Proceedings of The Institute of Acoustics

SOME FACTORS AFFECTING INTONATION AND TONE-QUALITY OF THE BASSOON

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The bassoon is a conical instrument blown with a double reed. In the modern (German pattern) instrument, the cone expands from a diameter of 4mm to around 40mm in a length of some 2.5m. The "missing" portion of the cone - up to its theoretical apex - is approximately 260mm. The range of the instrument is from Bb_1 (58.3Hz) to D_5 (580Hz) or a note or so higher. The tone-holes are distributed somewhat irregularly and are of widely differing sizes. Some are long and narrow, others (particularly at the outer end of the instrument) short and of larger diameter. Four or five holes are covered directly by the fingers. The fingering of the modern instrument is (moderately) regular up to the region of F_4 (349Hz), a tone-hole being provided to facilitate the playing of each note of the chromatic scale. Above this region, acoustical reasons introduce an apparently haphazard complexity into the fingering.

Basic theory of wave propagation in conical tubes gives the result that resonances occur at frequencies for which the cone length continued to the point is an integral number of half-wavelengths, provided the missing portion of the cone is a small fraction of the wavelength concerned. Departure from a sufficiently accurate fulfilment of this criterion leads to the requirement for corrections in the placing of tone-holes and to resonances of a given note that deviate from a harmonic series. Correction to achieve such a situation has been stressed by Benade (ref.1). Stability of the reed regeneration mechanism as well as the availability of accurately-tuned registers depends on this. For a given effective cone-length, as set by the fingering, corrective action is taken by the reed volume. Small-amplitude (linear) theory (ref.2) indicates that the effective volume contributed by the reed is the sum of (i) the volume between the reed blades in the playing condition, (ii) the volume corresponding to the acoustic admittance brought about by the reed motion and (iii) the effective volume associated with the reed damping. Substantial variations of (i) and (iii) are directly under the control of the player and (ii) indirectly so through selection and adjustment of the reed. The range of control is greater than is the case for the clarinet with its larger mouthpiece (and the experience of bassoonists is that it needs to be!). The reed volume must not be sufficient to correct the harmonic relationships completely. This is because of the frequency-dependent length correction to a tube terminated by a series of open holes. The high-pass filter characteristics of such a system lead to a greater penetration of the standing-wave into the open-hole region the higher the frequency of the resonance. The tone-holes lattice cut-off frequency and its effects have been extensively described by Benade (ref.3).

The traditional way of identifying resonances is to examine the input acoustic impedance (ref.4). The instrument was driven with a constant volume velocity at variable frequency and an acoustic pressure proportional to the magnitude of the input impedance measured at the plane of the input to the reed. The reed and its effective volume were simulated by a reed-shaped connector attached between the high-impedance source and the crook of the instrument. The criterion of adjustment of the connector volume was that the resonances for each note of the scale should be aligned as closely as possible to a harmonic series. This was achieved with moderate success but the fundamental frequencies were systematically lower than the required frequencies of the tempered scale.

The impedance traces show various features, some familiar and some unique to the bassoon.
(i) Low frequency resonance peaks, e.g. the first few resonances of the lowest notes tend to be of lower height than higher frequency resonances. This is a consequence of the missing apex of the cone being a smaller fraction of the lowest wavelengths than is the case e.g. for the oboe. This has consequences for the successful attack of the lowest notes at low dynamic levels or for the beginning player.
(ii) At higher frequencies there is a general reduction in peak height consequent upon increased internal energy losses with frequency.
(iii) Above a certain frequency (around 400Hz), additional peaks of smaller height and closer spacing appear. This frequency is the cut-off frequency above which the standing wave can inhabit the whole tube. Because of the presence of the open holes, damping and radiation is greater, but in the case of the bassoon, not so great as in the clarinet and saxophone where these resonances are effectively annihilated. The frequency-spacing of the peaks is appropriate to resonances of the whole tube, modified by the fact that the phase velocity of sound is inflated in the region just above cut-off.
(iv) For second-register notes, opening of a suitably-placed and sized speaker hole selectively reduces and/or displaces odd-numbered modes, leaving even-numbered ones in a harmonic relationship, so collaborating in driving the reed at the octave frequency.
(v) The highest notes of the bassoon - almost an octave of them - require fundamental resonances lying above the cut-off frequency. This is a unique feature of the bassoon and contrasts with the other woodwinds whose cut-off frequencies are at the topmost end of the playing range. The possibility of performance in this range is due to the presence of a not-too-small resonance and a reed resonance frequency that is only about an octave away (around 700 to 1000Hz). The nonlinear reed dynamics ensure that the reed can selectively support a resonant regime for which its own frequency is at the second harmonic of the peak frequency, (ref.5). The provision of a suitably-tall resonance peak is the function of the complicated pattern of open and closed tone-holes; the suitable tuning of the reed is critically dependent on its mechanical properties and the player's embouchure.

The spectrum of the radiated sound is determined by that generated internally and by the filtering characteristics of the open hole system. For the notes using only open holes in the long joint, this transmission begins at around 500Hz; for notes using open holes elsewhere, the cut-off frequency is around 400Hz as previously noted. Consequently the spectrum of any note played is weighted in favour of components above 400Hz. It is the placement of this cut-off frequency that carries with it a large part of the characteristic bassoon sound. A significant alteration to it (possibly as a by-product of altering tone-hole proportions in an attempt to 'rationalise' fingering) destroys the instrument's character.

The internal sound spectrum is, however, the basic ingredient operated on by the acoustic filter. Indeed, it is traditional to characterise the internal sound in terms of its spectrum, i.e. in the frequency domain. The nature of the internal pressure wave-form and its development is most easily understood in the time domain, as has been most clearly and succinctly demonstrated by McIntyre and his co-workers (ref.6).

For a low note on the bassoon, the pressure signal observed by a probe microphone inserted in the reed consists of a series of short pulses, each followed by a smaller rapidly-decaying oscillation. The pulse repetition rate is, of course, the fundamental period of the played note and the height of each pulse indicates that the pressure has risen approximately to that in the player's mouth. As the fundamental frequency is raised, the pulses stay approximately the same length, but are closer together, so crowding out and modifying the following oscillations. For a still higher note, the required pulse repetition rate is such that the pulses crowd together or are even shortened. Further, the edges become somewhat rounded off and the pulse train begins to take on the appearance of a sinusoid. A first attempt at an explanation of these effects may be made by examining the mass loading of the reed by the reactive part of the admittance of the conical air column. For a progressive harmonic spherical wave, the admittance at a distance x_o from the point of the cone is:

$$Y = \frac{A}{\rho c}\left\{1 + \frac{1}{jkx_o}\right\}$$

where A is the cross-sectional area at that location. This corresponds (using an electrical impedance analogy) to a parallel connection of inductor and resistor, the inductance being $\rho x_o/A$ and resistance $\rho c/A$. This parallel circuit is connected to the pressure source via the variable resistance of the reed. If the component values are considered constant and a pressure step P_o is applied to the reed, it is elementary to show that the pressure p developed at the entrance to the cone is the applied step followed by an exponential decay whose time constant is closely related to x_o/c . If now the reed is simply modelled as a switch which disconnects P_o when $P_o - p$ is sufficiently large, the decay of p eventually results in such a disconnection after a time τ . This generates a negative-going pressure which again decays towards zero. (In real reeds, the rapid closure is aided by the Bernoulli force at the blade tips, emphasising the care in reed preparation needed of every bassoonist.) The double pressure pulse so produced travels down the cone (of length l) where it awaits reflection by the collaborative effects of the open tone-holes and the end of the instrument (as well as the closed holes and any excresences due to poor workmanship or lack of care of the instrument). On reflection, the pressure signal is inverted and 'smeared out' and returns to the reed after a round-trip time of $2l/c$. There it encounters the closed reed and, since the first-arriving edge of the pulse is negative-going, the reed stays shut. However, the following pulse edge a time τ later is positive-going; it re-opens the reed and re-starts and re-invigorates the cycle of operations. Note that the cycle-time is $2l/c$ plus the 'pulse-width' τ . The latter is some multiple of the time-constant x_o/c , the exact number depending on the value of $P_o - p$ at which the reed dynamics cause it to close rapidly; a value 2 is a reasonable approximation. This gives a fundamental frequency of $c/2(l+x_o)$, the value predicted by wave theory for a cone. In fact, this is a physical explanation of the seemingly puzzling result that a cone of length l closed at the narrow end and with a short missing portion of length x_0 behaves as a doubly-open tube of length $l + x_0$.

In the case of the clarinet, described by McIntyre, there is no input mass-loading. The reed, once opened, stays open until it is closed by the returning negative-going pressure after a round-trip time of $2l/c$. It does not re-open until the initial pressure step (now positive-going again) has covered a further round trip; hence the fundamental frequency is $c/4l$. The pulse width in the case of the cone is a function of x_0. Consequently, for a given diameter at the reed, a more sharply-tapered cone will have a smaller value of x_0 and a narrower pulse width. Casting an eye back towards the frequency domain, this provides part of the explanation of Smith's observations (ref.7) on the variation of formant frequencies with cone angle and on the coarse tone emitted from a wide-angled cone.

An elaboration of this time-domain approach will reveal, via the pulse-length of reed opening, the intonational effects of reed volume and damping, as well as of reed flow-control characteristics, lip force and blowing pressure.

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