BODY VIBRATIONAL SPECTRA OF METAL FLUTE MODELS

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ABSTRACT

For years, flutist have argued over the tonal advantages of using different precious metals for their instruments. Occasionally, scientists have entered the fray and attempted to offer an objective point of view based on experimental measurements, However, their research often involved actual instruments and performers, ignoring variations in wall thickness, craftsmanship and human consistency. These experiments were conducted using a variety of methods; all concluded that the wall material has no effect on the tone. This paper approaches the question using simple tubular models, excited by a wind source through a fipple mouthpiece. The amplitude and phase of the harmonic components of the body vibrational signal are measured with a stereo cartridge. The results show a complex pattern of wall vibrations in the vicinity of a tone lattice at frequencies that match significant harmonics of the air column. The tube wall was found to expand in a nonuniform or 'elliptical' manner due to the asymmetry of the tone holes.

INTRODUCTION

Modern flutes are made from a variety of metals and alloys, including nickel silver, sterling silver, 5-14K gold, platinum and titanium. The choice of wall material is often the subject of a fierce debate between professionals with different personal preferences. Instrument manufacturers have an obvious monetary stake in maintaining the market for the more expensive materials. Flutists most often describe the timbre of the silver flute as 'brighter' than that of the 'darker' gold flute. These aural impressions are based on the perceived harmonic content. It is accepted (one might argue assumed) within the community of professional flutists that the wall material has a significant, if not dominant, effect on the timbre of the tone produced. However, there is no scientific documentation of this phenomenon. In fact, scientists who have investigated the question have all reached the same conclusions: that the wall vibrations are negligible and the wall material has no effect on the flute tone.

Clare graduated magna cum laude from Duke University in May 1999, with a double major in physics and music. This research was conducted during her senior year as an independent study laboratory course, qualifying as a senior thesis for Graduation with Distinction in Physics. The results were presented in 1999 at the conferences of the American Physical Society in Atlanta and the North Carolina Regional Chapter of the Acoustical Society of America in Raleigh. As an undergraduate, Clare was the principal flutist of the Duke Univesity Wind Symphony and Symphony Orchestra, and a student of Brooks de Wetter-Smith of the University of North Carolina-Chapel Hill. Clare is currently employed as an architectural acoustics consultant at Jaffee Holden Scarbrough Acoustics, Inc. in Norwalk, CT.

The earliest research that addressed the body vibrations of woodwind instruments was published in 1964. [1] The clarinet was the initial subject of this investigation, but the work was extended to other members of the woodwind instrument family. In the case of the flute, it was noted that the magnitude of the body vibrations was smaller than that of the reed instruments. Four flutes were used in this experiment : 0.012" coin silver; 0.014" gold; 0.020" coin silver ; and a silver alto flute. The magnitude of the body vibrations was measured at several locations and for several pitches at 3 in. from the embouchure hole. After comparing the values to the sound level at a distance of 1 foot from the instrument, it was determined that any radiated sound from the body vibrations was inconsequential when compared to the amplitude of the normal sound produced.

The seminal research in the field was published in 1971. [2] Three keyless flutes of 0.036 cm silver, 0.153 cm copper and 0.41 cm grenadilla wood were constructed. Identical plastic headjoints were attached to each flute. In a listening trial, a musical phrase was played three times behind a screen and the participants in the study were asked to identify which repetition was performed on a different instrument. For a performing trial, the three flutes were attached to a rotating apparatus in such a manner that the player could see only the identical headjoints and could not identify which instrument was currently in use. The participants played the three unseen flutes and indicated their personal preference. The apparatus was spun and the participants were asked to identify their original selection. Subsequent statistical analysis concluded that the success rate for both trials differed only slightly from the expected results for random guessing.

The effects of wall material were studied in a doctoral thesis in 1980. [3,4] Five flutes were constructed by the same manufacturer to have identical lengths, bore diameters, wall thickness, embouchure holes and tone holes. Wall material (palladium, white gold, 14K gold and two of sterling silver) and its subsequent weight were the only remaining variables across the set of flutes. Two professional flutists played the performance tasks on each of the five flutes inside an anechoic chamber. The performers were asked to play three pitches (G in each of the three registers of the flute) at two dynamic levels. Two condenser microphones in the anechoic chamber were connected to a spectrum analyzer. The harmonic content of the sound differed only between performers.

In 1990, a team in India observed body vibration patterns using conventional holography to produce time-averaged interferograms. [5] The instruments used were Indian flutes made of reed with 8 finger holes. The flutes were excited by an air ribbon through a mouthpiece made of glass and rubber and lightly clamped at both ends. The vibration patterns for different fingering configurations, frequencies and blowing pressures were reported but not interpreted.

In 1998, a study analyzed impulse responses in the time and frequency domains using a microphone positioned inside a flute. [6] Only two instruments were used, a nickel silver/copper alloy Bundy flute and a silver Muramatsu flute. The Bundy flute was found to be more ‘reverberant’, while the Muramatsu had more high frequency components. No change was observed for different microphone positions. The authors noted the ‘remarkable difference between the two flutes in tone quality’, but did not comment on its origin or possible consequences.

Numerous demonstrations have been given within the community of professional flutists. On several occasions, Coltman played on a concrete flute behind a screen and the audience was completely unaware. At the National Flute Association convention in 1998, James Galway performed on an array of flutes of different materials, all manufactured by Muramatsu. However, these exhibitions were never intended to be scientifically rigorous and the results were never published.

THE EXPERIMENT

Design Goals

The previous experiments were conducted using a variety of methods, but there are three recurring problems:

° The use of real instruments introduces several additional variabales that are often left uncontrolled. Flutes of different materials have different standard wall thickness. Instruments in different price ranges, as dictated by the choice of material, have varying levels of craftsmanship.

° The use of live performers raises questions about skill level, consistency and possible bias of the player. This makes the results difficult to reproduce. The flutist’s embouchure is the arrangement of the lips necessary to produce a sound. It involves varying the shape and tension of numerous muscles in the lips, mouth and jaw. It is extremely difficult, even for a professional player, to reset the embouchure on a different instrument and produce a tone in exactly the same manner.

° The data collected in the experiments were primarily qualitative, in the form of listener identifications or descriptions.

To address these concerns, the following design goals were identified:

1. Eliminate the additional variables present on actual flutes through the use of tubular models.
2. Ensure reproducibility of results with an artificial air supply.
3. Collect quantitative data with an oscilloscope and spectrum analyzer.

Tubular Models

A set of four models was constructed of standard stainless steel tubing (due to its availability and low cost) to examine the effect of tone holes on wall vibration. This thin-walled material was chosen to provide a large output signal. The models closely approximated the characteristic dimensions of an actual instrument as shown in Table 1.

Tube A had no tone holes and was used as a reference or control model. Tube B had 1 tone hole at the position corresponding to the first open tone hole on an actual flute. Tube C had the set of 6 tone holes necessary to play a diatonic scale. Tube D had the set of 9 tone holes necessary to play a chromatic scale. The spacing between tone holes was not exactly even, but increased slightly toward the foot of the model, as on a real flute.

The effective length of each of the tubes was determined by measuring the frequency of the tone produced by each

Dimension	Flute inches	Models inches
Length (excluding headjoint)	20.53	20.53
Bore diameter	0.748	0.750
Tone hole diameter	0.59	0.60
Wall thickness	0.010-0.18	0.010

Table 1

Body dimensions of a standard flute and our tubular models.

of the models. The length was calculated from:

$$L_{eff} = \frac{n\,v}{2\,f_n}, \qquad (1)$$

where $n = 1$ is the harmonic number, $v = 343$ m/s is the speed of sound in air at room temperature and f_1 is the fundamental frequency. Consider Tube A. With a length of 20.53 in (without mouth piece), it should have a fundamental frequency of 329 Hz. The measured value of 540 Hz occurs because we are resonating at the first harmonic (one octave above the fundamental) due to the air pressure. So, Tube A has a fundamental frequency of 540/2 = 270 Hz. From Equation 1, this implies an effective length of 25 in. Thus, the mouthpiece introduces a length correction of 4.5 in.

The effective lengths of Tubes B,C and D are significantly shorter than 20.53 in due to the presence of the tone holes. The first open tone hole on each of the models is located 6 in. from the end of the tube. This distance, in addition to the mouthpiece correction, yields effective lengths of approximately 10.5 inches for Tubes B-D, in agreement with the calculations in Table 2.

It should be noted that the most significant difference between the models and the real flute is the design of the tone holes. The tone holes of the models were simply cut into the metal tubing. On an actual instrument, the keys rest atop a small segment of tube that is drawn or rolled up around the tone holes. This simplification was unavoidable for the purposes of this experiment. While the drilled tone holes do remove some of the variations in craftsmanship, they are also somewhat removed from a realistic situation.

Equipment

A small fan was used as the air supply, regulated by a bellows-type apparatus as shown in Figure 1. An inner box of cardboard was allowed to move freely inside an outer box of plywood, acting as a pressure regulator. The air output was piped directly into the mouthpiece of the model.

A fipple mouthpiece, rather than a flute headjoint, was chosen to stimulate sound production in the models (see Figure 2). Fipples are normally found on whistles, recorders and organ pipes. In this case, a fipple was used to avoid the complications and ambiguities involved in modeling an artificial embouchure. The fipple mouthpiece for this experiment was taken from a standard Yamaha soprano recorder, made of plastic and slightly bored out for a snug fit with the tubular models.

Model	Frequency Hz	Effective Length inches
Tube A	540.0	12.50
Tube B	637.5	10.59
Tube C	647.5	10.43
Tube D	645.0	10.47

Table 2
Frequency produced by the various tubes and the calculated effective length of the models.

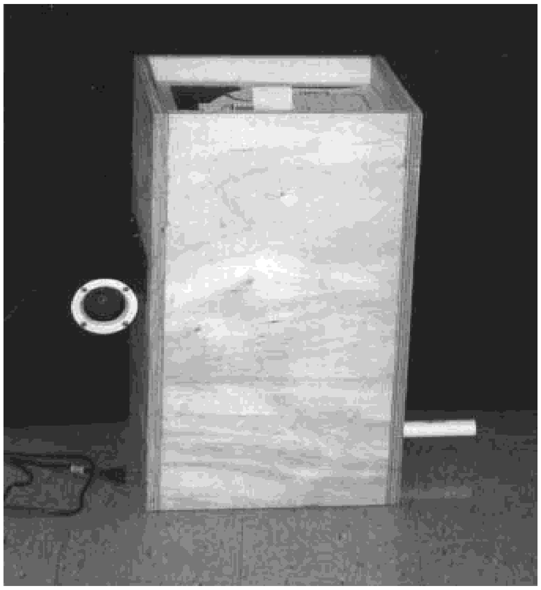

Figure 1
Air supply fan and pressure regulating apparatus.

The model was supported at the fipple end of the tube to allow the body to vibrate freely. The tube extended vertically, as shown in Figure 3, eliminating any torque doe to gravity. This means of support allowed for easy access from all azimuthal angles.

A stereo cartridge [7], such as that normally found on a record player, was mounted on a lever arm that could rotate freely around a horizontal cross-bar. This arrangement allowed the stereo cartridge to be in light contact with the wall of the tube without damping any possible vibration. The lever arm was adjusted to provide enough pressure to displace the stylus without clipping or distorting the signal.

The signal from the stereo cartridge was passed through a

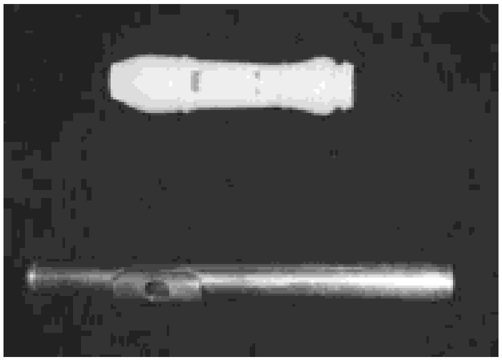

Figure 2
Fipple mouthpiece (top) and a flute headjoint with embouchure hole (bottom).

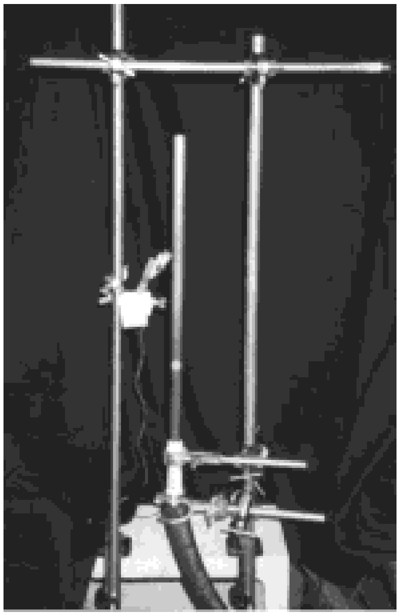

Figure 3
Vertical support system for the model flute. The support at the fipple end allows the body to vibrate freely and gives easy access from all azimuthal angles.

pre-amplifier [8] and displayed simultaneously on an oscilloscope and a spectrum analyzer [9]. The oscilloscope was triggered by the auditory signal picked up by a microphone [10] located at the first open tone hole of the model at an angle of 45˚. A cathetometer was used to measure the relative position of the stereo cartridge with respect to a fixed reference point. Figure 4 is a schematic diagram of our system.

We modified the design shown in Figure 4 to investigate the phase relationships of the wall vibrations. Two stereo cartridges were used to measure the relative phase between different points on the walls of the models. The cartridges were calibrated using a mechanical vibrator driven by a function generator. We found that there was no phase shift between the signals of the two cartridges. The signals from each of the cartridges were passed through identical band-pass filters [11] to isolate one harmonic.

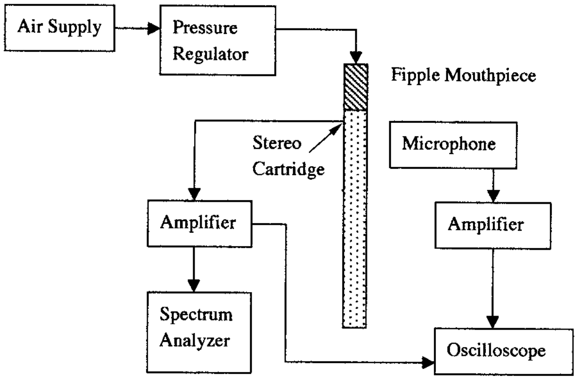

Figure 4
Schematic diagram of the experimental apparatus. A second stereo cartridge was later added to measure relative phases of the wall vibrations.

Although the experiment was conducted in the sub-basement on the building slab, significant interference from external vibration was encountered. The noisy air supply was isolated in a separate room and an intermediate joint on the air supply hose was mechanically grounded to the building slab. The entire apparatus was supported on cement blocks. The vertical ring stands were clamped to these blocks and counter-braced for rigidity. The stereo cartridge lever arm was electrically grounded to the building's water supply. These precautions resulted in clean signals.

DATA

The body vibrations were measured at intervals of approximately 1 in. along the length of each model at two azimuthal orientations relative to the axis of the tone holes (180˚ or 'the back' and 90˚ or 'the side'). Typical output signals fed into the oscilloscope had peak-to-peak amplitudes of approximately 40 mV. The amplitudes of the harmonic components of the signal were measured using the spectrum analyzer. We found first, third and fourth harmonics, corresponding to the harmonics of the acoustical signal in air. The data points were normalized and fit to curves.

Figure 5, showing the value of the third harmonic at the two azimuthal orientations at different distances from the fipple end of Tube B, illustrates the reproducibility of the results. The single tone hole is located at the 6 in. position on the tube.

The shape of the curves in Figure 5 can be understood by considering the structure of Tube B. The air pressure fluctuations in the tube have minima imposed by boundary conditions near the open tone hole and the end of the tube. These are coincident with the tube wall displacement maxima evident at these locations. The mechanical coupling to the fipple mouthpiece corresponds to a tube wall displacement minimum at 1 in. on the graph (the

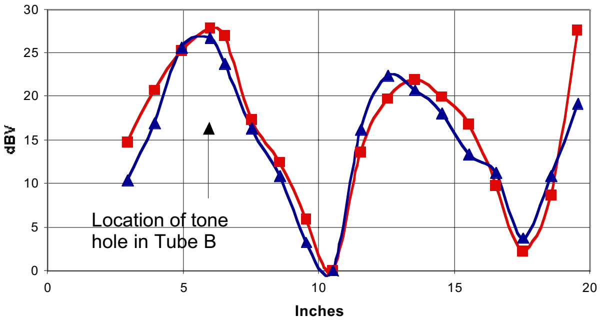

Figure 5
Amplitude of the third harmonic vs distance along Tube B. The location of the first tone hole is marked on the diagram.

effective end of the air column is at about -4.5 in. with respect to the scale on the graph). The other displacement minima are determined by the effective length of 10.6 in. One minima should be at this distance from the end of the tube and the other at this distance from the center of the tone hole.

The two lines on Figure 5 are identical, given the uncertainties of the experimental measurements. This implies that the wall vibrations of the model flute are independent of azimuthal orientation. This is consistent with the relatively small bore perturbation introduced by a single tone hole.

In general, the vibrational spectrum _is_ dependent on the orientation in the presence of a tone hole _lattice_. Figure 6 shows the first, third and fourth harmonics measured at the side of Tube C (90˚ relative to the axis of the tone holes) and the vibrational spectrum for the back (180˚). The back spectrum shows a less complex structure than the side spectrum. This indicates greater freedom to vibrate along the side of the tube that is nearest to the tone holes.

It should be noted that the third harmonic of Tube C (shown in Figure 6) displays the same basic structure as that of Tube B (Figure 5). The vibrational minima occur at the fipple mouthpiece (1 in.), around the midpoint of the length of the tube (10 in. - 12 in.) and close to the free end (17 in. - 18 in.) The third harmonic for Tube D (shown in Figure 7) also follows this pattern, although the overall structure is quite different. This may be due to the more regular spacing of the 9 tone holes on Tube D.

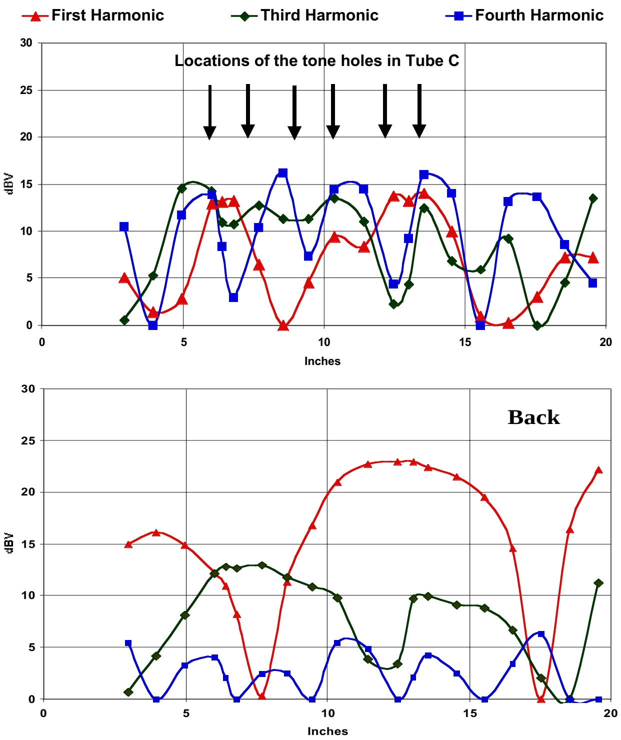

Figure 6
First, third and fourth harmonics as a function of distance along Tube C. The top graph is measured at the side of the tube and the bottom is measured at the back of the tube.

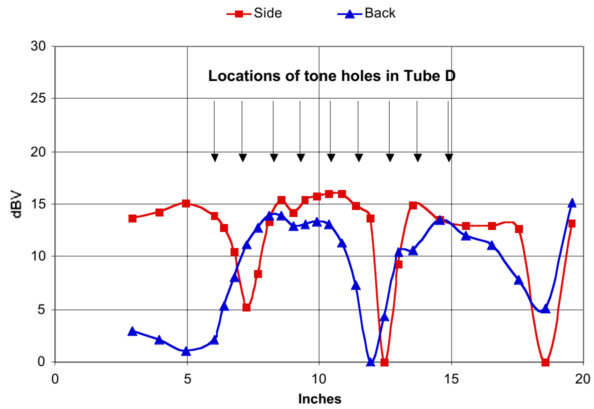

Figure 7
Amplitude of the third harmonic at both orientations on Tube D.

These patterns should not be interpreted as elastic modes within the metal itself. The velocity of sound in stainless steel is 0.233 in/μsec [12], so the corresponding wavelength is well over 300 inches. There should be no standing wave modes in the tube walls on the scale of these models.

Phase Relationships

The third harmonic was isolated for this study because this frequency is on the order of the cutoff frequency of the model tube. Above this frequency, the waves (in air) propagate down the entire length of the tube.

One of the stereo cartridges was kept in a fixed position (90˚ from the tone holes). The other stereo cartridge was moved along the length of each tube on the other side (270˚) and at the back (180˚). The fixed signal was used as the trigger for the oscilloscope. Using this set up, we could locate each phase reversal between the vibrations on either side of the tube within a region of 0.4 in. An example is shown in Figure 8 which shows the third harmonic amplitude data for Tube B superimposed on the phase data. The scale on the left is the amplitude and the scale on the right is relative phase. When tghe cartridges were located at the same relative position along the length of the tube, the signals were in phase, but the signal at the back was 180˚ out of phase. The phase reversals were also found to correspond with the pronounced minima of the vibrational signal.

These phase relationships hold true for the more general tone hole lattices of Tubes C and D. This implies that the vibrational harmonics observed were pure modes. It begins to provide a picture of how the tube wall vibrates. For a cylindrical tube, such as the reference model Tube A, one would expect to find uniform circular distortions of the tube's cross section as shown in the top of Figure 9.

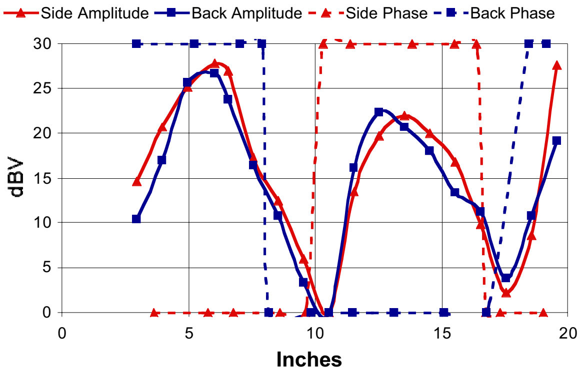

Figure 8
Amplitude vs position and relative phase vs position for the third harmonic on Tube B.

The phase relationships of Tubes B, C and D suggest that the open tone holes introduce a significant azimuthal asymmetry. The cross sections of these tubes undergo non-uniform 'elliptical' distortions as shown in the bottom of Figure 9. The scale and spatial distribution of the phase reversals imply that they could affect upper harmonics differently. This could provide a mechanism for the wall vibrations to affect the tone produced.

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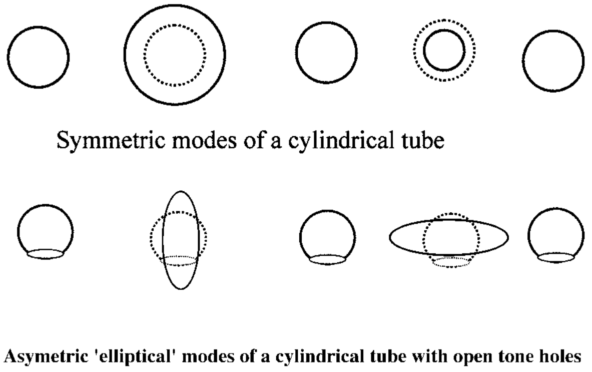

Figure 9
Possible modes of oscillation of the wall of a cylindrical tube. The top is a symmetric mode, the bottom the 'elliptical' mode which we detected. The sequence is: equilibrium radius, expanded radius, equilibrium radius, contracted radius.

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