REED ACTION IN THE BASSOON

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1. Pressure Waves in the Bassoon tube

The bassoon is a conical woodwind instrument played with a double reed. A typical internal pressure waveform is shown in fig. 1. This waveform has characteristic sharp spikes with intervening quasi-exponential regions. An important feature of the waveform is that, while the periodic time is that of the played note, the pulse length of the spikes is largely invariant. This is certainly the case up to a frequency of around 300 Hz where the period is about double the pulse length. This phenomenon seems to indicate that while, of course, the period of the played note is governed by wave reflections from the ends of the tube, the pulse length is determined by the reed and its environs. The pulse effect is not dependent on the presence of a double reed; a small single-reed mouthpiece of the clarinet type gives a similar result (and the characteristic bassoon sound is obtained).

The shape of the pressure waveform changes drastically as the point of observation is varied, but the pulses are always present. The change in shape is not surprising since the observed time-varying pressure profile is that of a standing wave - the sum of two oppositely-travelling pressure waves. By a judicious examination of the standing-wave pressure patterns at different locations, the outward-going wave from the reed can be disentangled from the returning wave from the outer 'open' end of the instrument. It then appears that the pulses are always negative-going in the outward wave and are reflected, as expected, as positive-going ones. Observed in the reed, the pressure waveform seems simplicity itself (fig. 3a). The negative pulses are the outstanding feature with but a few minor extra excrescences (see also [1]). It is clear that reflection at the reed results in a cancellation of pressure between the other features of the outward and inward waves.

It may be appropriate to recall the salient features of wave propagation in a conical tube. At the outer (open) end, a pressure wave is reflected with complete phase reversal. However, at the other end, the cone cannot continue to a point, it must be truncated at the reed location. (In the case of the bassoon, this truncation is some 280 mm from the theoretical point of the cone.) For the moment consider the tube completely sealed at the truncation. A wave having a wavelength much greater than the 'missing' part of the cone and returning towards the closed end is reflected with phase reversal plus an additional phase change that corresponds to a fictitious journey to the point of the cone and back. This means that the cone has the acoustic properties of a doubly-open tube of length equal to that of the complete cone. As the frequency rises and the wavelength of the returning wave approaches the truncation length, the time delay to the reflected wave becomes shorter than that for the round trip over the truncation length. A complex wave containing many frequencies will thus have its shape altered or 'smeared out' by such a reflection. If, however, a small cavity of appropriate volume - such as the reed has - is provided at the truncated end, the time delay can be made insensitive to wavelength up to a limiting frequency. This frequency is the resonant frequency of the resonator formed by the acoustic capacitance of the reed volume and the inertance of the conical entrance to the instrument tube. (This resonant frequency has other important consequences.) A judicious selection of the reed cavity volume thus results in a minimum of smearing of a reflection at the reed end of the instrument. This emphasises the importance of the correct reed volume and the facility for its adjustment under playing conditions. Such an adjustment is possible with a double reed where lip force can alter the volume; it is not so easy with a clarinet-type mouthpiece.

The reflection of the wave at the outer end of the instrument deserves a mention. Here there may be merely the open end (for the lowest note) or one or more open tone-holes. The filtering properties of this termination will give a frequency-dependent reflection. Again, the wave reflected is a modified or smeared version of the incident one and the instrument's tone quality and intonation will depend on the nature of this reflection.

What is the shape of the progressive wave? Look first at the beginning of a note (fig. 1a). The player blows into the open reed attached to the conically-expanding tube. There is an initial sharp pressure build-up followed by a more gradual decay. This pressure profile propagates down the tube and is inverted on reflection. On arriving back at the reed it is inverted once again and time-delayed. The combination of these two waves at the reed with the time delay results in a negative-going pressure pulse. All this time the reed has been standing open, but now, under the influence of the negative pressure, it begins to shut. In shutting, the flow of air into the conical tube is interrupted. Because of the inertance there, a much magnified and sharpened negative pressure is generated. The reed tends to close completely and an oscillation of the trapped air (compliance) against the inertance can take place. If the reed volume has been properly chosen, the half-period of this oscillation will approximate to the time delay between the returning and re-reflected pressure signals. The negative pulse that they have already produced is magnified and sharpened; the rising trailing edge reopens the reed and the process re-commences. The negative half-cycle of oscillation is added to the progressive wave and is a characteristic feature of the regeneration process. When the player ceases to blow, the sharp negative pulse disappears; the re-sharpening ceases and the pressure wave decays, becoming progressively more rounded in the process (fig. 1b).

2. Experimental

In this work, various features of the reed regeneration process and the pulse generation were examined. To aid this, an "artificial mouth" was constructed enabling the reed motion to be examined (fig.2). A plastic reed had to be used for these studies since it could operate dry. For measuring the internal reed pressure a small capacitor microphone was placed in a hole drilled in the tubular (non-vibrating) part of the reed. Each reed blade carried a small piece of aluminium foil acting as an electrode. These were connected to a pre-amplifier and polarising supply usually used with capacitor microphones. By this means the reed motion was transformed into an electrical signal. A hot-wire anemometer probe was placed a convenient distance (about 5 mm) in front of the reed opening. While it was impossible to measure the linear velocity of the air in the reed opening, it was possible to obtain a signal approximately related to the volume velocity of the air entering.

Stroboscopic illumination was also used. This soon disclosed that, as expected, the reed stood open for the major part of the cycle if a low note was being played. Its closure corresponded approximately to the negative pressure pulse and for part of this time it was completely shut.

The apparatus was difficult to set up! Only a limited amount of adjustment was possible compared to that of which a skilled bassoonist was capable. For certain tests the versatility of the human player was essential; of course he could not be as fully instrumented as the artificial one.

3. Variation of pulse length

If the pulse is a half-cycle of free oscillation of the reed cavity resonator, then it should be possible to alter it by variation of the volume or the rate of taper since the inertance depends on the cone angle. Consequently an instrument of bassoon proportions but having a different cone angle was sought. Fortunately a heckelphone was available. This is a type of baritone oboe sharing a similar reed size and tube entrance diameter with the bassoon. Its cone semi-angle is 0.013 rad. compared to the bassoon's 0.007 rad. As expected, the pressure pulses were shorter than with the bassoon. Stroboscopic viewing of the reed motion of both instruments confirmed a shorter period of closure with the heckelphone. Attempts to quantify the pulse length and to relate it, for instance, to the square-root of the inertance, were not very successful. This was largely because it was difficult to decide precisely what the pulse length was. Further experiments were done with a bassoon reed attached to conical tubes of varying angles. Varying pulse lengths (and different tone-qualities of the emitted sounds) were obtained, but not in a way that supported a simple physical law.

4. The regeneration process - triggering of the pulse

It would seem clear that the process by which the travelling wave is 're-sharpened' and the pulse generated is triggered-off by the pressure change in the reed brought about by the returning wave. However, the details of this and its precise timing required further investigation. The timing is of fundamental practical importance since it determines the tuning of the note played and must be under the control of the player. The three curves of fig.3 may shed some light on this. The uppermost curve (a) shows the pressure in the reed. It is supposed that the leading edge of each pulse is instrumental in setting off the closure of the reed. Curve (b) shows the corresponding volume velocity of air flow and (c) the reed displacement.

As the pressure in the reed falls, the reed blades move together, but the air flow goes through a maximum. This exemplifies the flow-control characteristics of a reed system succinctly described in ref. [2]. Starting with the reed fully open, a fall of pressure within causes the air flow to increase since the reed has not yet closed significantly. However, a further fall in pressure causes the reed to begin to close enough to reduce the air flow. The peak on the flow-time curve signals the instant at which the flow is about to be restricted by reed closure. Now the tapered entrance to the tube exhibits acoustic inertance; a pressure drop will result from any rate of reduction of volume velocity. If the rate of reduction is caused by the closing reed - rather than by a rising pressure - the resultant pressure drop will add to the already falling pressure and close the reed more rapidly. The sudden pressure drop and accompanying reed closure takes its cue from the instant when the volume velocity passed through its maximum. An elementary analysis of this process leads to the result that the reed pressure p_m for this to occur is:

$p_m = P - xs/2S$

P is the blowing pressure
x the static opening of the reed before the pressure is applied
s the reed stiffness
S the area of each reed blade

When the reed is about to be closed the internal pressure p is falling because of the returning pressure signal. Hence raising the value p_m at which the reed closure is triggered will advance this point, shorten the periodic time and raise the pitch. Flattening will result from a lowered value of p_m. From the above relation it can be seen that the pitch may be raised by:

(i) raising the blowing pressure P
(ii) reducing the blade separation x - possibly by increasing the lip force
(iii) reducing the blade stiffness; probably this is also achievable by increasing the lip force since the blade shape makes the reed a 'weakening' spring.

These tuning adjustments are additional to any achieved by altering the slope of the returning pressure signal resulting, for instance, from a change in the nature of the reflection at the tube end.

These ideas are in general conformity with playing experience, but many subtle details have been left out. No effect of the Bernouilli force between the blades has been considered nor has the inertia of the blades or that of the air flowing between them. Some hint of the effect of the Bernouilli force in triggering a reed closure in the absence of a pressure reduction is given below.

5. Higher order modes of oscillation - "overblowing"

The instrument's range is usefully extended by the employment of higher modes of oscillation of the tube. The reed must be made to operate two, three or more times during a single wave transit of the tube. Stroboscopic examination of the reed shows that, if the blowing pressure or lip force is increased, the reed "flutters" at some point between its closure pulses for no reason connected with the internal pressure. If the blowing pressure or lip force is increased further, this flutter deepens into a full-blown closure accompanied by the generation of pressure pulses and causing the pitch to jump by an octave or twelfth. A timely nudge from a pressure reflection returning from an open hole may help to initiate or stabilise things, but this is not in every case essential. The reason for the initiation would seem to be the Bernouilli force. If the air flow has built up sufficiently during the quiescent period between pulses, the Bernouilli force may start to pull the blades together again. High blowing pressure - meaning high air flow - and high lip force - meaning small gap width - will encourage this. The exact timing of the secondary shutting is not critical, as can be seen in the development of the higher mode oscillation in fig.4. When the full higher frequency oscillation has built up, the timing of the pulses will become stabilised by the shape of the newly-formed pressure wave. The slight conflict that ensues at the setting-up of a higher-mode oscillation is probably the reason for the characteristic transient that attends the middle- and higher-register notes of the bassoon.

REFERENCES

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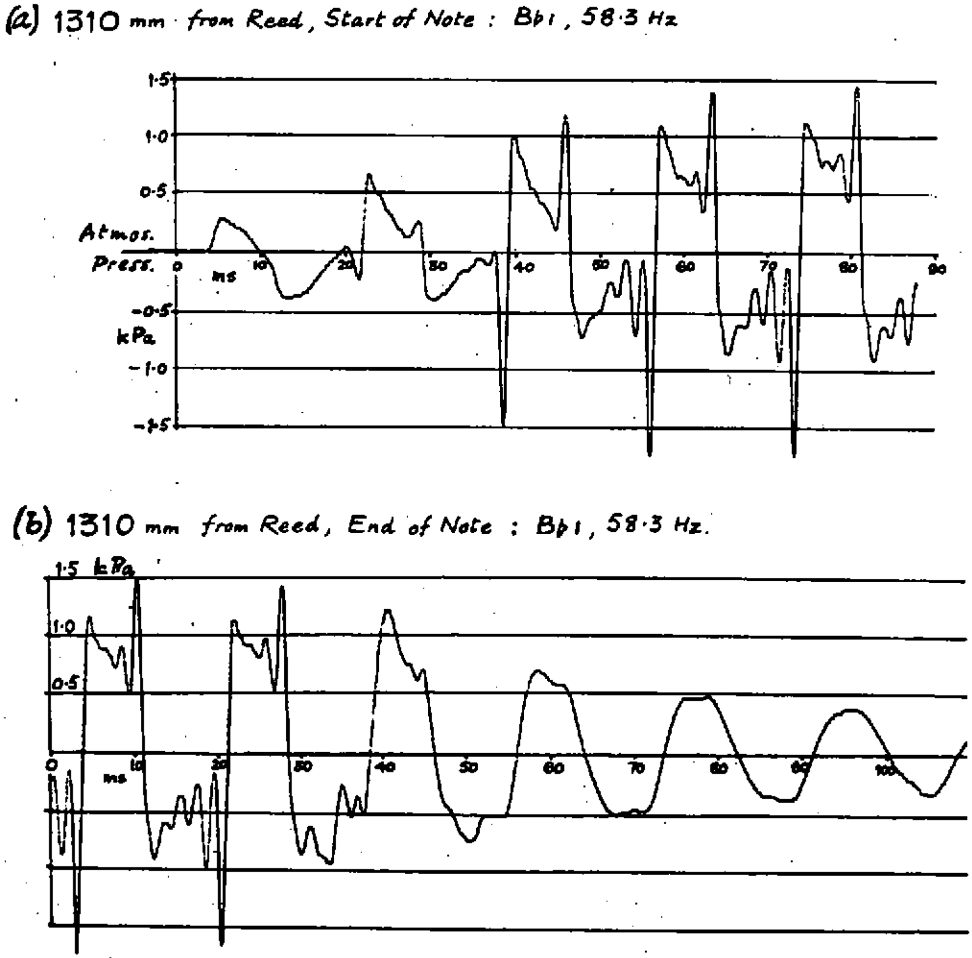

FIG. 1 Pressure Waveforms in Bassoon

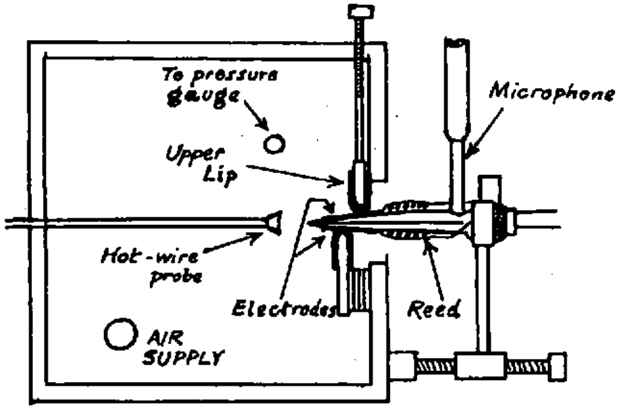

Fig. 2 ARTIFICIAL MOUTH

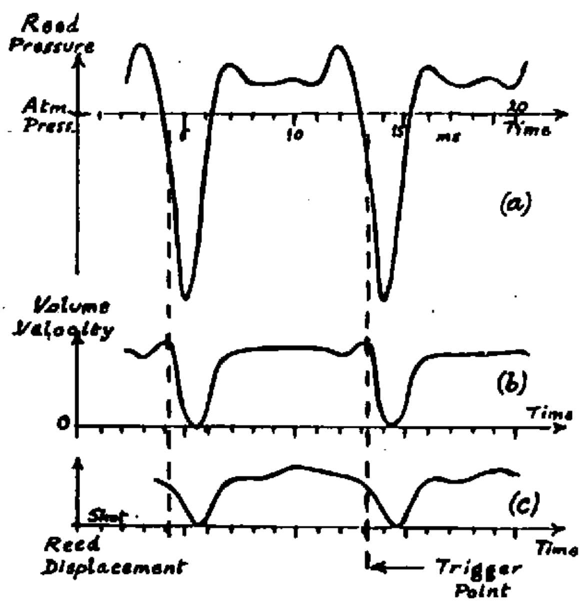

Fig. 3 REED EVENTS : A_2 110 Hz

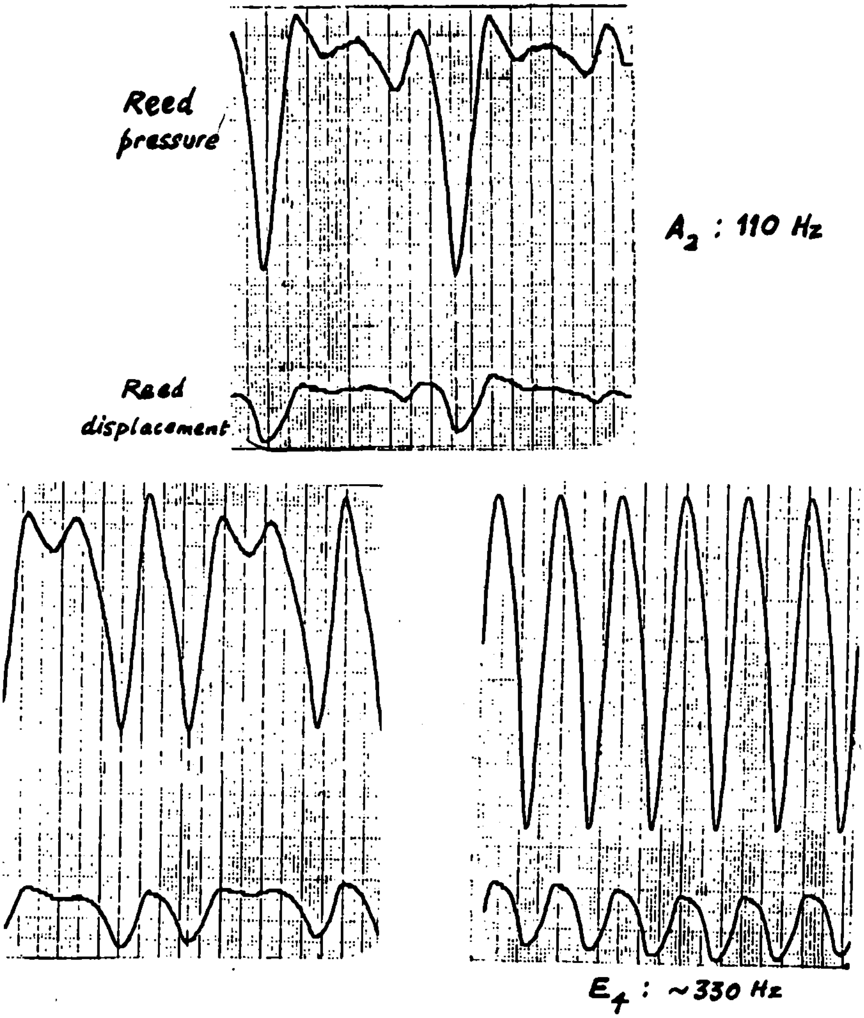

FIG.4 Three stages in the transition A_2-E_4
(upper traces: reed pressure, lower traces: reed displacement)