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ENTRY FORM

Title of Submission

Flute acoustics: new understanding and new tools for musicians

Principal Entrant

Group entry: Contact Joe Wolfe

Address:

School of Physics, University of New South Wales, Sydney, 2052

Telephone: 02-93854954

Email: J.Wolfe@unsw.edu.au

For Group Entry, Names of other members of the group:

Andrew Botros, John Smith, John Tann, Joe Wolfe.

200 word executive summary

Although music acoustics has considerable potential to help musicians, centuries of research have made relatively few contributions. Musicians are sensitive to very subtle changes, and are interested in a wide range of effects, notes and combinations. Consequently, effective help requires detailed understanding of the acoustics of their musical instruments and many precise acoustical measurements. We report a major advance that has been widely praised by its users.

Our research uses a novel technique, developed in our laboratory, for the measurement of acoustic transfer functions with high accuracy, dynamic range and speed. By studying systems increasing in complexity from simple tubes to entire flutes, a detailed, accurate computational model of the flute was developed. This was used to calculate impedance spectra for all 39,744 possible fingerings and to quantify features related to musical response. An expert system was devised to rank all possible notes by intonation and 'playability'.

Finally, a flexible, 'musician-friendly' web service was constructed to provide the world's flutists and composers with easier, better ways of playing difficult passages and chords. No comparable service exists for any wind instrument. Musicians use it hundreds of times each day and it has won the Australian Siemens Prize for Innovation.

Flute acoustics: new understanding and new tools for musicians

Why understand musical instruments better?

Musical instruments are far from perfect. Players — especially good players — will often practice the same phrase over and over, searching for a less awkward way to do it, trying to make it more in tune or the timbre more homogeneous. A broad and detailed understanding of the acoustics of a musical instrument can be used to guide makers. It can also make technical details easier for players, allowing them to devote their attention to other performance goals. However, any measurements and theories must be accurate and comprehensive. Musicians (and makers) are interested in very subtle effects, and in many different combinations or instrument configurations. First order approximations and applications to a small subset of cases are simply not useful.

Here we describe how fundamental and applied research into the acoustics of flutes has not only improved our understanding of the instrument, but also provided a popular, widely praised tool for musicians.

Why the flute?

The flute is older than history (Palaeolithic examples exist) and is used by almost all cultures. Yet, when our research began, no detailed measurements of the linear acoustics of the instrument existed. Many features of the performance of a wind instrument are determined by the spectra of the acoustic impedance at the "input" or embouchure. The problem is that the flute family is played with the embouchure open to the radiation field: i.e. the player leaves the embouchure hole uncovered. Consequently, the instrument plays at the minima of acoustic impedance spectra. To measure these minima precisely requires measurements with a large dynamic range. We have developed techniques for doing this precisely and quickly, so we accepted the challenge.

When it comes to providing services to musicians, the flute is a good place to start. The geometry of the flute is more standardised than that for almost any other instrument, so a single theoretical model can be applied to most modern instruments.

Acoustic impedance spectrometry with large dynamic range, precision and speed

Starting in the mid 1990s, we had developed acoustic spectrometers designed to measure the response of the human vocal tract in real time, during speech, without disturbing the speaker (Epps et al, 1997), a technique that we applied to speech training (Dowd et al, 1997). Further development of this technique led to a spectrometer capable of measuring (in a few seconds) an impedance spectrum with a dynamic range of over 80 dB and a frequency resolution of ± 1 Hz over 4 kHz (or over larger frequency ranges with smaller precision or greater time).

To do this we developed not only our own transducers and electronics, but also a new reference standard for impedance spectrometry: the effectively infinite waveguide. Because

the acoustic velocities of interest are measured in $\text{nm}\cdot\text{s}^{-1}$, precise measurement of acoustic volume flow is impossible, and all such measurements must be comparisons of acoustic pressure or impedance. An infinite waveguide is purely resistive and has no frequency dependence. It offers many practical advantages over finite systems, especially in dynamic range. A waveguide becomes effectively infinite if the measurement is made before the echo returns or if the waveguide is long and thin enough so that the echo returns with an attenuation greater than the desired dynamic range (80 dB for us). The details of this technique are described by Wolfe et al (2001a).

Measurements on the flute

Using the technique described above, we made a detailed investigation of acoustic impedance spectra for hundreds of fingerings on several representative flutes. (A combination of keys pressed or unpressed is called a fingering.) Representative sound files were also measured for these fingerings. The whole constitutes a detailed experimental database for the instrument, which was already of great interest to makers and players because it could be used to explain features of the performance of the instruments.

This database is published as an electronic archive by the Journal of Sound and Vibration (Wolfe et al, 2001b). It has around 200 pages with several hundred spectra. However, because of its interest to makers and players, we publish it also on the web, where it is supported by extensive explanatory material.

A theory of the flute

A three dimensional, finite element model of the flute is impractical. Tens of thousands of different cases are possible, and the mesh would have to be rather smaller than 1 mm to yield the high precision required. The calculations would be impossibly long.

Fortunately, because the wavelengths in question are considerably larger than the lateral dimensions of the instrument, a one-dimensional waveguide theory can be made to work accurately, provided that all of the diverse effects of the small scale three dimensional geometry can be empirically measured and accounted for in the model. Making such a theory is not new: it has been done by other researchers since the 1970s. Our main contribution is to the possible precision of such a theory. (One original contribution to the theoretical side is however the development of a method for treating the generation of non-propagating modes at discontinuities.)

We began the modelling with the simplest possible geometric elements and gradually increased the complexity until we reached a complete instrument. Thus, the determination of the parameters of the model is not a case of arbitrary fitting, but the direct acoustical measurement of the one or two empirical parameters that describe the effects of each added complication. This is described by Botros et al (manuscript submitted).

Because of the resolution and precision of our measurement technique, the constraints on the model and the values of its empirical measurements are severe. This is our major technical contribution to the modelling of wind instruments: to fit these data, the model must be very accurate.

The theoretical model thus developed was tested on the large, detailed database of measurements. Where discrepancies were discovered we returned to the model and made further measurements and changes until the agreement was satisfactory over the whole data set.

What can we do for musicians?

A theoretical model of the flute that can predict the acoustic response of the instrument with a precision acceptable to musicians has several practical applications. The first of these, recently completed, is called the Virtual Boehm Flute. This is a web service for musicians that provides online technical advice to flutists and composers. It provides alternative fingerings that have better tuning or different timbre, or that are less awkward in different contexts, or which can be used to play chords. We expand further upon its uses below. It is worth explaining here, however, that the playing of chords on wind instruments is a relatively recent development in music (the composer Berio was an early exponent). One of the limitations is that the number of possible chords is not known.

From theory to music

The minima in the impedance spectrum of the flute for a particular fingering are related to the notes and chords that can be played on the instrument with that fingering. The playing frequency is simply related to the frequency of one of the minima. The ease of playing, or playability, is related to the depth of the minimum and to the depth and frequencies of nearby minima, and the timbre is related to whether or not minima at higher frequencies are in harmonic or inharmonic frequency ratios.

Several factors determine the relationship between the frequencies of measured minima and the playing frequency: temperature and humidity of the air, the length and speed of the air jet, the shape of the player's lips and their position. Fortunately, these complicated relations have a practical constraint: players learn to adjust some of them so that the 'standard fingerings' play in tune. Thus, although we have measured some of the effects listed, we found it more practical to use the empirically measured dependence of frequency shift over the playing range of the instrument, averaged for several players.

'Playability' is an important, but more subtle and subjective quantity. Its relationship to the various features of impedance spectra was determined using an expert system. An experienced flutist determined the playability of 957 impedance minima from the spectra of 76 selected fingerings. These expert decisions, along with the aforementioned physical parameters of each impedance minimum (957 in total), were used to develop a playability decision tree. (Decision trees are an artificial intelligence technique which provide a structured set of human-readable rules. The first rule of our expert system, for example, is "An impedance minimum is unplayable if its magnitude is greater than $1.4 \text{ MPa}\cdot\text{s}\cdot\text{m}^{-3}$.") The expert system firstly determines whether an impedance minimum is playable or not, and secondly ranks playable minima on a continuous scale of 0 to 3. For any fingering, pairs and triplets of playable notes which are not harmonically related are predicted as possible chords.

Musically useful data are then generated by using the theoretical model, applied to every possible fingering, together with the expert system. The playable notes and chords of all 39,744 flute fingerings — typically a dozen for each fingering — were thus predicted, resulting in a substantially sized musical database.

The Virtual Boehm Flute

A web service titled "The Virtual Boehm Flute" (<http://www.phys.unsw.edu.au/music/flute/virtual/>) was developed to allow musicians access to the entire database of playable notes, alternative fingerings and multiphonic fingerings in a useful and intuitive manner. This web service provides a searchable interface to the playable notes and chords of every fingering.

Musicians may search for all available fingerings for a chosen note, ranking them by playability or intonation. This tool has a wide range of practical applications. It provides fingerings which may be considerably easier to play than standard fingerings (particularly for high notes such as F7). Flutists may find fingerings that are more in tune in particular contexts, or microtones (notes which lie between successive notes on a piano), or fingerings with more desirable timbres. To allow them to search for the least awkward fingering in a particular musical context, users may specify particular keys which must or must not be included in the resulting fingerings. This can greatly ease the difficulty of certain fast passages, such as the rapid B5-E6-B5 sequence found in Stravinsky's *Firebird*.

The large database of predicted chords provides the first substantial repository of multiphonic fingerings for the flute (or indeed any woodwind instrument). Many new chords for the flute have been discovered by our research and made available to composers and players.

Excellence in research, development and application

Our goals are not just research excellence, but making the results available to interested parties inside and outside the acoustical community. Our research data and publications are frequently consulted by both researchers and musicians. The Virtual Boehm Flute is widely used by flutists around the world, attracting high praise for its musical value and winning the Australian Siemens Prize for Innovation. Our novel and innovative approach to understanding the acoustics of wind instruments is producing acoustic excellence from the laboratory to the concert hall.

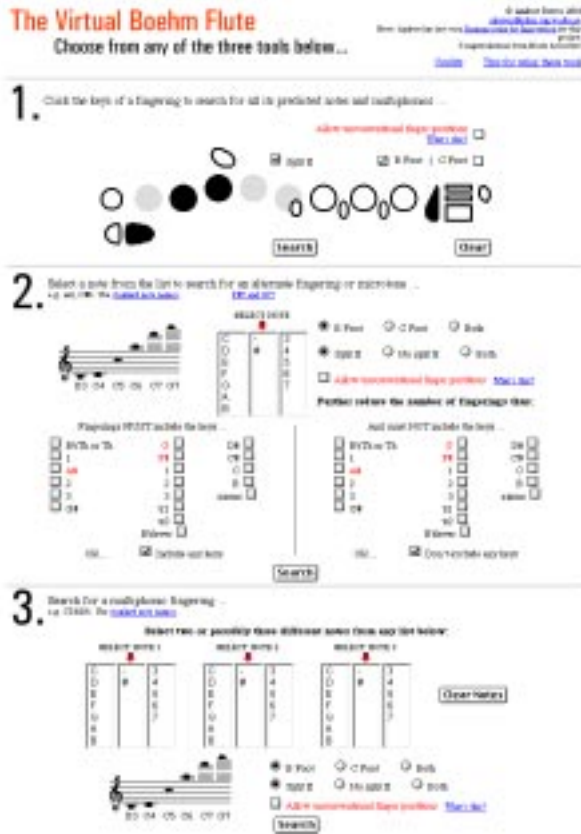
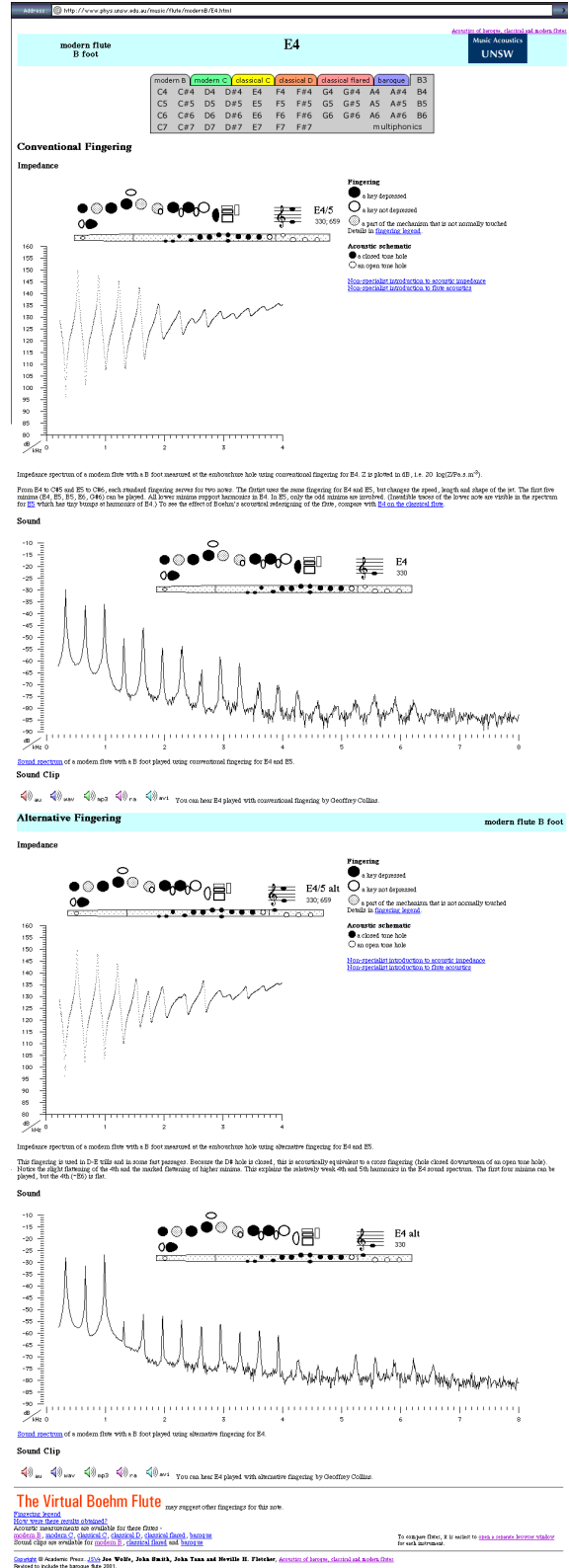


Figure 1. **Helping musicians.** The entrance page for “The Virtual Boehm Flute”: musician friendly access. (<http://www.phys.unsw.edu.au/music/flute/virtual/>)

Figure 2. **The published experimental database** contains ~200 HTML pages, several hundred graphs, 1,400 files, 40,000 links and is linked to extensive supporting and explanatory material. This is a typical page.



References and supporting material:

The website on Flute Acoustics is at <http://www.phys.unsw.edu.au/music/flute/>

Most papers listed below are available at:

<http://www.phys.unsw.edu.au/music/publications.html>

Journal articles on this aspect of our research:

- Epps, J., Smith, J.R. and Wolfe, J. (1997) "A novel instrument to measure acoustic resonances of the vocal tract during speech" *Measurement Science and Technology*, 8, 1112-1121.
- Dowd, A., Smith, J.R. and Wolfe, J. (1997) "Learning to pronounce vowel sounds in a foreign language using acoustic measurements of the vocal tract as feedback in real time." *Language and Speech*, 41, 1-20.
- Wolfe, J., Smith, J., Tann, J. and Fletcher, N.H. (2001) "Acoustic impedance of classical and modern flutes" *Journal of Sound and Vibration*, 243, 127-144.
- Wolfe, J., Smith, J., Tann, J. and Fletcher, N.H. (2001) "Acoustics of classical and modern flutes: a compendium of impedance spectra, sound spectra, sounds and fingerings" *JSV+*. Electronic publication at <http://journals.harcourt-international.com/journals/jsv/supplementary/suppindex.htm>
- Botros, A., Smith, J. and Wolfe, J. (2002) "The virtual Boehm flute—a web service that predicts multiphonics, microtones and alternative fingerings", *Acoustics Australia*, 30, 61-65.
<http://www.phys.unsw.edu.au/~jw/Botrosetal2002.pdf>

Journal articles submitted:

- Wolfe, J. and Smith, J. "Cut off frequencies and cross fingering in baroque, classical and modern flutes", submitted to the *Journal of the Acoustical Society of America*.
- Botros, A., Smith, J. and Wolfe, J. "A wave guide model for all fingerings of the Boehm flute.", submitted to *J. Sound and Vibration*..

Conference papers on this aspect of our research:

- Smith, J., Fritz, C. and Wolfe, J. (2000) "A new technique for the rapid measurement of the acoustic impedance of wind instruments" (Proceedings of the Seventh International Congress on Sound and Vibration, 4-7 July 2000, Garmisch-Partenkirchen, Germany. Eds G. Guidati, H. Hunt, H. Heller and A. Heiss) Vol III pp. 1833-1840.
- Wolfe, J. and Smith, J. (2000) "Acoustics of the air-jet family of instruments". Proceedings of the Seventh Western Pacific Regional Acoustics Conference, Kumamoto, Japan. pp 575-580.
- Smith, J. and Wolfe, J. (2001) "Tone holes and cross fingerings in wood wind instruments" International Congress on Acoustics, Rome, Session 8.09, pp 14-15.
- Wolfe, J. and Smith, J. (2001) "Embouchures and end effects in air-jet instruments" International Congress on Acoustics, Rome, Session 8.06, pp 8-9.
- Wolfe, J., Smith, J., Fletcher, N., and McGee, T. (2001) "The Baroque and Classical flutes and the Boehm revolution" Proc. International Symposium on Musical Acoustics, Perugia. D.Bonsi, D.Gonzalez, D.Stanzial, eds, pp 505-508.
- Botros, A., Smith, J. and Wolfe, J. (2001) "Alternative fingerings and multiphonics: measurements, analyses and databases" Proc. International Symposium on Musical Acoustics, Perugia. D.Bonsi, D.Gonzalez, D.Stanzial, eds, pp 509-512.
- Wolfe, J., Smith, J. and Green, M. "The effects of the placement of the head joint stopper on the impedance spectra of transverse flutes" Proceedings of the Seventh Western Pacific Regional Acoustics Conference, Melbourne (submitted).