
Hoots, Hertz and Harmonics:

Fundamental Physical Phenomena for Flautists.

MORE ABOUT HARMONICS AND THE TOP OCTAVE

By
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Part 4



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I have had many requests for back issues containing the previous instalments of Dr Robin Jakeway's excellent series Hoots, Hertz & Harmonics. To this end, all the instalments can be found on the BFS website at www.bfs.org.uk. If you want previous instalments and do not have access to the internet, please send a cheque for £2 sterling, made payable to The British Flute Society, and I will supply. Please use the latter option ONLY if you have no access to the FREE internet copies. Editor

THE PROBLEM OF INTONATION

Why we have difficulties in playing in tune and what we can do about it

What do we mean by playing in tune? I'm sure that most of you reading this will have been bothered at some time by this simple question. **There is no simple answer!** What we are going to do in this article is to explore and explain a few ideas which might help. Let's begin by thinking about how one musical note relates to another. This means looking at scales since it has been known for over two thousand years that a musical scale is not just a collection of sounds with randomly chosen frequencies. Now in Part 1 we saw how the octave and fifth appear like magic when we play with simple numbers like 2 and $1\frac{1}{2}$. We can use only these two intervals to make smaller intervals and a diatonic scale. Have a look at Box A (over).

Another way of constructing a scale is to look at frequency ratios. We select the frequency of each note so that, when we divide it by the frequency of the tonic, the result is the ratio of two simple numbers. This is illustrated in Box B (over).

We can see that D is the same note as in the Pythagorean scale but E is not. The ratio of E to C is slightly smaller. Some of the others are different as well.

Why is this a useful scale? Because when you play E, F, G or A with C the sound is pleasant or harmonious. Why is this? Well, harmony is a complicated business but we can get some idea by recalling what I said in an earlier article about harmonics. Suppose we play C and G together on real instruments so that the notes contain harmonics. The harmonics of each note are shown on the staff in figure 10 (over). Where the notes both produce the same harmonic (arrowed) the

SNAKES AND LADDERS ACCORDING TO PYTHAGORAS - AN ACOUSTIC GAME

Start on C, go up two fifths (two lots of $1\frac{1}{2}$ in frequency) and then down an octave (halve the frequency). You arrive at D and have “manufactured” a whole tone, C - D with a frequency ratio of $1\frac{1}{2} \times 1\frac{1}{2} / 2 = 9/8$. Do it again and you get to E, another whole tone and a major third above C with a ratio E to C of $81/64$! If you carry on with this game in a special way you can make all the notes of the major scale quite logically. The scale is attributed to Pythagoras (do you remember about right angled triangles and the famous theorem?). The interesting thing about it is that it is not quite the same scale as you find on the piano. It sounds broadly the same but every note (bar C) is slightly different from the corresponding piano note.

Box A

Note	C	D	E	F	G	A	B	C
Ratio of Frequencies	1	9/8	5/4	4/3	3/2	5/3	15/8	2

Box B

EXPERIMENT 1 - INVESTIGATING BEATS

Apparatus needed: Your flute, another flute player.

Play a low G together fairly quietly and at the same volume (NO VIBRATO!!). One of you must keep a constant pitch and the other should bend the pitch up or down by a small amount. If you start off very close in pitch you will hear a slow beating sound, i.e. the combined sound level will vary slowly. As you get further apart the variations get faster. The frequency of the beats is exactly equal to the difference between your two frequencies. Try other notes. When there are no beats you are dead in tune and have cracked the first problem of intonation.

Box C

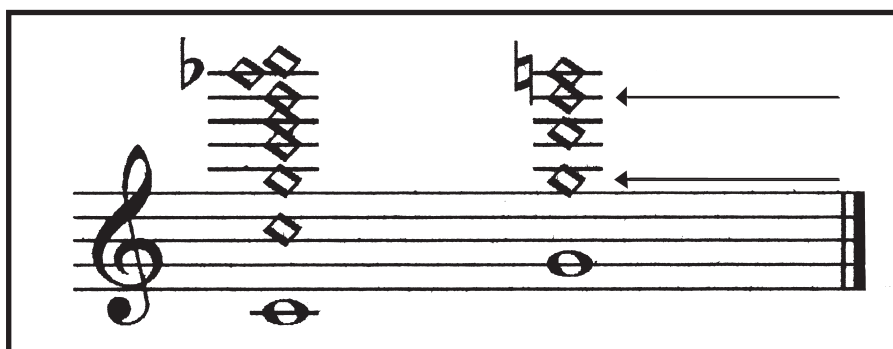


Figure 10
Some of the Harmonics of C and G.

The two notes produce Gs as identical harmonics. If we play the two together and want the sound to be as pleasant as possible then the Gs should have exactly the same frequency - giving a zero beat rate. Other sets of harmonics will also produce beats of course (C and D, high B flat, B and C for example) but the beats will be very rapid and not as noticeable as the slower beats between the two Gs when they are very close together.

combined sound will only be pleasant if the harmonics have exactly the same frequency. If they are not exactly the same they will beat (see Box C above) at the frequency difference and produce a rough noise. Some simple arithmetic tells us that they only have the same frequencies when the ratio of G to C is exactly $3/2$. The same is true of the major third, for example, the beats vanish when the ratio is exactly $5/4$.

This scale is sometimes called

the Natural scale and is different from both the Pythagorean scale and the piano scale. An interesting feature is that the interval D - E is not the same as C - D. The frequency ratio of E to D is equal to $5/4$ divided by $9/8$ which is $10/9$ - not too different from $9/8$ but enough for a musical ear to discern.

CENTS AND INTERVALS

People who are interested in scales measure intervals not in ratios but in cents. If you fancy

some arithmetic, have a look at the box. If not then simply remember that an octave is 1200 cents and a semitone on the piano is 100 cents. The useful thing about cents is that you add cents to make bigger intervals rather than multiplying ratios.

For example, a whole tone on the piano is two semitones or 200 cents. A major third is four semitones or 400 cents and so on. If you have a calculator handy you can work out that C - D in the Natural Scale is 204 cents but D -

CENTS AND LOGARITHMS

To find the number of cents corresponding to a frequency ratio take the logarithm of the ratio and multiply it by 3986. For example we know that an octave has a frequency ratio of 2. The logarithm of 2 is close to 0.3010. Multiply this by 3986 and the answer is very nearly 1200. The fifth has a ratio of $1\frac{1}{2}$. The logarithm of this is nearly 0.1761. Multiply it by 3986 and the answer is almost 702.

Box D

E is 182 cents!! C – E is the sum of these, 386 cents which is very different from the “piano” 400 cents. On the other hand C – E in the Pythagorean scale is 408 cents so there seems to be at least three kinds of Major Third!

Why do I keep going on about the piano? Because there is a serious problem with scales when you want to tune a keyboard instrument. We’ve already seen an example of this with the natural scale. The whole tone C – D is different from D – E so if we tuned a piano using this scale the scale of D would sound different from the scale of C. All sorts of

compromises (for example, mean tone scales) have been devised over the years to tune a keyboard so that different keys can be used. Most keyboards nowadays are tuned very simply so that every semitone equals 100 cents and then every key sounds exactly the same. This is called Equal Temperament and is a useful working system. Most of us get used to it and are quite happy but if you start to listen more critically – especially to a pipe organ – you might notice that some of the intervals are badly out of tune – i.e. the harmonics don’t match! The thirds in

particular are very bad.

So we come back to intonation and what it means. You can think of two sorts of intonation. One is when you play a single melody line and the other is when you play with someone else. An unaccompanied melody line (of Western music) sounds perfectly OK whether you use a Pythagorean scale, a natural scale, an equally tempered scale or a mean tone scale. There is some evidence that singers follow Pythagoras. As soon as you play with someone else, however, things are very different and good intonation means making

EXPERIMENT 2 - LISTENING TO A MAJOR THIRD

Apparatus needed: Your flute; another flute player; an electronic tuner (which should be calibrated in cents); an ear willing to listen critically (a third person will do and might be even better).

The idea is to play a major third and really learn what a proper one sounds like. Start with G and B above the stave.

First of all use the tuner to tune each of your notes as exactly as you can and then play and hold them (NO VIBRATO!!). Listen carefully. Now the person playing G should hold it at zero on the scale but the B should be bent down by 14 cents. Play and hold them and listen again. The interval will sound different and more pleasant as you bring the harmonics into tune. When they are exactly in tune and all the rough beats have gone you have made the major third ratio equal to $5/4$ or 386 cents. You will probably need to do this several times until you have trained your ear what to listen out for.

As a by product of being dead in tune you will hear a beat note between the fundamentals of each note and this should be exactly two octaves lower than the G. I’ll look at this in more detail in a later article.

If you get the chance, listen to some organ music played on an organ tuned in a mean tone scale - there are records around. The thirds are much better in tune and the whole sound is quite different. The trouble is that our equally tempered ears may not like it at first!

Box E

OCTAVE STRETCH ON A PIANO

Vibrating strings do not behave exactly as simple physics predicts. The harmonics are all a bit sharper than they should be. The second harmonic is a tiny bit more than an octave above the fundamental, the next harmonic is sharper still and so on. A tuner tunes the upper notes by listening to the beats between the upper note and the harmonics of a note an octave lower so the upper notes get progressively sharper. They can be up to about 30 cents at the very top. This means that a flute player has to play sharp in the upper register to stay in tune.

Box F

intervals that sound pleasant.

LESSONS LEARNED SO FAR

What has all this taught us about playing in tune? The major lesson is very important and is that there is no such thing as a unique “correct” set of notes on any instrument. Even on a keyed instrument like the flute the exact note that you play will depend on what else you are playing with. If you are enjoying yourself with *Syrinx* then you can let nature take its course and simply make sure that the intervals formed by successive notes are not too wildly out. This does not mean being sloppy but a natural scale, a Pythagorean scale or even an equally tempered scale will all sound acceptable. You almost certainly will not consciously use one of these scales, you will

simply use your musical experience. On the other hand if you play with a piano then you will mostly have to follow the equally tempered scale, especially when playing unisons. Octave stretch (see Box F below) makes life even more complicated here!

If you play with good string players then you have to listen very carefully to their notes. They will be playing in harmony amongst themselves and will probably be using “natural” intervals so you have to as well.

TUNING IN THE ORCHESTRA

In the orchestra everyone starts by agreeing formally with the 440 A from the oboe but after that it's every man for himself (OK, every woman for herself if you insist). That sounds awful but what I mean is that every

instrument will not play to exactly the same scale. The free pitch instruments (strings, trombone) will probably use something like a natural or pythagorean scale whereas the keyed instruments will probably be closer to equal temperament. In these circumstances playing in tune still means adapting to whatever else is going on by using your ears. If you have an interval like a major third to play with the oboe, make it a good one (386 cents) not a horrible 400 cent piano interval. If you have trained your ear it will tell you when it is right. It is no good saying to yourself, “when I blow an F# like this it is spot on with the tuner” and sticking to that through thick or thin because the tuner give you equal temperament rather than the “right” note.

BENDING NOTES

Obviously, to play in tune we have to be able to bend notes. Experienced players know what to do, of course, without thinking about it but if you are uncertain about what is happening or if you are teaching someone then a little physics goes a long way to help.

Three things are important in determining exactly what note comes out of your flute (see Parts 2 and 3).

1. *The precise acoustic length of the part of the tube that you are using.*
2. *The speed of sound in air.*
3. *The fact that the resonance effect in the tube is relatively ill defined.*

The acoustic length of the tube is the actual length (i.e. embouchure hole to first open hole) plus a bit at each end known as the *end correction*. This correction depends upon the size of the hole at the embouchure and at the lower end wherever that happens to be. We can't usually do much about the hole at the lower end except when we want a low C sharp on the piccolo and I'm sure that many players have learnt to curl their little finger over the end to get that note when it is wanted. What we can do is alter the size of the embouchure aperture although I am amazed by the number of people who are not aware (a) that they are doing it all the time and (b) why they are doing it.

Most of us play (I think) with about one third of the hole covered by our lower lip and this gives the nearest to the "correct" pitch under normal circumstances. Remember, when you did the resonance experiments with the bottle, flute and tuning fork I suggested that you tuned the bottle using water until it sounded a little flatter than the fork and that you pulled out the head on the flute by 15 mm or so. The reasons were that you partly cover the bottle neck with your lip when playing and so

flatten the note and likewise with the flute. So when you are playing your flute you can control the pitch quite reliably by changing the amount of cover. Different notes are affected by different amounts. Open C# has the shortest tube length so it is affected most by a change in the end correction and it can be bent from well below C to nearly D with little difficulty. Low C is affected considerably less because the end correction is a smaller fraction of the effective length. Just how you change the amount that you cover is up to you but my favourite method is to move my chin in or out. This changes the amount of cover in a controllable way. You might prefer to roll the head in or out. It doesn't matter how you do it as long as (a) you know what is happening and (b) it's under control.

WHAT HAPPENS IN COLD (OR HOT) CONCERT HALLS?

This is what really causes all of us enormous problems from time to time. People often ask "why do wind instruments go up in pitch in warm rooms?" Some of them know a little physics and know that the tube will expand when it heats up so they are greatly puzzled that the pitch doesn't go down! True, the tube does expand but only by a tiny amount. What changes by a lot is the speed of sound.

If the air temperature goes up by 10° C the speed of sound goes up by 1.7%. Since the frequency is directly proportional to the speed of sound the resonant frequency of the column of air in the tube will go up by the same amount and 1.7% is equivalent to about 30 cents or nearly one third of a semitone. Like me, many of you must have played concerts in cold churches from time to time and had dreadful problems trying to keep in tune. Now you know why!

What can you do about it? Well, you can't change the laws of physics but you compensate by (a) sliding the headjoint in or out and (b) altering the amount of cover of the embouchure hole. (a) Is OK up to a point but, since we now know about how the length affects the pitch it is not very difficult to see that notes played with a short tube (open C sharp, etc.) will be more affected than notes played with many keys closed. The important thing is the fractional change in length not the actual change in length. You might remember from part 1 that a 6% increase in the tube length drops the pitch by a semitone. If you change the length by the right amount for A, say 2%, then the change for C sharp will be greater than 2% and, for low C, less than 2% so every note changes in pitch by a different amount which is bad news. A combination of (a) and (b) is best but in the end you have to listen to every note and put it right as it comes. So, I have no magic solutions but I hope that, now you understand what is going on, you will be in a better position to cope with the situation.

The final intonation problem is associated with (3) above. We saw in part 3 why pitch changes with loudness and now we know that is all because of physics and not a personal defect then we should be happier in doing something about it. The cures are the same as for other pitch bending situations.

After all this I hope you can see that Physics – a much maligned school subject – is directly responsible for, or perhaps I should say can explain, some of the problems that we have when we play the flute. The main thing is that if you understand a problem then you are in a much better position to sort it out or help someone else, especially a pupil, do something about it. ■