, I aspired to have such a theoretical understanding of their general design that I would be able to make any simple flute, in any scale or tuning, on my first attempt at making it. (How hard could it be? Flutes are pretty simple, right?... Right?) Furthermore, I wanted to subsume this theory as understanding within my intuition-- that is, to be able to, with minimal measurements and little or no calculations, make a masterful albeit simple flute by ear, as it were. Quite a romantic endeavor. Rather, gradually I began to succumb to the crushing weight of the nuanced and subtle art of flutemaking.

I welcome and encourage any critique. Perhaps this text with further some sort of conversation. After all, I hold no masters degree; I am not a proper acoustician. I am sure there are flaws to be found in the simplifications of conceptual physics that I provide throughout. But after having spent countless hours away from the woodshop, digging through search results and textbook indexes, attempting to answer my own basic questions about flute design, it would be a shame for me not to compile and share that information in the form of a text that I wish I myself had had before. If you can't find the book you're looking for, maybe that means you should write that book.

As I approach what feels like a near-end to my study of theory-- and at the time of writing this, having experimented in making 67 flutes from various species and qualities of wood, in various shapes, sizes, and tunings-- there is still much to be practiced and much to develop.

Let's begin then where I began, with the idea of a flute.

The Idea of a Flute

When a flute is blown across, sound waves resonate within it. The length of the sound waves correspond to the length of the flute. Holes along the flute effectively shorten the length of the flute when they are opened-- opening the lowest hole is like bringing the end of the flute up to that point. So, as holes are opened, progressively moving up the flute, the wave length is thereby shortened, and thus the frequency is increased. This is all generally true, but in detail it is not accurate at all.

The remainder of this text will serve as an investigation into why this simple model of how a flute works is inaccurate-- problematizing the flute and thereby unearthing opportunity: distilling simple guidelines for the craft of flutemaking and collecting these concepts into a handy list.

1 Temperature

The temperature of the air inside and outside the flute affects the speed of sound and thus the frequency of the waves within the flute. This should be obvious enough and not need much explanation. The key point here, when tuning a flute, is to consider both the temperature of the air and the temperature of the flute itself. Warmer ambient air temperature or a warmed-up flute will play sharper.

2 Wall Friction

The macro or microscopic texture of the inner walls of the flute generates friction, turbulences and reflections between itself and the air, thereby quieting, flattening, and altering the tone. Nederveen notes that “friction and heat exchange of the air with the wall” results in “a damping and a change in the frequency” (Nederveen 11). While the body of the flute does not act as resonator as it does in a guitar or violin, the texture of the walls affects the air flow. Unless the wood is polished to a glassy smooth surface, differences in grain can have an affect on the quality of sound. It is extremely important that to avoid a difficult, weak tone and a small range, the inner walls of the flute should be as smooth as possible.

3 End Corrections

The length of the sound wave actually extends slightly beyond both the embouchure hole (mouth hole) and the end hole (either the end of the flute or the acting, open tonehole)-- so the wave length is invisibly longer than the flute in both directions. The reflection of the soundwave at the open ends of the flute is due to dynamics in the air pressure in and around the outside of the holes. Joe Wolfe does a good job of explaining this in detail within his pages on flute acoustics, at the website of the University of New South Wales. We already know that when “a hole is opened, the tube is acoustically shortened,” but this is a gross oversimplification (Nederveen 45). And even without opening a hole, the simple model is still hugely inaccurate. The length of the instrument, from embouchure hole to end hole, will always be significantly shorter than it’s associated wavelength. The difference between these lengths are what are commonly referred to as “end corrections”-- we add these corrections to the flutes physical length in order to determine the associated wave length. Understanding these corrections will be the subject of continued investigation here.

4 Size of Toneholes

In general, the size of a tonehole affects its acoustic admittance (how easily sound travels through it), and thus it affects the frequency of that tonehole. I have had great difficulty in searching for a quotation that states this basic fact clearly and concisely-- regardless, it is implied throughout the mathematics of many texts. Nederveen notes that “Variations of 10% in hole diameter […] cause variations in the tuning of about 10 cents” (Nederveen 65). Benade tells us that “decreasing the hole size relative to that of the bore […] flattens the played note” (Benade 450). And widening a hole will sharpen it, as articulated by Bouterse, “enlarging a hole rises the pitch of the tones which are tuned on that hole” (Bouterse 8).

Furthermore, Bouterse continues, “but [enlarging a hole] does that [raises the frequency] as a rule more with the tones of the second than the corresponding tones of the first register” (Bouterse 8). So the magnitude of this sharpening effect is frequency-dependent, having a different effect on higher notes than lower ones. Robinson also tells us, “Notes in the upper octave are apparently more sensitive to hole diameter than notes in the lower; so if the lower note is in tune, but its octave is flat, the note hole can be enlarged enough to sharpen the octave without noticeably sharpening the fundamental” (Robinson 29). As we will look at later, the size of a tonehole also has multiple effects on the tuning of other toneholes.

5 Undercutting Generally

In general, undercutting a tonehole at all will raise its frequency. Benade tells us much about how a lack of undercutting and “The presence of sharp edges brings about airstream turbulence” (Benade 500). He goes on to say that “the nature of the flow through the holes is such as to make them act as though their sizes had been changed, thus spoiling the careful voicing adjustments of the instrument” (Benade 500). From this we can infer that some undercutting is helpful to mitigate this effect. And while Nederveen mentions undercutting as “a practice used for fine tuning and (supposedly) reducing vortex losses at the sharp edges,” we can only assume that these effects are generally increasing the admittance of the hole (Nederveen 113). However, it is clear that undercutting acts as a widening of the perturbation of the bore at that point, which, as we will discuss later, would raise the frequency of the tonehole (see ‘Bore Perturbations in General’). In practice it is obvious that any undercutting will generally sharpen the frequencies associated with that tonehole.

6 Undercutting Directionally

Undercutting in a particular direction, either downstream or upstream, will raise the frequencies of both the fundamental and the upper registers, but will raise them at different rates, ‘shrinking or widening the octave.’ Nederveen rationalizes this, stating “Upstream undercutting means displacing the flow splitting point upstream, which increases the length of the tube piece downstream of the splitting point,”-- as we will see in the discussion of “Downstream Toneholes,” the lengthening of the tube downstream will have a greater flattening affect on the upper registers than the lower-- Nederveen concludes, “this will raise the frequencies of the higher modes less than that of the fundamental” (Nederveen 113-114). In summary we can rely on Nederveen’s statement that, “Instrument builders claim that the frequency ratios of successive modes shrink when the upstream side of the hole is undercut and stretch when the opposite is done” (Nederveen 113).

7 Downstream Toneholes

The frequency of a given tonehole is not only affected by the acoustic admittance of that tonehole, but also by the admittance of the tube and holes downstream from it. So, more, larger, and/or closer toneholes downstream will raise the pitch of toneholes upstream.

Benade describes that “where the lattice of open tone holes begins, the standing-wave pattern has a reversal of curvature, and it trails off in ever-weakening fashion down the lower part of the bore which, as a result, has only a very small influence on the nature of the vibration” (Benade 431). At this point in Benade’s text, he is trying to explain to us why the downstream portion of the flute is no longer very actively resonating-- hence his emphasis, “only a very small influence,”-- but for our focus here, we are interested in the fact that there *is* some influence. The best explanation, that I could find of this phenomenon, was clearly stated by Joe Wolfe in his recent article in Acoustics Today, “But the open tone hole is not exactly a pressure node [...] because the air in and near the tone hole has inertia and must be accelerated by the sound wave. Consequently, the standing sound wave in the bore extends some distance past the first open tone hole” (Wolfe 54). Nederveen also makes a detailed examination of the interplay of admittances at the site of a tonehole, but it is difficult to find a complete phrase that is not steeped in calculus! It’s very important to note here that not only must the size of holes downstream be taken into account when thinking about the admittance of the entire downstream portion of the flute, but also the distance to the next downstream tonehole; as Benade mentions, “making the interhole spacing larger will increase the magnitude of the correction” (Benade 450). The key thing to understand is that an increase in the admittance of the downstream portion of the flute will increase the frequency at a tonehole upstream.

Furthermore, this is frequency dependent, as Wolfe goes on to explain, “This effect increases with increasing frequency because the accelerating force for a given flow is proportional to frequency” (Wolfe 54). In other words, higher frequencies will find the open tonehole less attractive, and will thereby move on farther down the flute; thus higher frequencies are flattened and more affected by the admittance of the downstream portion of the flute. (This applies to our interpretation of how Nederveen rationalizes the effect of upstream undercutting as moving the flow splitting point-- see Undercutting Directionally. It will also apply to our later discussion in “Flattening of Upper Frequencies”).

8 The Cut-Off Frequency

Finally Wolfe concludes that, “at a sufficiently high frequency, the inertia of nearby air virtually seals the tone holes” (Wolfe 54). The notion of cut-off frequencies is of great importance to Benade, and, similarly to Wolfe, Benade says, “The wave is distributed throughout the whole air column […] almost exactly as though there were no open tone holes present!” (Benade 434). What’s going on here? Since the admittance of the toneholes is frequency-dependent, at high enough frequencies the tone-holes act as if they were entirely closed; this plays a role in determining the tone or timbre of the instrument, and somewhat sets an upper limit on the range of the instrument-- or at least on the range within which its toneholes function normally. Frankly, this subject is beyond the cut-off frequency of this text! The bottom line is, increased tonehole admittance may increase the tame range the instrument.

9 Forked Fingerings

'Forked fingerings' lower the admittance downstream from a tonehole and thus flatten that upstream tonehole. At this point it should be obvious that closing holes that are downstream from a given open tonehole, will flatten the frequency of that upstream tonehole at least by reducing the downstream admittance. The greatest flattening effect is achieved by covering the second most immediate downstream tonehole, and then maybe another in addition to that. Benade gives practical advise here for the application of forked fingerings to different registers, "many low-register semitones may be fork-fingered by closing two adjacent holes down the bore instead of only one […] On the other hand, the simpler kind of fork-fingering [closing one hole] will work in many cases in the second register [...]" (Benade 453).

Now, as we have already noted from Wolfe in our discussion of hole admittances, "the standing sound wave in the bore extends some distance past the first open tone hole" (Wolfe 54). This helps us understand Benade's description of the frequency-dependent nature of covering toneholes farther downstream, "At low frequencies the main standing wave does not 'visit' the region in which we have introduced an anomaly, and so is not perturbed by it. The higher-frequency modes (that still lie below cut-off) are progressively more influenced by such a closure, and the effect on them is always to lower the natural frequency" (Benade 451). Nederveen also derives this from his equations, and remarks that when closing a tonehole significantly farther downstream "it can be shown that closing this isolated hole hardly influences the frequency" (Nederveen 65).

10 Bore Size

The bore (the main tube) of the flute affects the frequency: a larger bore will have a lower frequency, and vice versa. This fact appears to be so accepted that it is difficult to find a simple explanation for! To my understanding-- which agrees with the next section, Bore Perturbations in General-- an increase in the size of the bore creates an increase in the compressibility of the air. When the air is more compressible, the areas of highest pressure function at a lower pressure than they would otherwise. When pressure is lowered, so is the speed of sound. Lowering the speed of sound lowers the frequency of the wave. The opposite is also the case: smaller bore, less volume, less compressibility, higher pressure, higher speed of sound, and higher frequency.

Note that if the bore were to be increased or decreased too much, the wave length would grow significantly longer or shorter than the tube length: therefore there is some ideal pairing of flute length and bore size; however, a flute is made to play at multiple frequencies, so a medium bore size must be found which supports both high and low frequencies appropriate to the desired range of the instrument. This is partly by taste or intention: for example, a bold low end can be sacrificed for an easier third register, etc.

11 Bore Perturbations in General

Any perturbations (i.e. expansions or contractions-- or nonuniformities, inconsistencies) to the shape of the bore will affect both the pressure and the speed of the air at that point; this means that some wave lengths will be affected differently than other wave lengths, depending on how the waveform of their standing wave lines up with the perturbation.

What are standing waves? I will explain this briefly, but I recommend Joe Wolfe's work and website for further understanding. Basically, within the flute, for a given frequency, there exists a stationary waveform which represents areas of high and low pressure-- where there is low pressure we call this a pressure node, and where there is high pressure we call this an antinode; there are also areas of high (antinode) and low (node) displacement or movement, where the particles are moving the most or least. Now this will be somewhat of an oversimplification, but moreorless true: Places where there is high pressure, there is also low movement; places where there is low pressure, there is high movement; so pressure nodes correspond with motion antinodes, and pressure antinodes correspond with motion nodes. (Note that different authors often use different terms for the motion aspect: sometimes it is called movement, or displacement, or velocity, or perhaps something else.) The nodes are stationary for a given frequency, hence the term "standing wave." Higher frequencies have more nodes per given length, and lower frequencies have less. In summary, different frequencies will set up a different pattern of nodes and antinodes-- a different waveform-- along the length of the flute.

Returning to our discussion of bore perturbations, if we shrink the bore at a point of high pressure (a pressure antinode) "the air flow will be opposed by a larger rise in the local acoustic pressure than would be present without the constriction" (Benade 474). Similarly to our earlier discussion of bore size, apparently Benade attributes this to a decrease in the compressibility of the air, as he goes on to tell us that "the reduction in cross section will produce a local increase in the springiness coefficient of the air within it" (Benade 474). The opposite would be the case for expansions of the bore.

In general, a perturbation to the bore will lower some frequencies and simultaneously raise others, as summarized by Benade, "A localized enlargement of the cross section of an air column (a) lowers the natural frequency of any mode having a large pressure amplitude (and therefore small flow) at the position of the enlargement, and (b) raises the natural frequency of any mode having a pressure node (and therefore large flow) at the position of enlargement" (Benade 474). Similarly, Nederveen derives from his equations that "the frequency increases when a widening is located in a velocity antinode and decreases when it is located in a velocity node" (Nederveen 56). (Note, this supports our earlier discussion of undercutting: since a tonehole is moreorless the location of a velocity antinode, a widening of the bore at that location will sharpen the frequency.) How much change in frequency? Benade answers that "the maximum percentage change in the frequency (up or down) is equal to the percentage change in the total air volume that is produced by the perturbation" (Benade 476).

But what about when we shrink or widen a longer length of the bore? Recall that the sharpening and flattening effects depend on the perturbation's location in relation to the standing wave's nodes and antinodes, and higher frequencies have their nodes and antinodes closer together (more per length); therefore, higher frequencies will have both nodes and antinodes within the longer area of the perturbation, and thus higher frequencies will be less affected by such a long perturbation-- that is, for higher frequencies (which have shorter wavelengths), the effect of a long perturbation will be evened out across both nodes and antinodes. Benade summarizes exactly this: "A more broadly distributed perturbation acts on the lower modes very much more than on the higher ones, whose weight functions W may oscillate appreciably across the space of the perturbation and so tend to average out" (Benade 477). Nederveen remarks that many woodwinds have a long, gradual shrinking of the bore toward both ends-- as is seen in conical flutes with tapered head joints; in agreement with Benade, Nederveen tells us that this bore shape "mostly causes a lowering of the lowest notes of the instrument" (Nederveen 57). (This frequency-dependent dynamic of long perturbations to the bore will prove very useful in our later discussion-- see "Flattening of Upper Frequencies"). The key point here is that longer perturbations act primarily on lower frequencies, and less so on higher frequencies.

As we will see in our following discussion of closed toneholes, the frequency dependent effects of long and short bore perturbations-- how a single perturbation can raise one frequency while lowering another-- greatly complicate the tuning of a flute. Essentially, every tonehole acts as a widening of the bore at that location; the effect of this is easy to understand for the given tonehole, but what about other frequencies? Not only does this present problems, but also opportunities: areas of the bore can be shrunken or widened in order to specifically affect certain sets of frequencies. Bouterse describes a simple device, called a "flute fish," used by flutemakers to identify the locations of nodes and antinodes: it is essentially a rod with a widened end that can be inserted into a flute to effectively shrink the bore wherever it is set-- as the flute is played, the flute fish can be used to identify the nodes and antinodes based on fluctuations in pitch (Bouterse 4). It is possible to map the locations of nodes and antinodes, for a variety of frequencies, within a flute (see Bourterse's publication for an example of this). Through tedious shrinking and widening of the bore in specific locations, flutemakers are able to simultaneously fine-tune multiple pitches within the instrument. Benade describes his experience with such a process in the case of a bassoon (Benade 478-480). With regard to this, Benade emphasizes, "Careful preliminary planning is essential if there is to be any hope of success in a game that is very similar to a diagramless crossword puzzle in three dimensions" (Benade 480). This is by far the most subtle and labyrinthine aspect of flute design.

12 Closed Toneholes in Particular

Now, if the bore affects the frequency, then so does the presence of the toneholes while they are closed. Closed toneholes act as alterations to the bore such that "the compressibility of the air [...] is slightly increased because of the increased volume provided by the tone hole cavity" (Benade 449). We can conceptualize this such that "[...] closed tone holes effectively enlarge and lengthen the air column" (Benade 448). For the most part, this means that closed toneholes "nearly always lower the frequency" of toneholes downstream from them; and note here that Nederveen says, "nearly always", presumably because closed toneholes, acting as localized perturbations to the bore can also have specific effects on specific frequencies, as we previously discussed (Nederveen 54). Naturally, we can conclude that larger holes and holes with more undercutting will have a greater effect due to their greater volume (space). (Unless a hole is large enough for the players finger-pad to extend down into it or into the main bore-- in which case, it would effectively decrease the volume of the bore and thus increase the frequency of toneholes downstream).

13 Wall Thickness

The wall thickness, at the location of a tonehole or the embouchure hole, affects the volume (space) of the tonehole when closed, and also affects the acoustic admittance of the hole when open and thus the frequency. Since a deeper hole means more volume of air-- and "the air in and near the tone hole has inertia"-- this decreases the admittance of the hole and flattens the frequency (Wolfe 54). In other words, the wave length and the end-correction is made longer as the wall thickness is made deeper, as noted by Benade, "making the interhole spacing larger will increase the magnitude of the correction, as will an increase in the effective wall thickness t_e" (Benade 450). The same holds true for the embouchure hole's end-correction. So, a thicker wall at the embouchure hole means a flattening of the entire flute, while a thickening of the wall at any given tonehole means a flattening of the frequency at that tonehole. Furthermore, for closed tone holes, an increase in wall thickness and volume acts as an increase in the perturbation to the bore at that point-- usually flattening the frequencies of toneholes downstream, but also having various effects depending on the location of the standing waves in reference to that perturbation.

A question arises here: but wouldn't the extra wall thickness thus the increased volume of the hole act as a perturbation in such a way that the open hole would have its frequency raise, much in the same way as is the case when a hole is undercut? I have not found an answer to this in our texts, but will suggest some hypotheses: first of all, undercutting a tonehole has a widening effect on the bore around the perimeter of the tonehole rather than immediately in line with the opening; secondly, the increased turbulences and increased admittance may outweigh any effects of such a perturbation; third, the increased wall thickness increases the length of tube (the tonehole itself) through which the wave must travel.

14 Flattening of Upper Frequencies

Toneholes' admittance is slightly frequency dependent, so that the admittance is lessened for the much higher notes, making them flatter. We have already looked at how the admittance of a tonehole is frequency dependent, specifically how higher frequencies receive more of a flattening affect from open toneholes, and so "this phenomenon by itself accounts for a flattening of any upper resonance frequency relative to the lowest one" (Benade 433). But there are more reasons for this flattening of high frequencies.

The flattening is exacerbated by a players tendency to roll the flute towards their mouth-- thus shortening the blowing distance and covering more of the embouchure hole with their lip-- and to increase the speed of the air, when playing higher notes. Note, the small stream of air between the players mouth and the edge of the embouchure hole has both a velocity and a length; apparently, the ratio of the streams velocity to its length "must take on a certain value for each frequency" (Nederveen 25). Referencing John Coltman's work, Benade tells us that "the presence of the stream lowers the natural frequency of the mode itself when the system is gently blown, and raises it under hard-blowing conditions" (Benade 495). Furthermore, the upper register of a given tonehole "does not have its frequency shifted by the excitatory airstream" (Benade 497). Now we can see that if, as Nederveen says, a player must increase the speed of their breath as they move up to the second register, then according to Coltman's findings this speed would sharpen the lower register-- thus shrinking the octave and essentially making the upper register flat relative to the lower.

Again according to Nederveen, in alternative to this increase in speed, the player can shorten the length of the stream: "For an even excitation over the whole compass, the hole is progressively covered by the lips as the frequency rises" (Nederveen 43). However, covering the embouchure hole reduces its admittance and therefore "the end-correction of the hole increases and the frequency is reduced" (Nederveen 43). All of this implies that a perfectly cylindrical flute that is well in tune in its lower register will tend to go flat in the upper portions of its upper register. That is, as one progresses up the toneholes, the distance between the fundamental notes and their overblown notes will decrease to less than an octave-- their 'octaves will shrink.'

How to solve this flattening? There are multiple possibilities, but generally "This flattening (which can amount to an appreciable fraction of a semitone) may need to be offset by alterations in the bore profile" (Benade 433). In conical flutes, the bore tapers gradually from just below the headjoint, shrinking all the way down to the foot of the flute. But rather, our authors here tend to focus on the Boehm-style taper, as Nederveen says, "The contraction of the bore towards the flute's embouchure-hole compensates for this [flattening] effect" (Nederveen 43). This makes sense when we think of it in terms of our earlier discussion of bore perturbations which extend across some length of the flute (see Bore Perturbations in General). In other words, a tapered head joint'-- a gradual shrinking of the bore as it nears the embouchure hole-- will lower the frequency of the lower frequencies, while leaving the highest frequencies unaffected-- thus solving our problem.

But there is more going on here for Benade and Coltman. The tapering actually puts the upper register "25-35 cents more than an octave above the measured first mode frequency [the lower register]" (Benade 495). In accordance with Coltman's notion of how the lower register sharpens under faster breath (louder playing)-- while the upper register goes unaffected-- without this widening of the octave, the upper register "will lie to low for good cooperation when the instrument is played loudly, since it does not move up as the blowing is strengthened" (Benade 497). In other words, by positioning the upper register sharper than the lower, when the instrument is played loudly, the lower register will rise to meet the upper.

15 The Upstream Space and Cork Placement

The extent to which the wave extends beyond the embouchure hole is partially dependent on the size of the "upstream space"-- the space between the embouchure hole and the cork or upper end of the flute's bore. The sum of the admittances of the downstream bore, the upstream space, and the embouchure hole "must be zero" (Nederveen 26). To really understand the physics of the upstream space, I recommend Joe Wolfe's website as a starting point: Wolfe describes the upstream space as acting as a frequency-dependent impedance. The importance of the upstream space is thus: the effect that the upstream space has on the embouchure hole's end correction is frequency-dependent: higher and lower frequencies respond to the length of the upstream space differently. Similarly, Benade tells us, "the magnitude of the embouchure hole correction C_{emb} varies with frequency" (Benade 494).

Terry McGee's website contains a vast contribution of research, and one page "Effect of Stopper Position," shows us a graph clearly indicating that the length of the upstream space has the most effect on the higher frequencies of the flute, allowing them to be sharpened or flattened. This is why many flutes are made with an adjustable cork enclosing this upstream space. As summarized by Trevor Robinson, "Moving the cork toward the embouchure sharpens the overblown note, and moving it away flattens it" (Robinson 29). But sometimes, for example, the lower toneholes' octaves are wide while the upper toneholes' are accurate-- in such a case, Robinson goes on to give flutemakers the practical advice, "For final tuning it is best to adjust so that the octave overblows most accurately at G [a mid range tonehole]. This gives the best compromise for other notes" (Robinson 29). The utility of this should be clear enough: "this serves to clean up the last subtle details of the air column perturbations that are needed for good alignment of the modes [registers]" (Benade 495).

16 The Shape of the Embouchure Hole

The size, shape, depth, and undercutting of the embouchure hole affect the frequencies of the entire instrument, both the fundamentals of the toneholes as well as the intonation of the registers. I can say this from experience. I can also say that it is difficult to find much research into the subtleties of embouchure hole design; no doubt: it is such a sensitive, small, and curiously shaped part of the instrument that a scientific investigation into its physical properties would prove difficult. While there is much discussion into the external shape of the embouchure hole-- whether it is circular, elliptic, or a rounded rectangle-- discussion of the interior undercutting of the embouchure hole, which has the greatest effect on its character, seems to be lacking.

We might begin with a basic understanding of how the embouchure hole functions. The breath is directed across the hole to the opposite edge. This edge is called the "labium". At the labium, the breath is first directed into the hole, beginning the sound wave; then, when the sound wave returns from the other end of the flute, the wave momentarily pushes the stream of breath back up out of the hole. In this way, the stream of breath alternates its flow in and out of the flute in accordance with the sound wave-- as described by Wolfe, "standing waves with large flow amplitudes at the embouchure hole can entrap the jet in a feedback loop that causes it to be directed alternately into and outside the bore, thus maintaining the amplitude of standing waves in the bore" (Wolfe 55). Put another way, by Benade in reference to blowing over a bottle, "the player's air is directed into and out of the bottle exactly in step with the governing oscillatory flow, so that we are assured that an oscillation will be maintained" (Benade 489).

It should be obvious that the embouchure hole has an affect on the intonation of the entire flute, since it is instrumental in any sound that the flute makes. As Bart Hopkin describes, "The size of the blowhole affects tuning of all the notes, with a larger hole raising the pitch"; and we already can deduce this from our understanding of admittance: a larger hole has more admittance and thus raises the pitch (Hopkin 63). Many flute players claim that a deeper embouchure hole gives the flute a stronger low end, and vice versa.

Luckily, a profoundly helpful letter was recently (April 2017) published in the FoMRHI Quartlerly (Comm. 2070). As described in the publication, after 40 years, a letter, from Benade to a student, eventually fell into the hands of Renaissance flutemaker Filadelfio Puglisi, who saw to it that it was published. In this letter, Benade gives extremely detailed descriptions of his style of undercutting Renaissance flutes. While the size, shape, and undercutting of the embouchure holes of Renaissance flutes are dramatically different from those of Irish flutes and modern cylindrical flutes, much of the advice that Benade gives seems to be easily translated-- in my experience.

By the time I came across this letter, I had already experimented with making about 50 flutes, and so I had established my own style of embouchure cut, to some degree; Nonetheless the letter did help me bring into focus some of my own experiences. In some ways, the shaping of the embouchure hole may be a source of proprietary secrecy for flutemakers, but in others, it is just nearly impossible to describe. Or flutemakers understand that it is idiosyncratic enough to the particular maker, that they wouldn't want to spoil a new makers process of learning for themselves. After spending so many hours beneath a work light, hunched over a flute, delicately shaping and gazing into an embouchure hole, my spatial awareness of its dimensions expands so much that it seems to be the size of a room, a hair of wood grain seems to be the size of a stick: I cannot believe how small they actually are! The feel for the tools and the appearance of a stark shadow on the inner curve could only have become familiar through practice.

This all being said, I will not deprive you of some simple advice-- so long as you accept that I am no master flutemaker. Begin with the embouchure hole much smaller than you would expect. Try to simultaneously undercut the embouchure hole, opening it from the inside, and also widen its general dimensions: in this way, you are both transforming it from a simply drilled hole into its final shape and also opening it up gradually at the same time. Measure and test the flute very frequently. You may wish to make the embouchure hole circular, elliptic, or a rounded rectangle, etc; you may wish to rotate the hole at some angle (rather than intending it to be blown across at a 90° angle from the length of the flute). Experiment with the symmetries of the outer shape of the hole. The opposite edge that is blown across (the labium; we call this direction 12 o'clock) should be slightly angled inward, but not too sharp. Across from the labium, the inner edge that is closest to the mouth can have much more substantial angling and rounding down into the bore. Now I will emphasize an aspect which Benade also emphasizes in his letter: flanking either side of the labium, at something like 10 or 11 o'clock and 1 or 2 o'clock, in the transitional areas between the opposite edge and the downstream and upstream sides of the hole: these portions of the wall should be angled but not rounded at all. You may experiment with subtly rounding the very center of the labium leading (12 o'clock) down into the bore. Farther along, the upstream area, say at 7 or 8 or maybe 9 o'clock can have some angling and rounding as well, but not too much. The downstream side, closer to the player, maybe at 4 or 5 o'clock, can have substantial angling and rounding; very deep undercutting here will serve to make the sound of the flute much stronger, although it may, according to your preferences, desirably or undesirably alter the timbre, the tone-- so pay attention. Learn to carefully morph all of these different rounded and unrounded areas gradually into one another, to minimize abrupt changes in angle. For me, the most abrupt change in angle is at the downstream side. My recent embouchure holes tend to make a sort of gradual, counter-clockwise curvature, leading from the labium, around and down the downstream side of the flute. I wouldn't be surprised if many flutemakers think this approach is ludicrous. If you want more quantitative or detailed advice, once again I recommend Benade's letter. Nothing will replace your own practice.

17 Human Intonation

The intonation of a flute is finally dependent on the players lips, tongue, soft palate, etc-- their body, breath and, of course, their subconscious. Let's consider some of the simple ways that a players embouchure creates the sound: "For example, a flute is supported rather weakly by the lip and fingers; its head can freely move up and down, thereby intercepting a varying amount of the jet flow and/or deforming the lower lip, varying the slit height" (Nederveen 134). Nederveen also remarks that changes in the players lips allow them to "easily" move the tone by 10 cents and that "fluctuations of this magnitude are common in normal playing" (Nederveen 95). Benade gives us a more detailed explanation of the physics of the airstream, particularly with regards to the "transit time" that is between the players lips and the flute's labium,

> "The flute player has great flexibility in tone production because there is a range of transit times that will suit the maintenance of each note of the scale. Furthermore, he has many optional ways in which he can attain the desired transit time, because he is free to trade off a larger or smaller stream distance d_s against a smaller or larger flow velocity. He can control the thickness t_s and the width w_s of the airstream by altering the spacing between his lips as well as the angle at which he blows." (Benade 492-493)

But our authors go on further to address the implications of all of this for instrument construction, as hinted at by Benade as he immediately continues, "All of these things permit the skilled player to elicit musically useful sounds from practically any sort of flute, whether it is properly made or not; on a well-made instrument, they give him an enormous (but seldom fully exploited) range of tonal possibilities" (Benade 493). We see this idea more fully expressed in Nederveen, who similarly begins by describing the behavior at the embouchure hole, "Moreover, by shaping his lips, the player is able to correct notes which are slightly out of tune, thereby blurring tuning differences between flutes. Especially for very high notes this technique is frequently used since the highest are not among the purest in intonation." But then Nederveen continues immediately with what is almost a concession: "We conclude that a painstakingly accurate investigation of the various corrections is quite unnecessary" (Nederveen 27). Later on, when reflecting on the experimental application of the mathematics and whether or not the player's embouchure can be mathematically accounted for, Nederveen tells us, "This experiment showed that there is no standard embouchure correction: all depends on the player. Taking the embouchure correction as a constant would be unrealistic" (Nederveen 75). And finally, more directly with regard to instrument construction, he tells us that this human factor removes the possibility of a fully determined, perfect instrument: "The flexibility in pitch implies that instrumental geometries are not critical within certain limits. Hence, mouthpieces, reeds, blowing methods, bores and holes may somewhat vary and yet yield equally satisfying results" (Nederveen 95). Strangely enough, this has profound implications for humanity: to recognize that, if the human is literally part of the equation, then the idea of a perfect flute implies the idea of a perfect human; Thus, we must embrace the variety of flutes in their differences, if we are to embrace human diversity.

The identification of the human with the instrument does not stop at the air stream and lips, but furthermore Nederveen tells us that even the resonances inside the players mouth and vocal tract play a role. He tells us that the vocal tract "is a resonator, though at the upstream end of the excitation. […] Coltman (1973) observed frequency shifts and increased losses in flutes due to mouth resonances" (Nederveen 133). And yes it is true, Coltman does say, "The presence of this coupled cavity can affect the flute frequency by as much at 10 cents, and may increase the losses in the system by as much as one-third" (Coltman 1). All of this should come as no surprise to flute players who are accustomed to adjusting their tongue and soft palate or feeling a sense of the resonance within.

Renaissance flutes are known for having a challenging intonation which *almost* doesn't lend itself to any particular tuning or temperament, but rather seemingly presents the player with a continuum of possibilities. In Nancy Hadden's dissertation, inarguably the most comprehensive investigation of existing knowledge of Renaissance flute, we see these flexibilities, the possibilities of the player's variations of tone, not questioned but rather embraced as an element obviously to be celebrated:

> "Melodic instruments are not constrained by closed temperaments. They adjust tuning by ear during playing. When playing with an instrument of fixed pitch, they must adjust somewhat to the temperament, but there is always the option for expressive adjustments. Tuning decisions are a moveable feast, changing according to context and mode; melodic 'pull', vertical intervals and cadence structures all influence how an individual player might choose to tune." (Hadden 280)

Yet we have merely brushed over the effect of a players grip, the pressure and formation of the pads of their fingers, enclosing the ceilings of the tone holes, fingertips larger or smaller, softer or more calloused skin. Once more we turn to Nederveen, who very aptly acknowledges that "a musical instrument tends to become an extension of the player's body and incorporates all natural reflexes pertaining to such a situation" (Nederveen 4). Indeed a particular instrument, with both its intentional tuning deviations and its unique set of unintentional tuning ~~imperfections,~~ eventually becomes one with its unique player in a such a way that any such variations become overwhelmingly outweighed by the players sensitivity and flexibility to play musically with this idiosyncratic 'extension of their body.'

But there is something deeper here: What of the players "reflexes?" What of the their diaphragm, or their exhaustion? What of their nervousness or their anticipation? Shouldn't tests for tuning be performed double-blind? So beyond or before the question of whether we should be asking 'tuning to what' versus 'tuning to who,' there is question of 'how tune?' How could we both consciously and objectively control minute elements of an instrument which is so sensitive, so versatile, and so human? Can our fingertips move faster than our tongues?

Summary of Guidelines for Flutemaking

> "A complete description taking all interactions into account, for example as a set of equations, is not possible with the present state of knowledge. Even if this could be accomplished, solving the equations would be a formidable, if impossible, task. However, solutions can be obtained after sensible simplifications, leading to understanding and practical applications." (Nederveen 109)

> "In making a tonehole wind instrument, you may be able to do your hole placement and tuning by instinct, trial and error, and subsequent fine tuning, dispensing entirely with preliminary calculations." (Hopkin 83)

I have decided to list these guidelines in the order in which they appear in the text, rather than grouping them by technique or effect. A technique, such as enlarging a tonehole, may appear multiple times within the list, in both earlier and later locations: one is encouraged to read the list all the way through and to cross check effects. Furthermore, these guidelines can often be contradicted by special circumstances: that being said, I'm *not* going to redundantly preface or disclaim most of the elements in the list with "in most cases" or "usually." In general, many of the factors at play here are interrelated by multiple dimensions and a linear list is not the best way for them to be represented.

Temperature

1. Warmer ambient air and a warmer flute will sharpen the frequency.

Wall Friction

2. Friction with the flutes walls quiets and flattens the tone.

End Corrections

3. For a given frequency and dynamic, the flute's physical length, measured from embouchure hole to tonehole (or end of flute), will be shorter than it's associated wavelength, and how much longer the wave length is than the physical length, at either the embouchure hole or the tonehole (or end of flute), is called an "end correction."

Size of Toneholes

4. Enlarging a tonehole will sharpen the frequencies associated with that tonehole.
5. Enlarging a tonehole has a greater sharpening effect on the higher frequencies (e.g. higher registers) than the lower frequencies associated with that tonehole

Undercutting Generally

6. In general, undercutting a tonehole will sharpen the frequencies associated with that tonehole.

Undercutting Directionally

7. In particular, undercutting upstream will have a greater sharpening effect on the lower frequencies associated with that tonehole, while undercutting downstream will have a greater sharpening effect on the higher frequencies associated with that tonehole.

Downstream Toneholes

8. More open toneholes downstream from a given tonehole will sharpen the frequencies associated with that tonehole, and this will have a greater effect on higher frequencies.
9. The closer that downstream, open toneholes are to a given upstream open tonehole, the greater the sharpening effect of the downstream toneholes will be upon the associated frequencies of the upstream tonehole-- and this will have a greater effect on higher frequencies.
10. The larger that downstream, open toneholes are to a given upstream open tonehole, the greater the sharpening effect of the downstream toneholes will be upon the associated frequencies of the upstream tonehole-- and this will have a greater effect on higher frequencies.

The Cut-Off Frequency

11. A flute has a cut-off frequency above which the toneholes no longer function normally.
12. Increasing the admittance of the toneholes in general will increase the cut-off frequency.

Forked Fingerings

13. Lower frequencies are less affected by forked fingerings than higher frequencies are; thus, to flatten by a half-step, lower frequencies may need two downstream holes covered while higher frequencies may need only one hole covered.
14. Closer downstream toneholes have a greater flattening effect when covered in a forked fingering.

Bore Size

15. A larger bore will have a lower frequency than a smaller bore of the same length.
16. Different ratios of bore size to flute length have different advantages and disadvantages regarding the flute's tone, range and playability: a medium can be found which best suits a given maker's taste or intentions.

Bore Perturbations in General

17. A perturbation to the bore (an expansion or contraction, etc) will have different effects on different frequencies, depending on how the standing waves of those frequencies line up with the perturbation.
18. Expansions of the bore will lower frequencies who's standing waves have pressure antinodes (maximums) at the locations of those expansions, and will raise frequencies

who's standing waves have pressure nodes (minimums) at those locations. The inverse is true for contractions to the bore.

19. Longer perturbations to the bore-- which spread out along some distance rather than only a smaller, more specific point-- have more of an effect on low frequencies than on high frequencies.
20. Areas of the bore can be intentionally perturbed so as to raise and lower specific sets of frequencies.
21. A "flute fish" is a tool that can be used to identify the locations of nodes and antinodes of standing waves within the flute.

Closed Toneholes in Particular

22. Closed toneholes act as perturbations to the bore.
23. Larger or more heavily undercut toneholes, when closed, nearly always lower the frequency of downstream toneholes.
24. For very large toneholes, a players finger pad begins to extend down into the tonehole, having an affect on its volume (space).

Wall Thickness

25. A thicker wall increases the volume (space) of a closed tonehole, thus causing it to act as a larger expansion of the bore.
26. A thicker wall flattens the frequencies associated with a tonehole, and this flattening effect is greater for higher frequencies.
27. A thicker wall at the embouchure hole will flatten the entire flute.

Flattening of Upper Frequencies

28. The frequency-dependent effects of tonehole admittance lower the higher frequencies of the flute, generally causing a shrinking of octaves between registers as one moves up the toneholes.
29. Increased breath speed raises the frequency of the first register but not the second register; this can contribute to the shrinking of octaves and is why many flutes are tuned such that the registers' octave is wide.
30. Increased lip coverage of the embouchure hole flattens the frequency, and in practice this behavior is known to contribute to the flattening of high frequencies.
31. This flattening of the high frequencies of the flute can be compensated for by tapering the bore of the flute as it nears the embouchure hole.

The Upstream Space and Cork Placement

32. The effect of the upstream space (between the embouchure hole and the cork or upper end of the flute) is frequency dependent.
33. Lengthening the upstream space will narrow the octave between registers, and shortening the upstream space will widen the octave between registers.

The Shape of the Embouchure Hole

34. Widening the embouchure hole will sharpen the entire flute.
35. The shape of the undercutting of the embouchure hole drastically affects the playability and tone of the entire flute.

Human Intonation

36. The length, speed, shape, and angle of the breath at the embouchure hole have effects on the intonation of the flute.
37. The shape of the players lips and the interior of their mouth and vocal tract affect the flutes intonation.
38. Fluctuations of pitch are normal and can be a celebrated aspect of flutes.
39. The human variable puts a limit both on the efficacy of mathematical predictions and on how 'in tune' we can call a flute without its human.
40. Given time to develop a relationship with the instrument, individual players incorporate the unique qualities of a particular instrument as second nature-- the two become one.

Appendix: Notes on Graphing and Predicting Flute Intonation and Tonehole Location

There are many multi-variable equations available for predicting the locations of toneholes-- some requiring calculus or trigonometry, others merely algebra. Often times these demand complicated processes in order to apply or make calculations with them. I would like to introduce a basic approach to graphing and predicting the intonation and locations of toneholes.

I cannot say whether or not this will be particularly helpful in avoiding extra work: with or without the predictions, you may still need to, as Hopkin recommends, "Make a series of instruments with identical tube dimensions. Make your mistakes and attempted corrections on the first; incorporate your best results into the second. Continue your refinements through a third and fourth and fifth if need be" (Hopkin 83). Today my methods of prototyping have returned to a much more informed trial-and-error approach, as I find the equations increasingly unnecessary and the iterations and experiments more crucial. Regardless, I was very excited when I recognized this mathematical approach, and so I have decided to include it here.

The idea is simple. Rather than trying to graph tonehole locations as absolute distances that are a function of absolute frequencies, instead we graph each of these as ratios relative to the fundamental of the flute: the ratio of the length from the tonehole to the embouchure hole versus the length from the end of the flute to the embouchure hole, represented as a percentage; and the pitch of the tonehole in terms of musical "cents" different from the lowest note of the flute.

First measure the length from the embouchure hole to the tonehole in question. Divide this by the length from the embouchure hole to the end of the flute. This is a percentage that will become your Y coordinate.

(The next part is a little bit trickier because it involves translating a difference in frequencies into a difference in cents-- which are logarithmic. Cents are logarithmic because there are always 1200 cents in an octave (100 cents in a half-step-- Get it now? Cents?), but octaves are relative: they are a doubling of frequency, so that an octave above 216hz is merely another 216hz higher (giving us 432hz) while the next octave is 432hz higher, and the next is 864hz. Anyway, you can study this more elsewhere.)

So secondly, measure the frequencies of the lowest tone of the flute and of the tonehole in question. Calculate the difference in cents between the two frequencies by using the equation,

$$c = 1200 \bullet \log_2(b/a)$$

where a is the frequency of the lowest note and b is the frequency of the tonehole. To do this calculation, first divide b by a, then use a calculator to take the $\log_2$ (log base 2) of that number, then multiple this by 1200. This gives you "c", or the number of cents from the frequency of the lowest note to the frequency of the tonehole. This becomes your X coordinate.

Do this for all of the toneholes and registers. You can even measure highs and lows by bending the notes as much as you can, although this will be a lot of frequency measurements and a therefore lot of math.

Make a graph numbered 0 to 100 on the Y axis, and 0 to 12, or maybe 13 or 14, on the X axis. The X axis is hundreds of cents (so it's as if you made it from 0 to 1200 or 1300 etc). And the Y axis is the location of the tonehole as a percentage of the total length, each measured relative to the embouchure hole.

The coordinate will approximate a curve which you can use to estimate the locations of holes for a new flute. Of course, given all of the factors affecting a flutes frequency-- in particular, holes' proximities to one another-- that we looked at in the earlier portion of this text, the curve will only give you an idea of where to begin.

Perhaps the process still isn't clear. Say you make two identical flutes, with identical bore size and embouchure holes, etc, without any toneholes yet. Say you want your final flute to have six holes. First you drill these holes in locations on the first flute, based on your intuition or a wild guess. Fittingly, these holes are wildly out of tune, but you widen them not more nor less than your ideal hole size-- plus you undercut them a bit. Then you make a graph of this flute. While the coordinates are way off from what you'd like them to be, they nonetheless produce *a curve* which tells you less about the particular locations of those toneholes, and more about how that particular bore and embouchure hole and upstream space and number and size of holes, etc, respond. So you can choose the X coordinates (cents) that you want for your next flute, and then line these up with the curve to find the associated Y coordinates (percentage length) which tell you at what length to place your new toneholes. Contemplate the guidelines-- specifically how nearby holes affect one another-- and then make some small intuitive adjustments before drilling. And of course then begins the process of widening and undercutting and tuning the toneholes, which is another story!

A cool thing about this sort of graph is that it can be used to compare flutes of various shapes and sizes, since the variables are all relative. So you can compare the curve of a piccolo to the curve of a bass flute. On the same graph, you can also compare the similar but slightly different curves of two similarly sized flutes with different scales or numbers of toneholes, etc.

If you've really got the gumption, you can approximate the curve with an exponential equation. Such as this one that I found for one of my low D flutes, with a 3/4" cylindrical, non-tapered bore, a 5mm wall thickness, a 5/8" upstream space, seven toneholes, and a small but deep embouchure hole:

$$y = 96.5(0.924^{x})$$

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[Jan Bouterse has many more, similar and relevant publications in FoMRHI. Bouterse also has published these as a book. Visit Bouterse's website at http://www.mcjbouterse.nl/handleiding.htm for more information.]

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