Mouth resonance effects in the flute

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Resonance of the mouth cavity while playing the flute has been found to occur near 1000 Hz. Experiments with an artificial mouth show the Q of this cavity is less than two when air is passing through the lips. 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.

Subject Classification: 6.8.

Conversations among players of the recorder occasionally refer to the desirability of holding the player's mouth cavity at certain volumes in order to affect the tone. Bak[1] has made some measurements on an artificially blown recorder looking for the effect of varying the volume of a resonator placed before the mouthpiece slit. Only very slight changes in the frequency were observed. Benade and French[2] have provided a mathematical analysis of what might be expected to happen to flute frequency due to coupling of a resonant mouth cavity with the vibrating air column at the mouthhole.

Because the effects predicted by Benade and French appeared to be substantial, and yet no clear identification of them in flute playing is generally recognized, it appeared worthwhile to investigate experimentally the nature and magnitude of any mouth resonance effects which may be present.

First we may ask, does mouth resonance occur, and at what frequencies? Benade and French hypothesized that it would be in the neighborhood of the lowest formant for vowel sounds like "ah," "aw," and "oh," and therefore in the range of 500–600 Hz. They observed, presumably by ear, "an appreciable shift" in flute frequency in the neighborhood of G♯ and A (near 430 Hz) when the tongue was moved from the "ee" to "oh" positions. Such a frequency seems extraordinarily low for the mouth cavity resonance frequency in the position for playing the flute. If one attempts to whistle a note without markedly changing mouth position from that used in playing the flute, frequencies in the neighborhood of 1000 Hz are more typical.

To pin this down, a small microphone was constructed that could be placed inside the mouth, with the lead coming out the mouth corner. It was possible to play the flute reasonably well with the microphone in place. Readings of the output of this microphone were taken as the scale was ascended. The resulting curve showed a peak and dip in the neighborhood of 1000 Hz, the remainder of the readings following a generally ascending trend with frequency. Later it was found that a piezoceramic disk microphone directly in contact with the outside of the player's cheek produced a nearly identical curve, while the playing was more comfortable. The combined results of a series of such trials are reproduced in Fig. 1. The points are averages of sound-pressure levels in decibels, and while the scatter is rather large, the peak and dip seem very real, especially since each trial, consisting of a chromatic scale, exhibited similar behavior. The driving force is not constant with frequency—it can be expected to rise quite rapidly with frequency as the blowing pressure increases, accounting for the rising trend of the whole curve. From the extent in frequency of the perturbation, we see the cavity Q is quite low.

No such perturbation was found in the region of 500 Hz. It is possible that the effects of tongue movement reported by Benade and French in this region were caused by the mouth cavity acting on the second harmonic of the flute tone, which is quite prominent in the spectrum. Of course, mouth sizes will vary with individuals, so we must consider Fig. 1 to represent only a single sample, though there is no reason to believe it is atypical.

To investigate in more detail the effect of the mouth cavity on the frequency of the flute, an artificial mouth

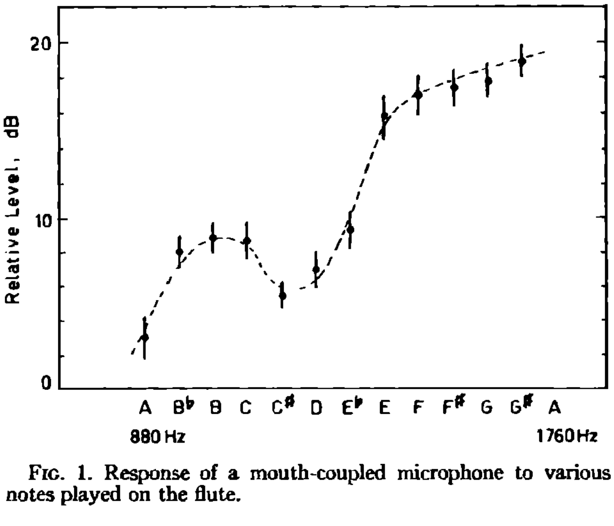


FIG. 1. Response of a mouth-coupled microphone to various notes played on the flute.

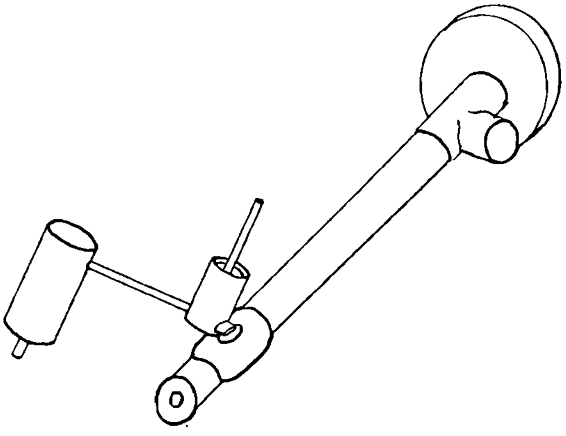
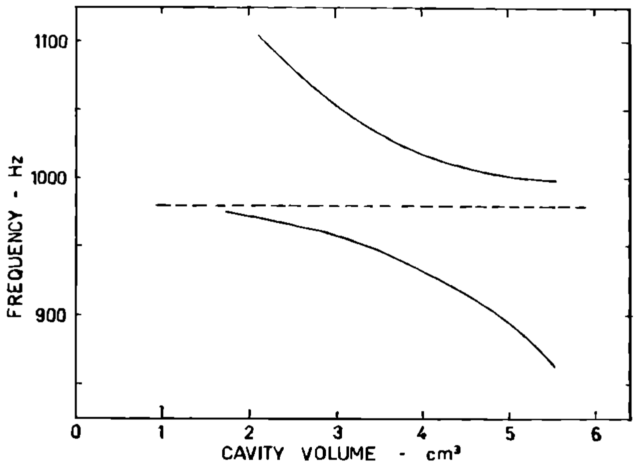


Fig. 2. Arrangement of the flute and artificial mouth. Not shown are the modeling-clay "lips" formed around the blowing tube.

was constructed. This consisted of a cylindrical cavity 1.9 cm in diameter whose volume could be varied by a movable plunger. Air could be introduced into the cavity through a small-diameter tube approximately $\frac{1}{4}$-wavelength long at the frequency of interest. This tube, leading into a wind chest, presented a high impedance so that the cavity resonance was not altered much by it. A short (6 mm long) brass tube, flattened to 1 mm×6 mm at its outer end, formed the blowing slit, and modeling clay was used to imitate the external geometry of the player's lips. The flute could be sounded adequately (if not charmingly) with this arrangement. The passive resonance frequency of the Helmholz resonator formed by the cavity and lip could be varied with the plunger from 750 to 1300 Hz, covering the range of perturbation observed in the first experiment. When resonant at 1000 Hz, the volume of the cavity was 3.6 cm³. The player's (author's) mouth, when playing this note had a quite similar volume, as measured by imbibing water.



Fiv. 3. Resonance frequencies of the coupled system of Fig. 2, as a function of volume of the mouth cavity. Dashed line is with cavity stuffed with cotton wool.

The cavity was placed as shown in Fig. 2 at the embouchure of a cylindrical flute head-joint, and this in turn was connected to a piston driver. A microphone in the tube nearby the driver was used to measure the response of the flute. The passive resonance frequency in the second mode was adjusted to about 1000 Hz with the mouth cavity tuned off resonance. Tuning the mouth cavity through resonance gave very pronounced perturbations in the resonance frequency of the head joint. The resonance in fact was split into two, as can be expected when two resonant circuits are coupled. Figure 3 shows the two branches of the observed curve. When the cavity is tuned to the flute resonance at 994 Hz, the splitting is about 80 Hz. Such effects are enormous compared to any frequency shifts observed in practice, and it was apparent that something was drastically wrong.

What was left out in this experiment was the effect of the air stream passing through the lip aperture, which forms the "neck" of the Helmholz resonator for the mouth cavity. Ingard and Ising[3] have shown that the acoustic resistance of an aperture is markedly affected by the passage of a continuous stream of air through the aperture. By putting a piezo-ceramic driver in the plunger of the cavity, and coupling a microphone through a hole in the wall, one can measure the resonance frequency and Q of the mouth cavity itself. The value is about 10 when the air is not blowing. Even a small velocity of blowing air lowered the Q so drastically that it was difficult to measure. Accordingly, tubing was added to the cavity to extend it a half wavelength, greatly increasing the stored energy for a given volume velocity at the neck. With this it was possible to measure, by the usual resonance width method, the Q with and without air blowing, and also with the neck blocked, so that the wall dissipation could be subtracted off.

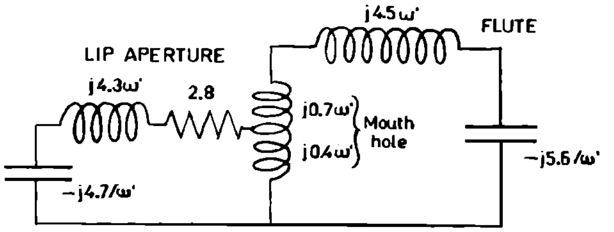


Fig. 4. Equivalent circuit characterizing the mouth cavity and flute near resonance.

The Q of this extended cavity, together with the known geometry of the tubular portion of the cavity, can be used to calculate the effective acoustic resistance of the lip aperture in the following manner: The tubular portion is considered as a transmission line of length L and cross-section area S. The tube is closed at one end and is terminated at the other by a restricted aperture whose impedance shortens the resonant line from its ideal length of $\frac{3}{4}\lambda$ by an end correction e. The acoustic resistance of this aperture is r, and its ratio to the characteristic impedance $\rho c/S$ of the line we designate as $R=rS/\rho c$.

Calculation of the energy stored at resonance in the tube and in the aperture for a given acoustic volume velocity i in the aperture, and comparison of this with 2π times the energy lost per cycle in R for the same i, gives the value of Q. It is found that

$$Q=(\pi L/\lambda+\tfrac{1}{4}\sin 4\pi\,\epsilon/\lambda)(R\cos^2 2\pi\,\epsilon/\lambda)^{-1}. \qquad (1)$$

Expression 1 was used to obtain from measurements of Q the value of R in the lip with various blowing wind velocities. For zero wind velocity R was found to be 0.44 while at the blowing pressure of 1.5 in. of water, R increased manyfold to 2.7. The variation was, except at the beginning, linear with the square root of the blowing pressure, as predicted by Ingard and Ising.[3] To find the Q of the original (unextended) cavity, Eq. 1 can again be used with the original length for L and the above determined values of R. For the length which tuned to 994 Hz, and a value of $R=2.7$, the Q is calculated to be 1.7.

The observed values of frequency splitting with the passive cavity (Fig. 3), the measured value of R for the lip and measurements of the flute head dimensions suffice to determine values for the equivalent circuit given in Fig. 4. This is essentially the circuit proposed by Benade and French, in which the resonant mouth cavity is tapped across a portion of the end correction inductance. In the frequency range treated, a simple LC circuit represents the flute, rather than using a transmission line, and the refinement of a stopper cavity reactance has also been omitted. We have chosen here a dimensionless frequency unit $\omega'=\omega/\omega_0$, where ω is the actual angular frequency and ω_0 is the angular resonance frequency of the flute head joint in the absence of the cavity.

Dimensionless impedance values are relative to the characteristic impedance of the flute tube, $\rho c/S$. The tube diameter for both cavity and flute head was 1.9 cm, the normal dimension of a modern flute. The stopped flute head is represented by a simple resonant series LC circuit, with an inductance calculated by using the stored energy implied by Eq. 1. An end correction of 4.7 cm was assumed, and the inductive reactance equivalent to this ($1.1\,\omega'$) was assigned to the mouth-hole. The frequency-splitting results of Fig. 3 dictate $j0.4\omega'$ as the value where the lip aperture is exposed to the acoustic pressure. No wall losses are shown, since they do not enter into what is to be calculated. The value of the capacitive reactance assigned to the mouth cavity in Fig. 4 corresponds to the cavity tuned to ω_0.

This equivalent circuit can be used to predict the frequency shifts and added losses due to the mouth cavity. The Q of the mouth cavity is now so low that no frequency splitting occurs. We take the resonance frequency as the point where the series reactance of the right hand loop is zero. In Fig. 5 the solid curve plots the calculated change in resonance frequency of the flute as the size of the mouth cavity is varied. The effect is only a few parts per thousand, and the major change occurs over a ±50% change in cavity volume. Also plotted here are experimental points taken by measuring the actual frequency of the artificially blown flute as the cavity volume was varied. Considering the small size of the effect, the agreement is very good. It was not possible to observe the expected rise as the cavity approaches zero size because the plunger cut off the air supply below the last point taken.

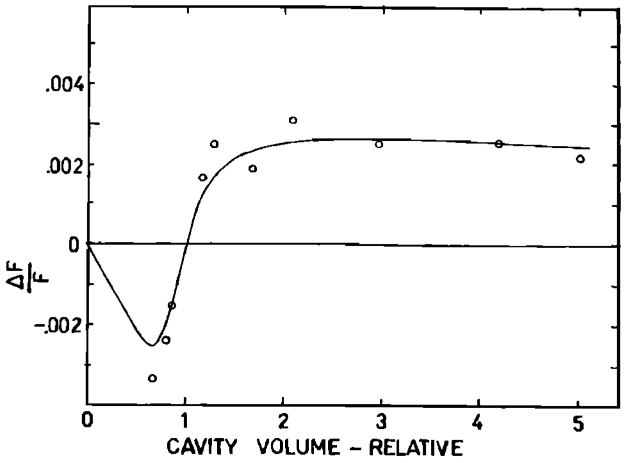


FIG. 5. Calculated and measured values of the frequency shift caused by varying the mouth-cavity volume.

Plotted in Fig. 6 are calculated values of the expected change in flute end correction due to a fixed cavity as a function of frequency at which the flute is played. This follows the course predicted by Benade and French. The entire effect amounts to about 3 mm, and the change

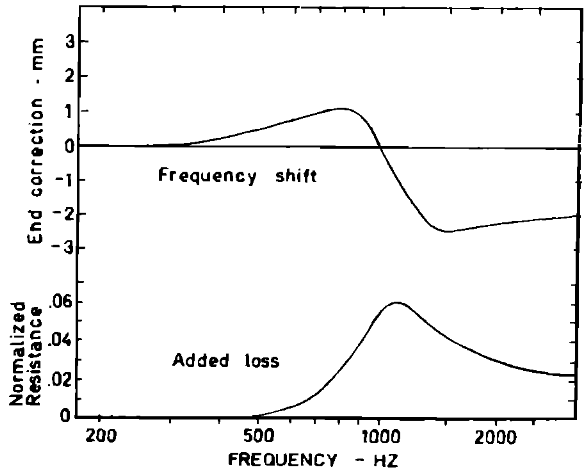


FIG. 6. Calculated effects of a fixed mouth cavity for various played frequencies. The resistance is relative to the characteristic impedance of the tube.

takes place over a whole octave. An increase in losses is also present, represented by the equivalent series resistance plotted in the same figure. The losses rise to a peak near the cavity resonance. The value of inserted resistance here is such as to give the experimental flute head a Q of 100 due to this resistance alone. This is not negligible, since typical wall-losses give Q's about 30. Measurements of the oscillation amplitude of the artificially blown flute show a drop in amplitude to about 70% of the normal value as the cavity is tuned through resonance.

It is concluded that mouth resonance does occur, somewhere in the neighborhood of 1000 Hz. Its effects on frequency when the flute is played are overall about 10 cents, and would be manifested as a slight upward perturbation as the cavity resonance frequency is approached from below, followed by a downward shift as the resonance frequency is passed. It takes more than an octave to go through this region, so these small effects are likely to be masked by other irregularities.

When air is not passing through the lips, the effects of mouth cavity resonance can be very much more pronounced. Measurements of passive resonance of the flute with the player's mouth in position, as reported by Coltman[4] and Nederveen[5] may therefore have been affected by a variable that was not controlled during the experiments. It is possible that this contributed to some of the discrepancies reported by Nederveen.

[1] N. Bak, Acustica **22**, 295–299 (1969).

[2] A. H. Benade and J. W. French, J. Acoust. Soc. Am. **37**, 679–691 (1965).

[3] U. Ingard and Ising, J. Acoust. Soc. Am. **42**, 6–17 (1967).

[4] J. W. Coltman, J. Acoust. Soc. Am. **40**, 99–107 (1966).

[5] C. J. Nederveen, Acustica **28**, 12–23 (1973).