The Anatomy of the Clarinet

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A concise explanation of the acoustical functioning of the clarinet and the principles involved in its design, comprehensible to the layperson but scientifically authoritative and stemming from in-depth practical knowledge of clarinet making, would be of great interest to performers and teachers of all backgrounds. Such presentations are difficult to find in the published literature and are absent from the programs of most ClarinetFests; this lecture will address that need.

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Sound is produced and sustained in any wind instrument through cooperation between two distinct but connected entities: a cavity containing air in which sound resonates (the body), and a sound wave generating device (the reed and mouthpiece, in the case of a clarinet).

Sound waves in a clarinet are generated by the reed beating against the mouthpiece facing at a certain frequency, which is controlled primarily by the resonance of the air inside the body and secondarily by the embouchure of the player. Harmonics (whole number multiples of the reed's beating frequency) are also produced.

When the sound waves pass through the air inside a cavity, there are certain modes or patterns of vibration of the air at which standing waves are possible, or in other words certain frequencies - the “resonance frequencies” - at which the sound waves reinforce each other as they bounce back and forth from end-to-end of the cavity.

A tone is thus produced when the set of frequencies generated by the reed/mouthpiece and the set of resonance frequencies of the air inside the body are aligned; the beating frequency of the reed is dictated by the dominant resonance of the body, and the harmonics of the reed vibration attempt to find further resonance frequencies to excite. How effectively this collaboration takes place determines the strength, stability, clarity and ease of response of the note.

The resonance frequencies of a woodwind instrument are determined both by the shape of the bore and by the tone holes, some of which will be open and some closed when a given note is fingered. Since the bore of a clarinet is approximately a cylinder with the reed end closed and the bottom end open, in the simplest approximation the resonance frequencies should be the odd numbers of a harmonic series (e.g., 100Hz, 300Hz, 500Hz...). However, the tone holes (both open and closed), as well as frequency-dependent end effects at the reed and bell, modify the resonance frequencies considerably. This must be compensated for by alterations in the shape of the bore.

A sound wave travelling down a woodwind bore will be reflected back from a point at a certain distance below the highest open tone hole. Higher frequencies travel further past the open hole; we could say that higher frequency waves “see” the hole as being smaller than lower frequency waves. Thus in any woodwind, the second and higher registers will tend to be flat, unless this is counteracted by changes in the bore shape. Above a certain frequency, known as the “cutoff frequency”, the waves ignore the tone holes completely and travel all the way down to the bottom end. The closed tone holes also make the bore behave as if it were both enlarged in diameter and stretched lengthwise slightly; this must also be taken into account when designing an instrument.

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The bore of the clarinet, while simplistically described as “cylindrical”, is modified considerably from a pure cylinder. The addition of a bell produces more efficient and even sound radiation. And, some of the inherent tuning deficiencies of a strictly cylindrical bore are addressed by minor perturbations in the bore diameter according to the following principle:

A localised enlargement of the bore lowers the frequency of vibration of modes which have high pressure in the region of enlargement, and raises the frequency of modes having low pressure in that region. A contraction of the bore has the opposite result.

We can experiment informally with this process by placing something - a sliding ring, a lump of modelling clay, etc. - inside the bore of a clarinet at different places and measuring the changes in intonation.

The subtle shape of the bore in the upper joint (the so-called “polycylindrical” bore is one example) is a result of applying this principle; it is also exploited when designing the barrel.

The bore of the clarinet has evolved over the past two centuries along two basic lines, the French (with a long, flaring expansion starting around the middle of the lower joint) and German (with a cylindrical lower joint apart from the very bottom end), each of which addresses tuning issues in its own way, and each of which has characteristic tonal features.

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The speaker hole functions by disturbing the strength and frequency of the fundamental mode for a particular note to the point where it cannot cooperate with other resonances and hence cannot form the basis of a musical tone, while leaving the second mode unaltered. For a clarinet, the hole must thus be positioned roughly one third of the way down from the reed end.

The speaker hole is located ideally for one point in the scale (around A/E or Bb/F); in this region, the pitch of the second register note is independent of the characteristics of the speaker hole, and in fact is the same whether or not the speaker hole is open. Toward the top and bottom of the scale, however, the fact that the register hole is misplaced leads to the upper register notes being pulled sharp. This can be demonstrated on any clarinet by playing the second register, closing the speaker key and listening for the change in pitch.

The degree of widening of the twelfths at the ends of the scale increases with the size of the speaker hole. Thus the problem is exacerbated by using the speaker hole also as a tone hole for throat Bb; on clarinets with a separate or supplementary tone hole for throat Bb, the speaker hole can be considerably smaller, and the tuning between the first and second registers is noticeably improved.

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The tone holes of a chromatic woodwind instrument are, simplistically speaking, positioned so as to terminate the tube acoustically at each semitone of the scale. In order to give constant tone colour and resistance throughout the scale, the holes need to be smallest at the top of the tube, larger further down. In contrast with the rationally designed tone hole lattice of, for example, the flute, the tone holes of a clarinet are an apparent hodgepodge of varying diameters, depths and spacings; this is reflected in some inhomogeneity in the scale, though acoustically the system is not as irregular as it looks.

The pitch of a given note depends on the location of the tone hole principally involved in producing that note and on its open hole end correction (the distance the sound waves travel beyond the hole before bouncing back). The end correction varies with a number of characteristics of the hole: its diameter, the spacing between it and the next hole, its depth, and the height of the pad over it. The note is sharpened by enlarging the hole, moving the next hole closer, reducing the depth of the hole or raising the pad; it is flattened by doing the opposite.

The cutoff frequency (of a particular tone hole or of the instrument in general), the frequency above which sound waves ignore the open tone holes, is an important value, which can tell us a lot about the character of an instrument, since it is a quantitative measure of tonal "brightness" or "darkness": a high cutoff frequency gives a sound which we describe as bright, a low cutoff frequency a dark tone.

Large tone holes (relative to the bore), short hole spacing, shallow holes and high pads give a high cutoff frequency; small holes, wide hole spacing, deep holes and low pads give a low cutoff frequency.

The lower the cutoff frequency, the more serious is the flattening of the upper resonance frequencies relative to the fundamental. Fork fingered notes, with large spacing between open holes (e.g., low B on the Boehm system clarinet), or notes produced by abnormally small tone holes (e.g., low C#), have much lower cutoff frequencies than fully vented notes; this explains why these fingerings are especially troublesome, with "strange" tone qualities and a tendency to be sharp in the low register and/or flat in the upper registers.

The degree of undercutting of the tone holes has a significant influence on the personality of a clarinet. An undercut hole has roughly the same effect on pitch as a large hole with respect to the low register, but has the lower cutoff frequency of a smaller hole, giving a darker tone colour.

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The lecture is assisted by the use of visual aids and by playing examples, including the use of specially-constructed demonstration instruments.

References:

Arthur Benade: Fundamentals of Musical Acoustics (revised edition Dover, 1990; original edition 1976)

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