The following article is the fifth in a series by L. Hugh Cooper (1920-2007). He was a Professor of Music (Bassoon) at the University of Michigan from 1945 to 1997, and a Co-Founder of the International Double Reed Society.

Tuning and Voicing Double Reed Instruments — Correcting Intonation and Timbral Faults in Double Reed Instruments and Other Woodwinds

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ACOUSTIC RATIONALE

Choice of horn shapes: Two acoustical attributes that must be produced by any horn shape used for musical purposes are: it first must produce a repeatable overtone (partial) recipe regardless of length and second, the overtone recipe must consist exclusively of whole number multiples of the fundamental in order to concur with the natural modal creativity of man's non-linear hearing mechanism (the Natural Overtone Series).

The complete family of Bessel horn shapes (definition — any horn whose sides flare at some constant positive exponent) fulfill the first requirement by producing a repeatable overtone recipe regardless of length. Out of this infinity of Bessel shapes the only family members whose partial recipe contains exclusively whole number multiples of the fundamental are limited to:

1. A Bessel horn with a flare exponent of zero, representing the cylindrical bore clarinet family if closed at one end, or the cylindrical bore flute if open at both ends.

   Note: *Because of their uniquely different wave propagation patterns, a clarinet sounds one octave lower in its primary mode than a flute of the same effective length and overblows a perfect twelfth and subsequent odd number partials, while the flute overblows the complete overtone series starting with the octave.*

2. A Bessel horn with a flare exponent of two, representing the straight sided standard cone shape of the complete double reed and saxophone families. These instruments also sound an octave higher than a clarinet of commensurate length and produce a complete spectrum of natural overtones analogous to the flute.

   See Figure 1 *(page 124), for pictorial representation of "Standing Wave Forms in the Various Types of Woodwind Instruments."*

3. A third mathematically contrived shape useful in the design of musical wind instruments is the Arithmetic Dual or Reciprocal of the straight sided cone. The diameter of this shape at any point is derived by dividing the diameter of its corresponding reference cone at any point into a factor of one (1/d). So far, with the exception of Arthur Benade's experimental "Dual" bore single reed instrument, this shape has only been used in the design of cup-mouthpiece brass instruments. For examples of this shape observe the aesthetically pleasing contour of any brass instrument's bell section.

In reality, to maintain whole number harmonicity (resonance) a successful woodwind design must deviate from these "ideal" geometric shapes in order to compensate for other acoustic pertubations such as: truncation, reed effect, tone-holes, etc. These needed corrections are controlled by the following acoustic principles.

THE GENERAL BORE WEIGHTING THEOREM AND ITS COROLLARIES

Constricting a resonating pipe at a pressure node (point of minimum fluctuation in acoustic pressure) will lower its frequency of oscillation; while constricting the pipe at a pressure antinode (point of maximum fluctuation in acoustic pressure) will raise its frequency of oscillation. Enlarging a resonating pipe at a pressure node will raise its frequency of oscillation, while enlarging it at a pressure antinode will lower its frequency of oscillation.

> ***Note:*** *the above bore weighting theorem could also be stated in terms of displacement, a normal approach in describing the wave patterns of strings.*

The relative magnitude in frequency shift is maximum in scope directly at the node/antinode points and diminishes in degree as the locus of the change (perturbation) in bore dimension migrates to either side of a respective node/antinode point. The perturbation's effect on pitch ultimately reaches zero at a point lying approximately half the distance between the given node and its adjacent antinode. At this magic point anything can be done to the bore dimension without disturbing that specific resonance frequency.

Excursion beyond the zero effect point begins to reverse the directionality of pitch change, gradually increasing in magnitude until again reaching a maximum, but opposite effect, at the next node/antinode. Thus, there are specific points in a resonating pipe where:

1. Constricting a pipe at a pressure nodal point will lower the emitted pitch of a given note or a set of harmonically related notes while:
2. Enlarging a pipe at the same point will raise the emitted note(s) in frequency.
3. Any change can be made without affecting the pitch of a given note.

   ***Note:** Pressure nodal points always exist at or near the first one or two open tone-holes which are emitting the sounding note. Therefore, the sounding note's venting tone-hole(s) afford a convenient access point at which corrective bore weighting techniques can be applied. (See "Basic Rules Governing Open Tone-Hole Modifications" below for guidance.)*

Multiple additional pressure node/antinode points, other than at emitting open tone-holes, exist for each note within the instrument's range. However, these correction points lie distributed in a hidden but somewhat predictable manner throughout the length of the instrument. To locate these hidden corrective areas and determine their relative impact on the resonance frequencies of all three types of woodwind instruments, refer to Figures 2 (page 125), 3 (page 126) and 4 (page 127) which depict "Bore Pertubation [Weigh Function] Graphs" based on Arthur Bonade's 1969 calculations, presented during his series of Acoustic Seminar Lectures at the University of Michigan School of Music, Fall Term 1974.

It would be relatively simple to make such needed corrections if each note were to have its own discrete individual pipe like an organ. Under such circumstances anything deemed necessary for correction of the pitch and/or resonance of an individual note could be done without affecting others. But such is not to be, for wind instrument bores (including brass) must be all things to all pitches within the instrument's range. A modification that dramatically improves one note might, and often does, destroy another. Extreme caution must be exercised to diligently seek out those few areas that will have a maximum impact on the flawed pitches, with little or no negative effect on others. (Primary venting open tone-holes represent one such type of idealized location.)

The author advises the inexperienced to limit their initial "voicing" attempts to productive but reversible modifications, such as the appropriate placement of tape in tone-holes and bore, while leaving any needed major "excavations" to an experienced expert.

Length: Assuming that all else remains constant, theoretically the frequency of a resonating pipe varies indirectly with its length.

1. Doubling the pipe's length halves the frequency (lowers the original pitch one octave).
2. Halving the pipe's length doubles the frequency (raises the original pitch one octave).
3. Reducing the pipe's length by 1/3 raises the frequency a perfect fifth.
4. Adding .059463 of a pipe's original length to the pipe (1.059463 = the twelfth root of 2) lowers the pitch one equi-tempered semi-tone.
5. Reducing a pipe's length to .943874 of its original length (the reciprocal of the twelfth root of 2) raises the frequency one equi-tempered semi-tone.
6. Etc.

Acoustic Damping: by definition. "Anything that reduces the amplitude of oscillation of an oscillatory body." In short, "Acoustic Friction."

Increased damping:

1. Reduces the amplitude (acoustic power, usually expressed in deciBels) of the emitted sound, thereby limiting its upper dynamic range.
2. Reduces the amplitude of the sound's upper partials in an exponential manner, affecting the partial mix and changing timbre.
3. As the amplitude is decreased the instrument's "Response Band Width" broadens, thus increasing flexibility while losing its projection.

4. There is also a slight lowering of the pitch center.

Obviously a commensurate decrease in damping would have equal but opposite effects. The relative amount of damping inherent in an instrument's design represents a key factor in determining the instrument's musical merit. Too much damping and the instrument becomes resistant, stuffy and non-projective, while too little results in a harsh, strident, difficult to control monster.

Finally: With knowledge, insight and experience, the above four acoustic phenomena can be manipulated in practical ways to positively influence the resonating frequencies and timbral characteristics of a woodwind instrument.

TONE-HOLE FUNCTION AND MODIFICATION

Toward a Common Nomenclature: To ensure accurate communication a concise means of identifying specific tone-holes and/or keys is imperative. Many students and also some professional bassoonists make frequent errors when describing either the tone-holes or the keys of the German-system bassoon. Here are the principles of nomenclature the author feels we should standardize:

1. *Tone-hole* nomenclature is determined by the hole's primary venting function when *open*. For example, the first tone-hole which is covered by the right index finger (boot joint) is called the "c tone-hole;" the only tone-hole of the bell joint is called the "low B♮^{1} tone-hole."
2. *Key* nomenclature is determined by the name of the primary note produced when the key is depressed. All keys normally held closed by spring tension have the same name as the tone-hole(s) they cover. For example, the low E♭ key covers the low E♭ tone-hole; the high a^1 key covers the high a^1 tone-hole. All keys normally held open by spring tension have a nomenclature which is a major or minor second beneath the name of the tone-hole it covers. For example, the low B♭^{1} key covers the low B♮^{1} tone-hole; the low E ("pancake") key covers the low F tone-hole.
3. Illustrations have been included to help visualize a standard tone-hole and key nomenclature. Figure 5 (page 128), is a chart listing the tone-holes of the German-system bassoon (Cooper, L. Hugh. "Towards a Common Nomenclature," *To The World's Bassoonists*, Volume V, No. 1, 1975) and Figure 6 (page 129), is the "Key to Schematic Diagram of the Bassoon," a drawing excerpted from the book *Essentials of Bassoon Technique*, co-authored by L. Hugh Cooper and Howard Toplansky, published in 1968.

In essence, the name of a given tone-hole is derived from the name of the primary note that it *vents* when *open*, NEVER from any pitches produced when it is *closed*. Innumerable bassoons and other woodwinds have been mutilated by misguided individuals attempting to correct a problem note by working on the wrong tone-hole. For example, the bassoon's normally flat third space E cannot be raised in pitch by enlarging the wing joint's first (index) finger-hole, for this hole is already closed when sounding E. Actually this hole primarily vents the fourth line F and enlarging it will only succeed in making the already sharp, strident open F more obnoxious. Obviously, to change the pitch of the third space E you must identify and modify *its* vent hole, which when sounding E happens to be the first *open* hole on the wing joint, waiting patiently to be closed by the left middle finger to produce third line D. The ability to correctly identify a tone-hole's primary function and resultant nomenclature is paramount to successful tone-hole voicing.

Another common misconception relates to the change in a tone-hole's venting area (diameter). Predictably, in accord with the bore weighting theorem: 1) Constricting a pipe at a pressure node (the first open tone-hole for a given note represents an easily accessible one) will lower the pitch, while 2) Enlargement at the same open hole will raise the frequency.

Unfortunately for many long suffering woodwind instruments, the majority of performers and repair technicians believe otherwise. For example, the author recently had occasion to observe a vintage 8000 series Heckel on which every hole venting a normally sharp note had been grossly enlarged, while those normally flat in pitch had been stuffed up with various fill materials. When these acoustic indignities were corrected, the bassoon again found its marvelous voice. Also, many individuals frantically seeking guidance with tuning problems report that they have already greatly enlarged a tone-hole in size but that its note is still sharp, while after partially filling another hole with tape its emitted pitch remained flat. Even when correctly informed otherwise by the author, many have difficulty accepting that making a tone-hole larger raises its emitted pitch while making it smaller lowers it. After all, doesn't a piccolo have smaller holes than a baritone sax?

BASIC RULES GOVERNING OPEN TONE-HOLE MODIFICATIONS

1. Alteration in cross sectional area
   a. Enlarging a venting tone-hole will raise its emitted pitch.
   b. Constricting a venting tone-hole will lower its emitted pitch.
   (In essence, larger = higher; smaller = lower)
2. Alteration in effective distance from generating source (bore length)
   a. Moving the effective center of a tone-hole up the bore will raise its emitted pitch.
   b. Moving the effective center of a tone-hole down the bore will lower its emitted pitch.
   (In essence, shorter = higher, longer = lower)
3. Alteration in tone-hole chimney length (chimneys, actually function as extensions of the bore)
   a. Shortening the chimney will raise the pitch.
   b. Elongating the chimney will lower the pitch.
   (In essence, shorter = higher; longer = lower)
4. "Fraising" — modifying the vertical contour of tone-hole chimneys to adjust modal relationships
   a. "Undercutting," or decreasing the tone-hole diameter relatively more at the pad (finger) end with contoured tape, or other fill material, *diminishes* the modal relationship between the fundamental and its higher partials. Undercutting raises all partials but raises the fundamental more. Constricting the top of the chimney relatively more with contoured tape lowers all partials but lowers the fundamental less.
   b. "Flaring" the tone-hole diameter toward the pad (finger) end, or decreasing its diameter relatively more at the bore end of the chimney with contoured tape, or other fill material, *augments* the modal relationship between the fundamental and its higher partials. "Flaring" raises all partials but raises the fundamental less. Constricting the bottom of the tone-hole chimney relatively more with contoured tape lowers all partials but lowers the fundamental more.
   c. "Undercutting" only the upstream aspect of a tone-hole chimney at the bore end primarily raises the fundamental with less effect on upper modes.
   d. Constricting only the upstream aspect of a tone-hole chimney at the pad (finger) end, lowers the higher partials with less effect on the fundamental.
   e. "Undercutting" only the downstream aspect of the tone-hole chimney at the bore end has little effect on the fundamental but lowers the upper modes.
   f. Constricting only the downstream aspect of a tone-hole chimney at the pad (finger) end, has less effect on the fundamental but lowers the higher partials more.

   ***Note:** great care must be used when applying the last four fraising techniques to correctly identify the "upstream" vs. "downstream" aspects of the chimneys, especially in the double bore boot joint where the direction of the air-flow is reversed after the U-tube.*

   Also, combining technique c with d, and e with f in rather dramatic ways can maximize the modal adjustment. For example, the great artist craftsman Hans Moennig often drastically undercut the low G tone-hole on the upstream side to raise the low G and then placed a rather massive tapered cork shim upstream at the pad end to pull the fourth space octave G back down.

For sketches of actual tone-hole modification with tape or other fill material, fraising techniques, and baffling see Figures 7 (page 130), 8 (page 130), and 9 (page 132).

VOICING

Voicing is a term used to describe the application of various tone-hole modifications and bore pertubation techniques to maximize results in tuning, timbre, and modal relationships. The variety of combinations are endless. For example, there are an infinite number of tone-hole placements (bore lengths) and venting area sizes that will produce a frequency.

A smaller hole placed further up the bore will produce the same pitch as an appropriately larger hole located further down; however, the sound emitted from the smaller hole will be proportionally more resistant, "darker" and less projective while, the sound emitted from the larger hole will be relatively less resistant, "brighter" and more projective.

With this in mind, one can envision a hypothetical instrument with a series of closed holes gradually diminishing in size as they march inexorably up the bore, which when each is opened individually would all produce the same frequency, but with increasingly greater resistance and less projection — sort of the ultimate device for producing timbral variety. While another imaginary instrument with only one variable size tone-hole could produce a full range of fundamental pitches without ever changing its position, simply by increasing or decreasing its cross sectional area. Both such instruments would be impractical and serve no useful musical purpose as the timbral characteristics produced would vary dramatically.

The challenge is for the designer or artist craftsman to find an ideal combination of bore length (including chimneys), tone-hole size, chimney contour and bore pertubation balance, that will produce the best tuning, timbral, and modal relationship throughout the range of the instrument. But, like Santa Claus, the perfect woodwind instrument doesn't exist. At best, moving the various components of the puzzle around will only result in a more advantageous compromise.

VARYING EFFECTIVE LENGTH

Reed contribution: This phenomenon represents the reed's effective equivalent length (phantom bore) which in bassoon theoretically ranges from approximately 262mm (10.25") when playing in the highest register, to a maximum of 375mm (14.75") in the lowest register. The maximum reed contribution equivalent length actually exceeds that of a Heckel #2 bocal which measures approximately 336mm (13.23"). (This explains why a compatible reed's high side "tap pitch" sounds 1/2 step lower than the bocal's tap pitch, while the reed's low side tap pitch sounds a full step beneath that of the bocal.)

The great majority of intonation faults experienced between registers are caused by use of reeds incompatible to the instrument. Discrepancies in shape, size, and function at this critical area affects the relative tuning of the registers in a near exponential way. See Figure 4 (page 127), *Weight Function Graph for Cones* depicting massive differences in frequency that can occur in the reed area's first 10% of the bore, where the modal gyrations are at their peak. For additional information see "Bassoon Clinic Series II, Reed Contribution," *International Double Reed Society Journal*, XIII, No. 3, by L. Hugh Cooper.

Bocal contribution: again a critical element in determining pitch and resonance. Each change in bocal number, within a given maker's numerical system, theoretically raises or lowers the pitch centrality approximately 1/10 of a semi-tone. Thus, the available bocal pitch excursion, ranging from a #00 through a #4 represents a total shift in frequency of 1/4 step or approximately 13 Hertz at A440. No single bassoon or reed style can accommodate such a drastic change in effective length without serious consequences. One bocal number shorter or longer than a player's "normal" length is the accepted range. "Pulling" a bocal can work in an emergency but can cause other problems. Heckel markets a bocal extension "nib" that converts a favored #1 into a #2, etc. A Franz Groffy development that works quite well.

Body length: Little can be done by an individual to actually change the bore length of an existing instrument except to pull the tenon joint at the various junctions. In general this is not a good idea however. In the author's opinion, pulling the long joint approximately 4mm improves the playing qualities of *most* bassoons. The advantage stems not only from the additional length but the resultant "jog" in the bore size at the bottom of the tenon socket. The expansion acts as a reflective point near the low F tone-hole that strengthens the primary register's standing wave patterns. Try it! The improvement can be truly amazing. This was one of Hans Moennig's favorite tricks. A readily available spacer ring is a 1–1/8" rubber slip-joint washer (for under the sink), available at all hardware and plumbing shops. (Somehow seems appropriate.)

Often pulling one of the other joints slightly will correct specific notes. John Miller's former 9000 series "bracked" constantly on the first B above the staff, unless the bell joint was pulled approximately 1/2mm. Then the bassoon was happy and so was John.

The U-joint gasket can be made thicker, thereby lengthening the bore at this critical point by *twice* the amount added to the gasket (bore doubles). This often helps tame top-line A and other second register notes. Again worth a try, but preserve the old cork so you can get "back home" if you don't like the results. The same gasket can also be made thinner which will shorten the bore a commensurate amount with opposite results.

Experiment a little, pulling and pushing the joints varying amounts, in different combinations. It doesn't cost anything and sometimes can bring about a metamorphosis in the instrument.

Linear placement of tone-holes: Little can be done (or should be) by an individual to markedly change the position of tone-holes on an existing instrument. However, the instrument can be acoustically fooled, by manipulation of the tone-holes, into "thinking" that it is longer or shorter than it really is. See Figure 7 (page 130), for sketches of the following examples.

1. Placing tape (or other material) as in sketch A, produces a compound flattening effect:
   a. Decreases the cross sectional area of the venting tone-hole = lower pitch.
   b. Moves the effective center of the tone-hole down the bore = lower pitch.
   c. Placement A produces a maximum change in pitch, coupled with a minimum change in resistance (timbre).
2. Placement B, or laid equally around the complete circumference, produces a single flattening effect:
   a. Decreases the cross sectional area without moving the center of the hole.
   b. This placement is used primarily to correct known errors in tone-hole dimensions.
   c. Such modification is also used to lower a sharp second register somewhat more than the fundamental.
3. Placement C produces a compensatory effect:
   a. Decreases the venting area = lower pitch.
   b. Moves the effective center of the tone-hole up the bore = higher pitch.
   c. Placement C produces a maximum change in resistance (timbre) coupled with a minimum change in pitch.
4. An additional variable to consider is that the fundamental pitch is more responsive to a change in length, while the higher partials are more sensitive to a change in the venting area.
5. The effects of examples A and C can be enhanced by carefully removing material opposite from the upstream or downstream tape placement. However, an inexperienced individual should initially *stick* to tape modification.

Selective fraising: discretely influences modal relationships, raising or lowering the individual frequencies of various registers by changing the vertical contour of a venting tone-hole chimney. This topic has already been discussed above and is additionally covered in Figure 8 (page 130); however, the reader should be warned that ambiguity exists in the directional use of fraising, principally between the rules governing small bore, displacement controlled instruments such as the recorder, and those beliefs of the author and others applying to the bassoon. The differences in concept perhaps can be rationalized by observing Figure 4 (page 127) where the three modal curves still differ markedly in weight as they enter the bassoon's long tone-hole chimney, while in Figure 3 (page 126) the weighting curves for flute type instruments are equal in magnitude as they approach the flute's shorter chimney.

The oboe, because of its very small bore and tone-hole size requires the most extensive and sophisticated fraising in its tone-hole lattice. Only by this complicated means can the oboe maintain homogeneity of timbre and acceptable tuning between registers. On the other hand, modern flutes (Boehm) and saxophones with their larger bores and venting tone-holes, manage without any type of fraising. While the bassoon having mid-size bore and tone-holes, normally gets along with very little such modification, except slight flaring on the wing and boot joints combined with "undercut" tone-holes on the long joint and bell.

Bore Weighting: The same weight function graphs can and are used to locate additional multiple areas in the bore of a woodwind instrument which can then be used in a selective way to tune the various registers. For example,

1. Placing fill material in the bore of a flute type instrument at 50% of its resonance length would sharpen the 1st mode and flatten both the 2nd and 3rd. While placing material at 25% of the distance down the bore would have no effect on the first mode but sharpen the 2nd mode, and flatten the 3rd. Enlargement at the same bore locations would have an equal but opposite effect on intonation.
2. Use of the conical bore graph is more complicated because of the cone's non-linear shape. For instance, constricting at 33% of bore length would have no effect on the second mode, but sharpen both the 1st and 2nd with greater (about twice) the effect on the 2nd. While enlarging at the same point would flatten both the 1st and 2nd modes in a similar manner.

3. To effectively use the bore weighting graphs it is important to remember that the length of the vibrating air column *changes* each time a different fundamental length (note) is fingered.
4. In any respect the bore weighting graphs do work, but sharing this information is somewhat analogous to giving a child a loaded gun to play with.

CONCLUSION

It is hoped that the information and techniques presented will offer insight and directionality to those concerned individuals seeking to improve the musical capabilities of their instruments. Although the complex subject of tuning and voicing often tends to intimidate and confuse, simple understanding of a few basic acoustic principles allows one to diagnose and correct an infinite number of problems. But first, know the instrument like a parent knows its child. Become intimately acquainted with its unique set of strengths and weaknesses in order to instantly recognize any change in the instrument's normal response patterns. Don't try to fix something that isn't broken, but be able to ascertain when something is and take immediate and appropriate steps to correct it. Retain, if necessary, a "primary physician" in the guise of an artist craftsman to address major traumas and administer six month checkups, but at minimum be able to personally address the minor "sniffles" that arise on a daily basis. For woodwinds, like living creatures, are sensitive to even minor changes in their environment. Thus, even after achieving an instrument's full potential, it remains a constant challenge to maintain the status quo.

Finally, (as suggested above) there is *no* conclusion, as the art of tuning and voicing woodwinds doesn't really lend itself to closure.

Good luck and happy voicing!

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