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SOUND GENERATION MECHANISM IN THE FLUTE

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ABSTRACT
Hot wires and laser anemometry techniques have been used together with cine photography to study the air reed mechanism of sound production in the flute as well as the swirling flow patterns which form inside the instrument.

1. Introduction

The mechanism of sound production in the flute is particularly fascinating because of the basic simplicity of the instrument and the enormous range of tone qualities which can be produced by the performer. These are brought about by changes in the embouchure which effect the shape and direction of the air-stream impinging on the embouchure hole. Certain characteristics of the flow are well known to all flautists since these can easily be observed by looking at the condensation pattern inside the head joint and on the lip plate. Perhaps the most striking feature is the way in which the flow swirls down the instrument in a pattern somewhat resembling a spiral. A pictorial representation of this is given in Ref. 1. In fact the condensation pattern on the lip plate is sometimes used by teachers to diagnose faulty blowing technique.

The main features of the sound spectrum from the flute are deduced by considering it as a simple cylindrical tube open at both ends. The pressure fluctuations within the tube are maintained by the energy fed in from the oscillations of the air stream blown across the embouchure hole, generally referred to as the air reed mechanism. This aspect of the sound production mechanism has been studied by a number of authors (Refs. 2 and 3) although their measurements have been primarily qualitative in nature. Our aim is to carry out a quantitative investigation of the air reed mechanism and the flow patterns within the flute using the methods of hot wire and laser anemomentry together with cine photography. This is part of a broader program of study into the design of flutes and head joints. Other areas of interest include the effect of different head joint tapers and tone hole chimneys.

2. Film of Air Reed

In order to gain an overall insight into the air reed mechanism a cine film was made so that the movement of the airstream could be visualised throughout the acoustic cycle. A standard concert flute was clipped to play its lowest fundamental note C_4 and tuned to 261.6 Hz. An artificial jet was arranged so as to energise the instrument. A 1mm bore plastic tube was araldited just above the jet so that smoke particles could be introduced into the jet with minimal disturbance.

Smoke was generated by passing air in parallel through two 2" diameter glass tubes filled with glass beads to increase surface area. Tube one contained hydrochloric acid and tube two ammonia. The two air streams were mixed in a third chamber to produce ammonium chloride particles in air. The larger particles were immediately deposited in the chamber but sufficient smaller particles remained suspended in the air stream to provide a good visual marker of the gas flow.

The optical arrangement for the cine photography is shown in Fig. 1. A is a 16mm Arriflex camera with reflex mirror shutter. Double acting contacts were fixed to the shutter mechanism so that each rotation of the shutter produced a flash for visual monitoring and one flash for exposure. The speed of the camera motor was adjusted to stabilise, as far as possible, any movement of the air reed, in this instance strobing at one flash in approximately twenty cycles of the air reed. A later development of the equipment will control the strobe flash with a microphone pickup and frequency divider. The phase of the air reed can then be recorded by control from the camera running speed.

Illumination of the air reed at the embouchure was by 'dark ground', the camera viewing the flute axially through a hole in the centre of a mirror made of aluminised Mylar sheet (M2). The strobe light source and the air reed were both placed at the appropriate foci of spherical mirrors (M1).

Figure 2 shows a complete flow cycle from the cine film. Note, however, that the pictures are not consecutive frames from the film and it is not possible to specify the time scale because of the phasing problems already discussed.

3. Photographic Visualization of Swirling Flow

In order that the swirling flow patterns could be observed, a transparent flute was constructed from a plane glass cylindrical tube fitted with a circular metal embouchure hole and blow tube at one end (Fig. 3). This has the feature that the direction of the blowing tube can be rotated relative to the axis of the tube. This allows us to assess the importance of blowing direction in tone production. Although all modern flutes are side blown, many makers in the past have experimented with end blown instruments. One might expect that the swirling flow pattern would not be produced when blowing along the flute axis and if this flow pattern was intimately linked with the acoustic pressure fluctuations then the sound quality would be less good. Experiments showed that the sound quality was in fact best when the instrument was blown transversely although the effect of changing the blowing direction was only small. In fact the swirling pattern was always formed although less clearly defined in the case of end blowing.

For the flow visualization the tube was mounted vertically with the embouchure lower most. Pollen was injected into the airstream and was illuminated from below. Fig. 4 shows the flow pattern for the third harmonic, the fundamental being C_4. Although the pollen follows the swirling flow pattern it also collects at amplitude nodes as in the Kundt's tube experiment. The three nodes can be seen clearly in the photograph.

4. Whistle Flute

In sections 5 and 6 we will describe hot wire and laser anemometry flow measurements. For these a simplified flute was constructed from a referee's whistle and a perspex tube of internal bore 22mm, the total length being 38.5cm including the cork cavity (Fig. 5). It was found that this had most of the sounding characteristics of the normal flute including a pronounced swirling flow pattern. It had the advantage of a 22mm x 7mm rectangular embouchure hole, much wider than on a normal flute and a wide bore. These two features simplified the problems associated with the insertion of hot wire probes.

The whistle flute sounded Bb_4 (slightly flat) in its fundamental mode. The spectrum of its sound can be compared with that of a normal blown flute in Fig. 6. It is seen that there is close agreement. An Apple computer programmed for FFT analysis was used for these measurements.

5. Hot Wire Measurements

A Disa hot wire probe was used to measure velocities in the fluctuating jet and also in the swirling flow inside the flute. For the jet measurements a phase comparison with the pressure fluctuations was required so it was necessary first to enumerate the extent of unknown phase lags in the hot wire and probe microphone systems. For this purpose the two probes were placed together inside the tube excited to resonance by an external loudspeaker. The hot wire was sensitive enough to pick up the sinusoidal velocity fluctuations although it did not differentiate between positive and negative velocities. This problem was overcome by introducing a very small mean flow through the tube using the suction from a fan unit. This was adjusted so that it gave just sufficiently high a pedestal value to eliminate negative velocities. From the velocity and pressure records phase calibration was straightforward since it is known that in a standing wave the pressure should lead the velocity out of the tube by 90^o.

The hot wire was aligned along the tube axis and traversed through the embouchure hole along a diameter. Figure 7 shows a set of velocity traverses throughout one cycle. These were obtained by reading values from oscilloscope traces and then linearising using the appropriate hot wire calibration. The traverses show the extent of the flow field fluctuations and their relationship to the pressure, which was measured in the centre of the tube by the embouchure hole. The velocity records themselves were far from sinusoidal, an example trace at the centre of the jet being shown in Fig. 8.

Mean velocity measurements were also recorded across the diameter with the probe inserted through the embouchure hole. The traverse is shown in Fig. 9. Note that the velocities are high close to the edge of the tube but die rapidly to small values close to the centre.

It appears that there is no simple relationship between the swirling (tangential) velocity component and the pitch of the note, e.g. a fluid element does not circle once round the tube for each pressure cycle. This can be seen in Fig. 10 where the tangential velocity measured 3mm from the wall has been plotted as a function of pressure head. The circumference at this diameter is 5cm so in the fundamental mode one revolution takes approximately .025 sec., whereas the acoustic period was 0.002 sec., an order of magnitude smaller.

6. Laser Doppler Measurements

The hot wire technique was not suitable for measuring velocities along the axis of the tube because of its lack of directional sensitivity. For this reason a laser Doppler anemometer was used, employing a phase shifting device and the photon correlation technique for signal analysis. The method is described in detail in Ref. 4.

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In this situation there is a mean velocity through the tube but superimposed on top of this is a sinusoidal perturbation due to the acoustic resonance. In the fundamental mode the perturbation was expected to be a minimum in the centre and a maximum at the ends. This in fact was found to be the case. For a sinusoidal fluctuation the correlogram is damped by a Bessel function term (P221 Ref. 4) and by measuring the number of cycles appearing between the zero phase lag point and the first minimum it is possible to evaluate the amplitude of the velocity fluctuation in addition to the mean velocity. Fig. 11 shows correlograms measured half way down the tube and close to the open end both using a sample time of 0.35μs and a frequency shift of 500 kHz. In the first case the correlogram is a lightly damped cosine curve whereas in the second case (11 (b)) the Bessel function beating effect is present the number of cycles to the first minimum being five. The amplitude fluctuation in this case was calculated to be $1.2ms^{-1}$ which was surprisingly high in view of the fact that the mean velocity was only approximately $0.4ms^{-1}$. This value was measured from a correlogram using a smaller phase shift in order to improve accuracy.

The effect on the correlogram of changing the magnitude of the velocity fluctuations can easily be seen by introducing additional excitation through an external sound source. In the above case, placing a loudspeaker, tuned to the resonant frequency, close to the end of the tube, decreased the number of cycles to the first minimum from five to four, indicating an increase in velocity amplitude in this ratio.

7. Research Programme

The results presented here will form the basis for a more detailed program of work. The stroboscopic photography technique is to be improved as already described and we also plan to use high speed photography to obtain real time records of complete acoustic cycles. It is planned that the laser anemometer will be used for a more detailed study of the velocity distributions within the flute. Particularly we will be looking for any structure in the flow pattern. With this in mind we have programmed an Apple computer to gate the photomultiplier signal so that the correlograms can be linked to particular phase positions in the pressure cycle.

References

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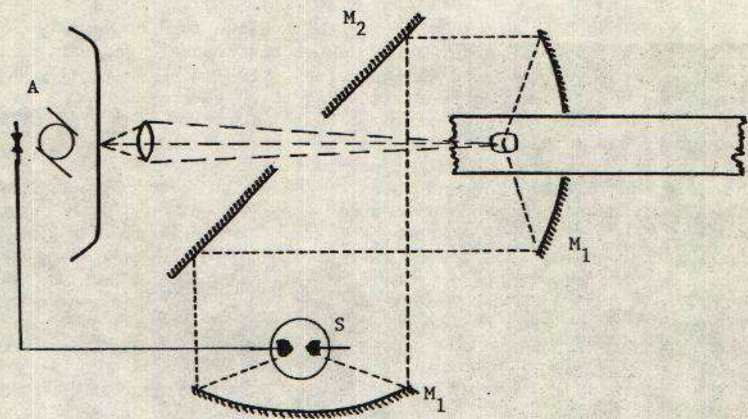

Figure 1. Dark ground system used for filming the air reed.

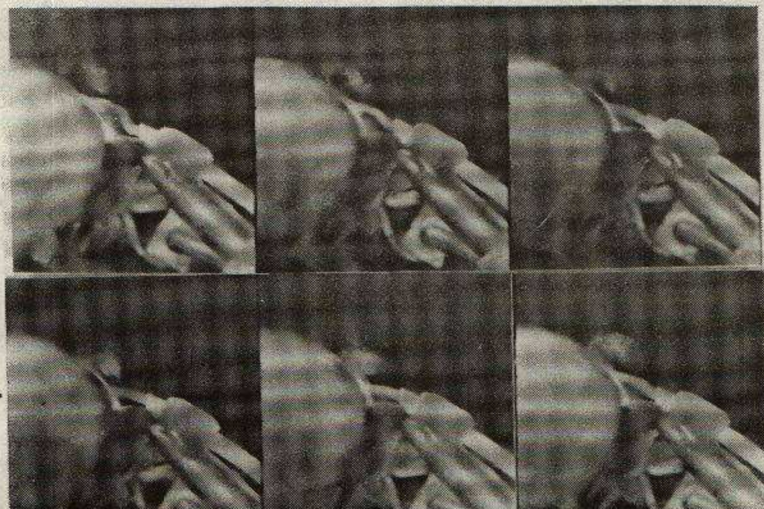

Figure 2. Selected frames from a film of the air reed oscillation.

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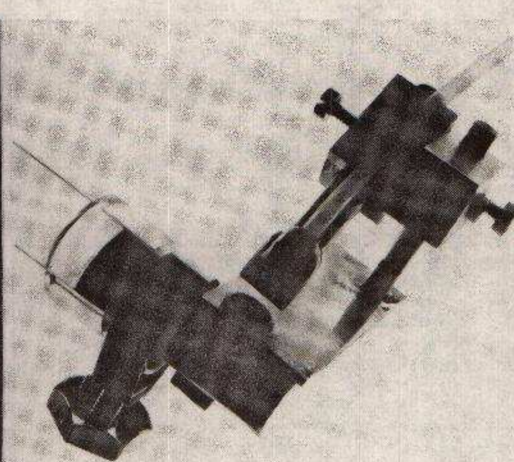

Figure 3. Glass flute fitted with an artificial embouchure which allows the air stream to be rotated.

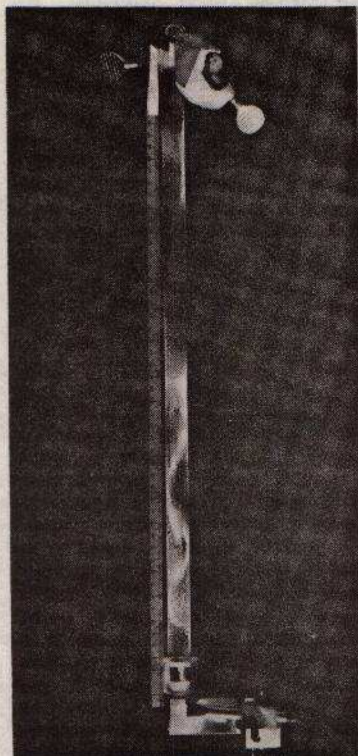

Figure 4. The swirling flow pattern in the third harmonic mode with fundamental C_4.

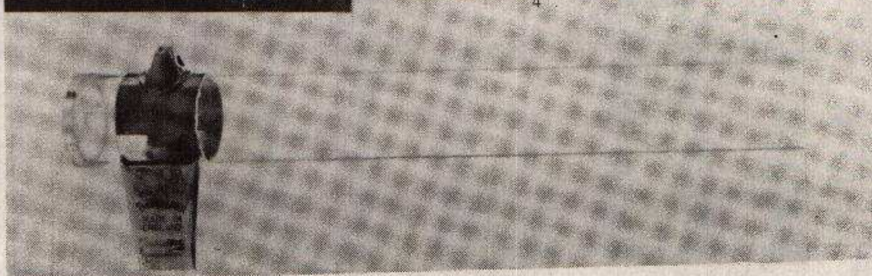

Figure 5. Simplified Whistle Flute

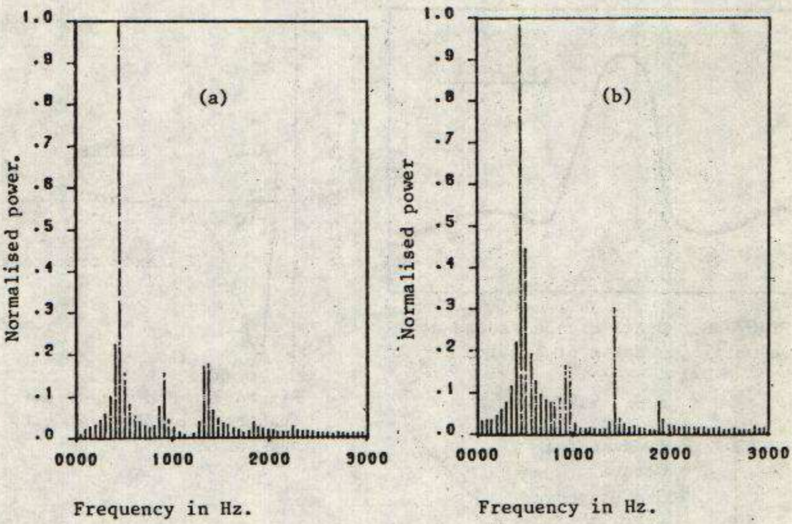

Figure 6. Comparison of the sound spectra produced by (a) the whistle flute (b) a standard concert flute, both sounding B♭$_4$.

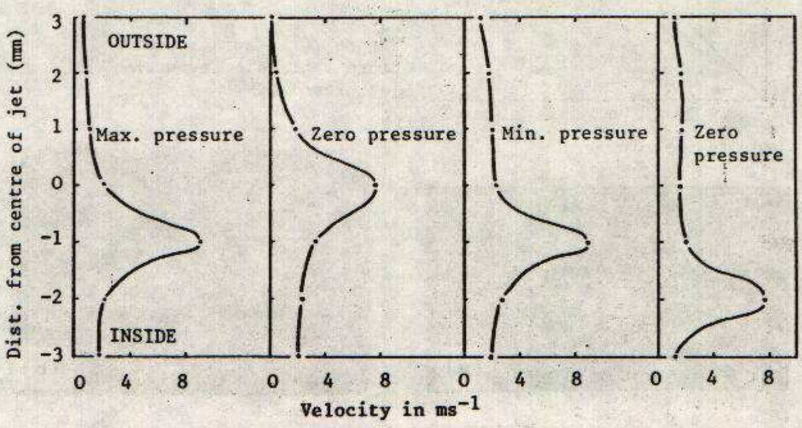

Figure 7. Velocity traverses across the jet at different phase positions.

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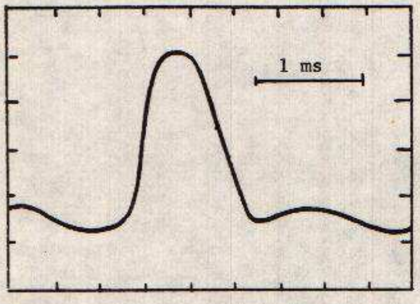

Figure 8. Oscilloscope record of velocity in centre of jet.

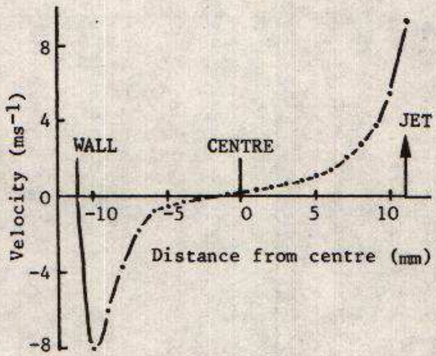

Figure 9. Profile of swirling (tangential) flow velocity across the tube.

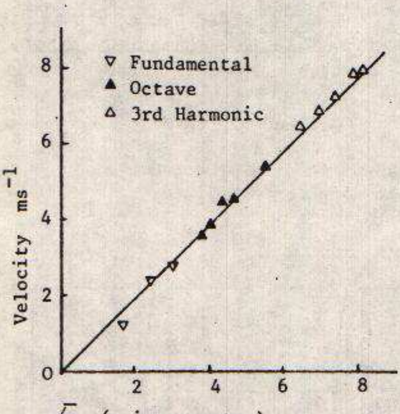

Figure 10. Variation of tangential velocity with jet pressure.

Figure 11. Photon correlograms recorded with a frequency shift of 500 kHz and sample time 0.35 μs at (a) centre of tube (b) close to open end. Jet pressure is 4 cm of water.