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THE 'VIRTUAL FLUTE': ACOUSTIC MODELLING AT THE SERVICE OF PLAYERS AND COMPOSERS

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ABSTRACT

Among the difficulties facing woodwind players are (i) awkward fingerings for rapid passages, (ii) intonation defects in instruments, and (iii) performing exotic effects such as microtones and multiphonics. In many cases these may be ameliorated by alternative fingerings.

We report the construction and use of a web service for the flute. An expert system was trained by an experienced flutist to determine playability from features of 957 minima in measured acoustic impedance spectra **Z**(f) for 76 selected fingerings. Measurements on successively more complicated acoustic systems yielded an accurate waveguide model of **Z**(f) of the flute, which generated the minima of the 39,744 different acoustic configurations of the flute. The expert system, coupled with the waveguide model, produces a large database of alternative fingerings, microtone and multiphonic fingerings. The database is accessible to flutists and composers via a user-friendly interface that includes user determined constraints on key combinations and ranks fingerings by playability or pitch. This service, located at http://www.phys.unsw.edu.au/music/flute is used hundreds of times per day. We report some of the service's uses and discoveries.

1. INTRODUCTION

One of the applied aims of music acoustics is to use the scientific understanding of music and instruments to help musicians. *The Virtual Flute* (TVF) is one such application [1]: it is a widely used web service that supplies flutists and composers with solutions to a wide range of technical problems. These include awkward transitions between notes, intonation and timbre difficulties. It also gives fingerings (key combinations) for microtones (non standard pitches) and multiphonics (chords). We describe briefly the strategies and techniques used to construct TVF. We also report examples of its use. The interest in such examples is that they illustrate the sometimes subtle difficulties faced by musicians and the steps that may be taken to remove them. These in turn illustrate some of the details that must be addressed by scientists aiming to help them.

In *The Virtual Flute*, an expert system relates features of impedance spectra **Z**(f) to the perceived musical behaviour of the instrument. A waveguide model, developed and tested on a large database of measurements, predicts the **Z**(f) for every possible fingering, determines the pitch and 'playability' of all possible notes and lists possible multiphonic combinations of notes. A musician-friendly interface allows musicians to search the resulting database according to appropriate criteria and constraints.

The Virtual Flute is currently used several hundreds of times per day. Here we choose a small number of problems and their solutions to illustrate some effects of acoustical and biomechanical interest and some ways in which the musical possibilities of the instrument have been extended.

1.1. Alternative fingerings

All instruments are imperfect compromises. When a good player rehearses a single phrase many times, s/he may be seeking ways to correct the pitch of one note, to control an inappropriate loudness or stability, or just finding ways to execute or to avoid awkward finger movements. A particular combination of keys depressed is called a fingering. Most players have a repertoire of alternatives, which are used in fast passages or to produce more appropriate pitch and timbre in different circumstances.

For the flute, there are either 13,248 or 26,496 different fingerings, depending on whether the lowest note on the instrument is B3 or C4. We know of no previous attempt to make a complete study.

1.2. Microtones, timbres, multiphonics

Solo and chamber music since the 1950s increasingly calls on woodwind players to play notes that fall between those of standard temperaments, notes with varying timbres and chords [2,3]. Only a subset of the possible combinations of notes are playable on the flute and we know of no previous attempt to list them all. Dick [4] gives an extensive collection of fingerings for these exotic effects but it is far from complete.

The two lowest registers of the flute are usually played with simple fingerings: nearly all of the tone holes downstream from a particular point are open, while all of those upstream are closed, except for register holes. In cross fingerings, some tone holes downstream from the first open hole are closed. This often increases the end effect and so flattens the note, creating the possibility of a microtone. The inertance at the tone hole affects higher resonances more strongly, so the resonances cease to be harmonic. Higher resonances thus contribute less to the vibration regime, which creates the possibility of a darker timbre. See [5] for a detailed discussion.

Further, the impedance mismatch at a single open hole may partially reflect a travelling wave. The transmitted portion may be reflected at a subsequent open hole. Thus a cross fingering can be considered as a set of resonators with different frequencies. In general they are not in a simple harmonic series, which creates the possibility of the superposition of two or more standing waves to produce a multiphonic.

2. STRATEGY AND IMPLEMENTATION

Because they are open to the air at the embouchure, flutes operate near minima in the acoustic impedance spectrum **Z**(f). The ease of playing the note associated with a minimum in **Z**(f) depends on properties of that and other minima. In principle, one might hope to understand this in terms of properties of the jet-bore interaction and a knowledge of the extent to which players control the jet. This is a difficult question. Fortunately, flutists know how hard it is to play a note. So we asked an expert flutist to attempt to play a note corresponding to each of 957 minima identified on the measured **Z**(f) data. When the note was playable, it was assigned a playability from 1 to 3, with 0 for unplayable notes.

We expected that the playability of a note associated with a particular minimum might depend on its depth, its bandwidth, the proximity and magnitude of nearby extrema, and whether or not higher minima were harmonically related to it. These were quantified and used as inputs. Three methods were tried to determine playability from these input data. Neural networks were unacceptably slow, even when the input parameter set was reduced. Linear regression was unhelpful and uniformative, partly because of strong correlation among the parameters. A decision tree method, using the C5.0 algorithm suite, an artificial intelligence technique developed by Quinlan [6,7], proved successful. The first tree used only the binary data, 'playable' or 'unplayable'. Training the tree on subsets of the data and testing on others enabled the rejection of unimportant input parameters. The final tree ranks a minimum as unplayable (i) if $Z > 1.35$ MΩ or (ii) if 1.35 MΩ $> Z > 0.68$ MΩ and if the next higher minimum is more than 35% lower, or (iii) if 0.68 MΩ $> Z$ and if the next higher minimum is within 261 Hz. ($1\ \Omega = 1$ Pa.s.m^{-3})

The quaternary playability ratings (0-3) were used as inputs to Cubist, the continuous version of C5.0. Its output gives playability as a function of the parameters listed above, but again it is not very informative because of the correlation among the parameters.

To obtain playing pitch from the frequency of an impedance minimum measured or calculated at low temperature and humidity is complicated in principle, but here is performed by a simple empirical relation determined by comparing played frequencies with those of the minima. An average embouchure effect is already included in the measurements [8]. This method introduces errors, but they are not greater than the variations among players and instruments.

One dimensional waveguide models to calculate **Z**(f) have been made by various authors [9,10]. The parameters for our model were determined by measuring successively more complicated combinations of bores, finger holes and keys. It was then tested on the database of measurements [8,11]. **Z**(f) was then calculated for all 39,744 fingerings, and the frequency, magnitude, bandwidth and harmonicity of all minima were determined. From these, the expert system constructed a database of about 150,000 possible playing regimes. Inharmonically related minima are used to construct lists of multiphonic possibilities.

The web service itself was constructed according to recommended principles [12,13], and the user interface designed after consideration of the needs and knowledge of flutists and composers, the principal users.

2.1. The web service

Three tools are offered. One allows the user to enter a fingering via a graphical interface and then returns the predicted playable notes with their predicted playability and pitches and the multiphonic possibilities. The second allows input of a note name to search the database for all suitable fingerings and ranks them by intonation or playability, which are included in the displayed output. This tool also allows the user to constrain the search by excluding (or including) any keys that would inconvenient to use (or not to use, respectively), in the circumstance. The third tool invites input of two or three notes and searches the multiphonic database.

3. APPLICATIONS AND SIGNIFICANCE

3.1. Awkward passages and trills

Flutists write fingerings using the numbers 1,2,3 for the keys usually operated by the long fingers of each hand (left given first), Th for the left thumb key, and then individual names for the other keys. A vertical line separates the two hands. For instance, the standard fingering for F6 is written Th 1 - 3 | 1 – – D#, with the D# operated by the RH fourth finger.

A trill between the note F6 and A6 is rather awkward using the standard fingerings. The fingering for A6 is Th - 2 - | 1 - - D#. (The reader can appreciate this by attempting a rapid alternation between 1 – 3 and – 2 – with the left hand.) The flutist needing to accomplish this trill sought an alternative fingering for F6, specifying that all the keys used for A6 be included (this ensures that all fingers will move together on the trill). TVF returns Th 1 2 3|1 - - tr2 D#, which gives a comfortable trill in which three fingers move in the same sense.

In trills and rapid passages, less than perfect intonation may be tolerated: if a note that lasts 0.1 s, its frequency cannot be resolved to much better than ±10 Hz .

3.2. Stable transitions

In rapid transitions, there is insufficient time to adjust the embouchure optimally for each note: for a rapid trill, no attempt is made, and for a rapid passage, the embouchure can only change to follow the overall shape of the phrase. A rapid alteration over a large interval can lead to the possibility of 'splitting': the production of an unwanted transient between desired notes. (The possibility of splitting is almost as bad as the effect itself: lack of confidence that the notes will sound properly distracts musicians from interpretive and other issues.)

Flutist Jane Cavanagh reports this example: Stravinsky's *Firebird* requires an acciacatura from B5 to E6 to B5. Figure 1 shows why this is difficult. The standard fingering for B5 (also used for B4) will comfortably play F#6, the third harmonic of B4. That for E6 will also play G#5 and A6. For a slow transition, the flutist would shorten and/or quicken the jet to play the E6. How much? Too much to play G#5 but not enough to play A6. S/he would then lengthen and/or slow it enough to play the B5. To play this acciacatura (or a trill), there is no time to adjust embouchure: one simply forms an intermediate embouchure and lets the flute fingering select the note. The danger of the split here is that, if the embouchure compromise favours the high note, one risks playing B5-E6-F#6-B6, because the transient unwanted F#6 (the 'split') is only a tone above the higher target. If the compromise embouchure is too low, one will play B5-G#5-B5, or B5-nothing-B5, because the E6 is not a particularly stable note.

This player requested an alternative E6 fingering and found Th 1 2 - |1 - - D# tr1 tr2. The note is stable and easy to sound, although slightly flat. According to TVF (and players), the minimum immediately below that which supports E6 (Fig 1c) is unplayable, so there is little danger of the E6 'dropping down'. Consequently, the embouchure may be compromised more towards B5 and less to E6, which minimises the chance of sounding F#6. It is a comfortable, safe solution.

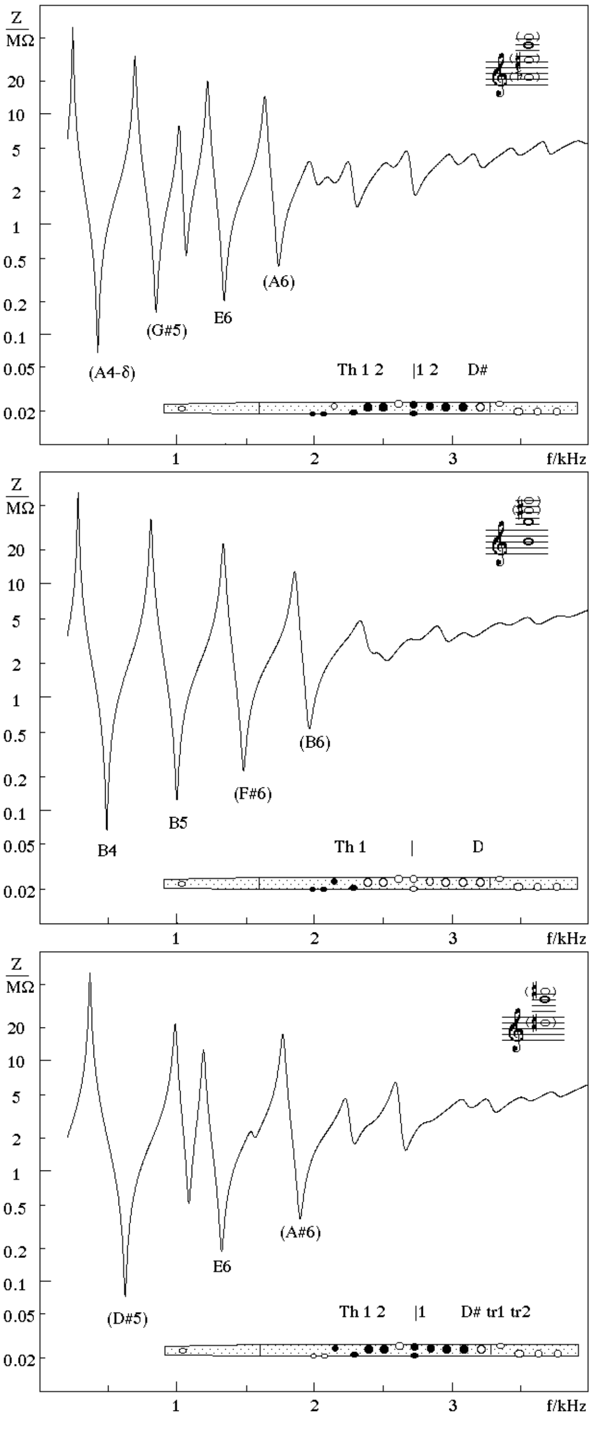

Figure 1: ***Z****(f) for the standard fingererings for (top) E6 and B5 (middle), and for the alternate E6 fingering*

3.3. Awkward high passages

High passages are awkward for several reasons. First, the resonances of all wind instruments are inherently weaker (extrema in **Z**(f) are less pronounced) because of visco-thermal damping in the bore. In the flute, this effect is exacerbated by the Helmholtz resonance in the head [11,14]. Second, the individual fingerings are complicated and smooth transitions between them more so. Simple fingerings do not work because either the end effects in the array of open tone holes put them out of tune, or because the wave propagates too far into the array. Indeed, for notes above the tone hole cut off frequency, all notes are overtones of the whole length of the pipe, and several open holes along the length act merely as register holes or tuning perturbations [11,14]. Third, the resonances are closer together, so the danger of undesirable transients, like that discussed above, is greater. Some of the standard fingerings are difficult to play softly, so players seek stable soft fingerings (effectively, those with deeper minima in **Z**(f)). They also seek sequences that are less awkward. The job is even harder when composers call for microtones.

Kathleen Gallagher, who specialises in the contemporary repertoire, cites two examples. The British composer Chris Dench, in *Closing Lemma*, writes a final flourish of high notes landing on a sharp E7. This pitch is well above the tone hole cut off frequency, and well into the 'shorting' range of the Helmholtz resonance, so easily played fingerings are rare. Further, the composer wants a microtone. TVF obliges with 12 - | - - 3 D# tr2.

Welsh composer Richard Barrett, in *What Remains* for flute, bass clarinet and piano calls for a slurred, fast passage sharp C7, sharp B6, E7, flat D7, flat E7, D7, Eb7, Bb6. This player uses standard fingerings for Bb6, D7 and flat D7, but found the rest of the fingerings from TVF, thereby creating a solution to a bar that has produced anxiety and performance approximations for many flutists attempting this work.

3.4. High notes and soft high notes

The range of the flute ends somewhere near the middle of the fourth octave, and notes near the end of the range are often difficult to play softly, and sometimes difficult to play in tune. So flutists are keen to seek improvements: minima in **Z**(f) that are deeper and closer to the right frequency. TVF offers a fingering for F7 whose minimum is about 30% lower than that of the standard fingering, and which allows even flutists of modest ability to play this very high note, and even play it softly.

3.5. Multiphonics

Multiphonics are rare in the low range of wind instruments because an open tone hole acts as a shunt. In the high registers they abound. Composers and flutists routinely use *The Virtual Flute* to find multiphonics and to find how to play them.

3.6. Further work

Application to other instruments has begun. The clarinet has a geometry that is almost as standardised as that of the flute's but it is complicated by having very many more fingering possibilities. And the bassoonist among the authors earnestly desires an application to the instrument in which alternative fingerings are most used—and needed.

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4. REFERENCES

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