Benade's NX Clarinet: Its Genesis

by Arthur H. Benade

[Note by Virginia Benade: This paper was dictated to me by my late husband in 1987 near the end of his terminal illness, when he realized there was nothing on paper about what he was thinking of as he designed what he called his NX clarinet. No further revision was done by Art; he did not consider what he had dictated to be a finished paper and trusted that others would help put it into publishable form. Guided by the comments of several of Art's associates, I have made a few changes for clarity plus deleting two brief discussions of theory. George Jameson, who worked closely with Art from 1969 until his death, contributed two short notes, here prefaced by his initials and enclosed in brackets. A slightly longer version of the paper forms the middle part of an article co-authored by Art's former doctoral student, Douglas H. Keefe; it is due to appear in the March 1995 issue of the Galpin Society Journal, which is published in England. A paper on mechanical considerations of the NX by George Jameson will be submitted to *The Clarinet* for hoped-for inclusion in the next issue, and a discussion and demonstration of existing models of the NX clarinet will be on the program at Clarinetfest '94, to be held in Chicago in July.]

By about 1978 or 1979, I knew enough about the playing properties of a wide variety of clarinets (all the way back to the five-key Mozart-era ones) that I could say that I was familiar with them. I knew a lot. And I had noticed that many of the clarinets before about 1820 had, from the player's point of view, some rather remarkable virtues — provided that the player was willing and able to use his "chops." Acquaintance with these instruments made it quite clear that they were able, in a relatively easy way, to perform the tremendous leaps and bounds that were common in the lighter-weight music of the time. I had had good success in designing my conical, Boehm-fingered, baroque flute, and I became more and more attracted to the idea of making a clarinet that retained the virtues of the old instruments while sidestepping some of their problems. At the beginning, I paid little attention to any problem arising from the fingering systems, because it had always been easy for me to learn another system.

The register-hole system

In the year that followed, a qualitative instrument maker's and player's design evolved in my head. I knew enough to stay out of physics trouble and to lay out something that would be at least partially playable. I decided the first item of significant difference in my design would be to return to the old small-diameter (approximately 2 x 12 mm) register hole. The virtues of this change would be apparent to all, leaving only the challenge of coping with the problems brought in by doing this. To deal with these problems, one has merely to ordain a separation between the functioning of the register key and the throat A4# key.

At the time of the earlier parts of my imaginings, I was quite aware of the functioning of the reed resonance (Benade, 1976/1990, pp. 436, 439, 462; Thompson and Benade, 1977). On the clarinet, I had noticed that if one paid attention to tone color alone, the setting of the embouchure tension that gave the best reed-resonance effects at the upper end of the clarion register tended to pull the playing pitch down about 15 cents, which is just enough to pull the scale into very nice tune if the smaller register hole is used. The normal large register hole pulls the playing pitch up some 25 to 30 cents, so that if nothing is done to the bore, a player will have to pull the pitch down by lip tension to an extent that is some 10 to 12 cents below what gives the best tone. An analogous phenomenon obtains at the low end of the clarion register scale. It is therefore a happy accident of physics — which was empirically discovered by the early makers — that a single small register hole, as described above, will permit players simultaneously to achieve a good scale, including plausible twelfths, and to get good tone and response over the entire clarion register by adjusting embouchure tension for the approximate alignment of one reed resonance or another of the note being played.

The fact that a properly chosen register hole can be played off for tone against a controlled sharpening effect in the second register means, first of all, that only one register hole is needed, instead of the two or more that add greatly to the complexity of today's bass clarinet. If the player is unwilling to use his chops, present standard design practice shows that good tuning can be obtained, but only at the expense of tone and response at the two ends of the clarion scale. However, using the smaller register hole makes it possible for any player who is willing to use his chops to improve the tone at both ends of the clarion register to match that of the always-satisfactory middle area of that register. [GJ: In 1975, when writing his second book (Benade, 1976, p. 478), Art was still speaking in favor of two register vents, so placed that the sharpening effect of the vents would be less severe at the ends of the clarion register.]

The instrument described above is in fact rather close to Mozart's clarinet, which, because it had few keys, paid for these virtues by having a very bad A4# along with other rather unsatisfactory throat tones.

The air column

Nothing has been said so far about what guides an instrument maker's choice of a basic shape for an instrument's air column. If one were concerned only with the clarion register, it could be of any shape that was even vaguely cylindrical, the scale being brought into tune by the selection of tone-hole positions and sizes. Notice that any virtues of tone color and response in the clarion register can be achieved without great difficulty by the mutual proportioning of bore and tone holes, without destruction of the playing scale. This flexibility comes from the fact that the only resonances that need be aligned are the second-mode resonance of the air column and the reed resonance, which can be set anywhere between 2000 and 3000 Hz by the player.

The freedom to choose any available air column shape for exploitation in the second register is not available for the low register. In the low register, the regimes of oscillation require the cooperation of the mode-1 and mode-2 resonances, so that the air column shape must be proportioned in conjunction with the volumes and spacings of the closed tone holes that are essentially always present when a note is played.

For proper low-register regeneration (using here the language of physics), mode 2 of the desired air column must have its frequency in exact harmonic (3-to-1) relation to the frequency of mode 1; it is obvious that such a tube is, in essence, cylindrical, with an excitation mechanism that functions as though the tube is closed at the top. This gives the physicist's prototype of a clarinet which, as most people know, overblows to the musical interval of the 12th. Since the main effect of a row of closed tone holes is to make the air column cross-section effectively larger in the region of these closed tone holes, it is not surprising that the instrument maker compensates for this by enlarging the diameter of the bore itself in the regions above and below the main part of the instrument body, where the holes are arranged. The NX-clarinet design incorporates these enlargements, as do most other clarinet designs to varying degree.

Second-order effects

The second (and again quite visibly physics-related) set of phenomena that influenced the evolution of this new/old clarinet was my awareness that second-order effects in the air column and its accompanying tone-hole system were continually showing themselves in the domain of practical work with instruments. However, they had been stubbornly invisible in laboratory measurements, in large measure because none of the drive mechanisms available with the various impedance heads then current (Benade and Ibisi, 1987) were able to attain signal levels that would reach into the mathematical domain of the second-order wave equation. And there was a great deal of experimental work still to be done using playing experiments that made use of the domain of the first-order theory. At the time I was first working on this, it was generally sufficient to keep an eye on the appearance of nonlinear phenomena in the course of any playing experiments; this was a period when all such experiments were carried out at high levels of musical dynamics. It is not difficult to attain levels of 140 dB SPL in an ordinary clarinet mouthpiece attached to a simple 250-mm piece of clarinet tubing using a medium-soft reed at maximum possible blowing pressure.

In the latter part of this period of work in Cleveland, Douglas Keefe (1980) had occasion to look scientifically into the possible implications of the second-order equation for the behavior of musical instrument air columns. The second-order equation includes two source terms that take their excitation from the squared pressure aspects of the first-order equation. The effect of the first of these source terms has been studied in detail by Blackstock and others, but the second one, a Lighthill or convection term, had received relatively little attention because of its mathematical nature, which includes the summation of the product pairs of all the derivatives of the sound pressure field at the source point. This term could be dubbed the complicated-flow term, and it becomes appreciable only in wave guides having boundaries of complicated shape. Perhaps no one but a woodwind acoustician would even think of allowing himself to be entangled with an air column system having as many corners and irregularities as those belonging to the tone-hole system of most woodwinds!

The equations that describe a woodwind tone-hole lattice have several terms that indicate that complex flow effects are appreciably active only at three places: in the immediate neighborhood of the tone-hole entrance into the bore, at the exit of the tone hole into the room, and, quite significantly, in the region under a pad that has been opened, unless it is lifted quite high. Within the tone hole, whatever disturbance is set up at its inner end will smooth itself out on its way to the outside over a distance somewhat less than *b*, the tone-hole radius, unless the chimney of the tone hole is short. In that case, the outward extension of the inner disturbance can overlap and interact with the inward extension of the external disturbance, thereby "complication the complexity" and drastically increasing the magnitude of any phenomena descended from the Lighthill-source term.

It was considerations of the sort just outlined which led Keefe and me to devise a pair of experimental tone-hole lattices. Everything in classical transmission-line theory depends on the impedances of the holes, on the spacing between them, and, to a limited but familiar extent, on the small damping effects within the tone-hole lattice. [GJ: Art gained entry to the realm of clarinet behavior by seeing the math and physics similarity between a tube with a series of closed and open holes and an electrical transmission line containing capacitive and inductive impedances.] For these reasons, our two lattices were designed to have the spacing of the holes (which are uniform) of one of the lattices identical with the spacing of that of the other. Another design requirement was that the imaginary part of the impedance of the tone holes should be the same in both lattices. One lattice was provided with *small holes* that had *short chimneys*, while the other had *large holes* and *tall chimneys*. The recent work of Keefe (1980, 1982a, 1982b, 1938) on the theory of woodwind instrument tone holes made it easy for us to calculate, in advance, accurate *a priori* values for the effective length of the two sizes of the tone holes so that the two lattices would be alike (according to first-order theory) and the machine shop would be able to provide us with these two first-order-related objects. All this insured that the tone holes would not need the small trimmings and paintings that might otherwise make the results we were seeking ambiguous. The first of these lattices will clearly have complexity effects, while in the other such effects will be small.

When these tone-hole lattices were attached in turn to a piece of clarinetlike tubing as a termination and the input impedance was measured with an ordinary low-level impedance head, the response curves proved to be almost precisely alike, thereby implying that we need expect no difference between the playing behavior of these two clarinetlike air columns at low dynamic levels. On the other hand, we hoped that with stronger blowing, we might detect at least some evidence of the complexity phenomena.

Keefe, who is a strong saxophone player and who is also able to play a clarinet, found the tall-chimney version of our "clarinet" responsive and easy to play and possessed of a very pleasant tone. On the other hand, he needed several trials to get the short-chimney version to sound at all. My own trial of both instrument versions confirmed those of Keefe. The tall-chimney one spoke promptly and easily, while my "universal embouchure" managed to get the short-chimney clarinet to speak only reluctantly and with a harsh, stuffy, squeaky tone. We at once noticed very strong acoustical streaming issuing from the tone holes of the short-chimney instrument.

Clearly, our "player's experiment" on the pair of clarinet lattices to see whether the complex flow source term in the second-order wave equation had an effect had been a success. This was an experiment in which it was known from earlier work that a player could easily detect a 1% change in either the damping (first order) or in the condition of the feedback loop. What we found was an extremely prominent effect essentially sufficient to disrupt the clarinet's oscillation.

(Many physical phenomena do not display themselves in a direct physical measurement until enough physically guided "players' experiments" have been carried out to map out the territory and give an idea how to make a measurement. The domain of a player's sensitivity and the way he detects phenomena can be widely different from those belonging to the physicist.)

From the point of view of an instrument maker wishing to minimize Lighthill-term disruptions in the oscillations of his instruments, our experiment has the following major implications. First, if one is to minimize the disruptive interactions taking place at the inner and outer ends of the tone hole, one should keep the length-to-diameter ratio, $t/2b$, reasonably large. The use of open pads over tone holes should be minimized to reduce the additional complexity associated with flow out from under a pad. (As pads began to develop, there was much complaint among musicians that the use of pads spoiled the tone.) Toward the upper end of the instrument where the tone holes get progressively closer together, one should keep the interhole distance as large as possible. At the top end, the requirement of keeping the tone-hole lattice cutoff frequency constant makes it very easy to maintain the $t/2b$ ratio at a satisfactory value. In the lower part of the instrument, on the other hand, this lattice cutoff frequency requirement leads to ever-larger holes that are often drilled through ever-thinning walls, so that the $t/2b$ ratio becomes progressively less favorable. This last remark is a description, not an implication.

There is one more point well worth noting that can cause considerable difficulty at the upper end of a modern instrument, whereas it has no effect on the older ones. A slavish following of the precepts of Theobald Boehm gives a situation of "full venting" in which, for any note, the adjacent tone holes just below the playing hole are all open. Up high on the instrument, the semitone scale sequence places these tone holes dangerously close together, so that the complexity belonging to the inner ends of adjacent holes can interact strongly. The outer-end disturbances can similarly interact.

Conical and other bells

The bell is the third point at which the history of woodwinds joined with what my current understanding of the acoustics of air columns to influence the design of the NX clarinet.

Transmission-line theory tells us that a cone of suitable length and taper attached to a tone-hole lattice will behave acoustically as a pseudo tone hole, i.e., as if the lattice has been extended by one unit. The pseudo hole will appear to the reed to be exactly like the real holes of the lattice. This means that an abrupt change from cylindrical bore to conical bell forms a near-perfect extension of the tone-hole lattice. Since it is the tone-hole lattice that all-but-completely determines the musical value of a woodwind, this means a finite-length instrument can have one more good note in its scale than can an instrument with a smoothly flaring bell of the sort that is familiar today.

In the early Beethoven and pre-Beethoven clarinets, one frequently finds truly conical bells, and it was only later that intellectual efforts at "rationalization" began to modify the shape toward the more trumpetlike form. Most players of the modern clarinet are aware that the notes E3 and B4 have a tendency to blare if the player does not control his embouchure; these are notes that do not normally bray or honk on the conical-bell instruments. This blaring is especially obvious if one attempts to slur abruptly to these notes from ones that are a considerable distance above or below them in pitch. The major explanation of this is that these "blare" notes are produced using the entire air column, and this air column is terminated by a trumpetlike bell whose radiation and reflection properties are quite different from those characteristic of the extended tone-hole lattice that forms the prototype for a woodwind air column. It is a well-known but somewhat surprising fact that to have even one open hole at the bottom of a woodwind will serve in large measure to isolate the effects of a flaring bell. However, in the NX clarinet the adverse effects of a flaring bell were avoided (on even the bottom note of its scale) by putting a conical bell on it.

Endnotes

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