SCI220 – Foundations of Musical Acoustics
Cogswell Polytechnical College
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Week 13 – Class Notes

Brass Winds (FMA)

Chapter 20: The Brass Wind Instruments

20.1 A Model of the Brass Player's Excitation Mechanism

A brass instrument consists of a long and carefully shaped metal duct coupled to a flow-control mechanism which converts steady wind supply from the player's lungs into oscillations of the air columns contained within the duct. The flow of air from the player passes between his lips, which open and close rapidly in response to the acoustical variations within the mouthpiece and so admit a periodically varying flow of air into the mouthpiece. The air column is kept oscillating in its longitudinal vibratory motion because of these periodic puffs of air supplied via the lip-valve.

The brass-player's lips perform a flow-control function as they open and close under the influence of the acoustic (oscillatory) pressure variations that take place within the mouthpiece cup. This principle can be summarized in the following manner:

1. A pressure-operated reed-valve will collaborate with an air column to favor the maintenance of oscillation at frequencies closely matching one or another of the natural frequencies characteristic of the air column itself.

20.2 Multiple-Mode Cooperations: Regimes of Oscillation

Let's say that we have a tube in which mode 1 produces a frequency of 110 Hz, mode 2 at 196 Hz, and mode 3 and 4 with 294 Hz and 523 Hz respectively. If the brass-player's lips vibrate at 196 Hz, there will be a collaboration between this vibrating frequency and mode 2 of the column that admits repetitive puff trains whose flow recipe include harmonics partials al whole number ratios from 196 Hz. These additional components in the flow recipe arise form the non-linearity of the valve-control characteristic. These upper harmonic components do not contribute to the maintenance of oscillation and thus drain physical resources from the player and can disrupt the original air column oscillation.
We can say the following:

2. If the reed-valve is nonlinear (the flow varies in a non-proportional way with regard to the acoustic pressure controlling it), then oscillation is favored if the air column has one or more natural frequencies that correspond to one or more of the higher partials of the tone being produced.

It must be recognized that when lip- or reed-valve and air columns are used, the independent existence of the various characteristic air-column modes is destroyed by the mutual influence that these modes have on one another via the nonlinearly shared flow through the reed-valve. The heterodyne frequencies generated at the valve by a pair of oscillatory components can stir up air-column oscillations that alter the lip or reed motion. The valve and the air column must therefore mutually adjust themselves to produce a definite multifrequency oscillatory state. This is called:

3. *Regime of oscillation* – state of collective motion of an air column in which a nonlinear excitation mechanism collaborates with a set of air-column modes to maintain a steady oscillation containing several harmonically related frequency components, each with its own definite amplitude.

20.3 Acoustical Measurements and Playing Experiments on Simple Air Columns

For a duct having a strictly uniform cross-sectional area A, the wave impedance is the ratio of the pressure to the volume flow injected into the duct. Its value:

$$wave\,impedance = \left(\frac{1}{A}\right)\sqrt{Bd}$$

Where d is the density of air and B is its bulk modulus (measure of springiness of air when a small volume is compressed). If the cross-section of the duct varies somewhat in the region next to the input end, the wave impedance will have a value that is somewhat different from the one given here, and this value depends on the excitation frequency used in measuring it.

The flow disturbance, for a piece of cylindrical tubing, produced by the source gives rise to a pressure wave that travels down th length of the pipe. This pressure wave loses amplitude as it goes because of viscous friction and the transfer of heat from the wave to the walls of the pipe. At the far end, where the pipe opens into the room, there is a strong discontinuity in wave impedance since the room is imagined as a second duct of enormously large cross-sectional area that has a small wave impedance. The acoustic pressure pulse is almost totally reflected at this junction, with the reflected wave having its phase inversed. A high pressure pulse is reflected as a rarefaction. This reflected wave combines with the newly injected waves to produce a standing wave.

The traveling waves in the duct reinforce one another, and they will produce a large pressure disturbance in the pipe. Meaning that is we excite the pipe at one of its characteristic frequencies, the corresponding vibrational shape builds up in the duct. At certain frequencies the returned pressure wave arrives out-of-phase with the excitation, producing a minimum air column response.

For a duct of finite length, the response of it is defined by the *input impedance.* The measure of input impedance is larger or smaller than the duct's wave impedance, depending on the relationship of the excitation frequency to the natural frequencies of the duct.

For a real brass instrument that has a flaring bell extension at its open end, it can be observed that the resonant peaks of the air column are shifted toward lower frequencies, in comparison to a straight cylindrical tube with no bell, as a result of the longer time to make a round trip. The peaks are less tall and after a certain frequency it can be observed that the peaks and dips have disappeared almost completely.

20.4 The Influence of the Mouthpiece on the Heights of Resonance Peaks

An air column of different shapes have to meet the requirement in which their natural frequencies must be suitably related if they are to join the player's lip-valve to set up stable regimes of oscillation. The more resonances that are present to cooperate and the more accurately these are aligned, the easier it is to play these notes.

For a tube with a flaring bell, we previously mentioned the fact that after a certain frequency the input impedance peaks almost completely disappeared. This is explained by the fact that high-frequency sound sent down toward the bell is transmitted almost completely into the room and very little of it returning to set up a standing wave with its resulting resonance peaks and dips.

If we excite and measure the response of a duct consisting of a trumpet mouthpiece connected to an extremely long piece of tubing, we do not expect the wave impedance to remain constant, because of the variation of cross section found at the driving end of the composite duct. Measurements of this sort using trumpet parts show that, at very low frequencies, the wave impedances starts out with a value equal to that of the pipe alone. It then rises to around 850 Hz to a value almost five times larger. Above this frequency the wave impedance steadily decreases, falling below the simple pipe value in the region above 3500 Hz.

This broad peaking of the wave impedance near 850 Hz corresponds with the fact that the mouthpiece has a first natural frequency at around 875 Hz (also called popping frequency). This resonant influence shows that the mouthpiece retains some sort of independence when it is put in a tube. The remaining mouthpiece resonances do not show up clearly in the wave impedance curve.

*explain relationship between input impedance peaks and ease of playing for certain notes (p.402-404)

20.5 Musically Useful Shapes: The Flaring and Conical Families of Brasses

As a wave travels into the enlarging portion of any horn its pressure amplitude will decrease systematically, simply because the acoustic disturbance is being spread over an ever-wider front. We can suspect that in a duct that starts out with a gradual taper and then flares out abruptly (as in the bell of a brass instrument) waves traveling toward the large end might well find themselves reflected at some point where the increasing flare causes an excessively rapid change in the wave impedance. This is a gentler version of the reflection that happens at the end of a tube opening into a room.

It should be easy to understand that sounds propagate with different speeds as they travel through different parts of the horn: wherever the duct walls curve outward to produce the flaring shape of a trumpet, the speed is greater than the 345 m/s expected in open air; on the other hand, in any portions of the horn where the walls are straight-sided, cylindrical part of a trumpet, the velocity of sound is exactly the same as it is in free air.

For a flaring horn, the first three characteristic shapes of the pressure distribution (fig. 20.8) resemble sinusoids that are progressively stretched-out in the parts nearest to the open end (due to the increased wave velocity in the region). These patterns lose their sinusoidal shape in the rapidly flaring part of the bell. The modes are similar in shape to those found in a cylindrical pipe whose length is chosen to give an equal frequency for this mode. Also, the successive modes have an odd number of humps in their vibrational shapes such that the nth mode has (2n-1) half humps. These half humps near the mouthpiece end look fairly sinusoidal, whereas the one nearest the bell has significantly different shape caused by the reflection behavior at this region.

The shape of the flaring portion of a brass instrument can be found in the so-called Bessel-horn family. The diameter D at any point is defined in terms of the distance *y* from the large open end:

$$D = \frac{B}{(y + yo)^m}$$

where B and *yo* are chosen to give proper diameters at the small and large ends, and *m* is the “flare parameter” which dominates the acoustical behavior of the air column. A non-flared cylindrical pipe member of the Bessel-horn family has m = 0, whereas trumpet and trombone bells have m = 0.5 – 0.65, and a French horn with m = 0.7 – 0.79.

The characteristic frequency for a Bessel horn closed at the small end, can be calculated in terms of its overall length L, the flare parameter m, and the speed of sound in air v. For the nth mode, the frequency fn is given by:

$$fn = [\frac{v}{4(L + yo)}][(2\mathrm{n} - 1) + \frac{2}{\pi}\sqrt{m(m+1)}]$$

For m = 1, the successive resonances become exact number multiples of the first mode frequency such that

$$f1 = \frac{v}{2\mathrm{L}}$$

whereas for m = 0, the frequencies are in odd-numbered multiples of the first mode frequency,

$$f1 = \frac{v}{4\mathrm{L}}$$

Intermediate values of m have resonances arranged in non-harmonic relationships, and thus they fail to set up useful regimes of oscillation.

In the case of conical tubes, the speed of the pressure waves remains constant as the waves run toward the large end, rather than increasing as it does with the case of flaring horns. For this reason, simple cones have a reflection at the open end (rather than at the acoustical region in the large part of the horn), and thus leak sound at lower frequencies than flaring tubes having the same bell diameter. This leakage deprives conical instruments of their upper resonances.

The wave impedance at the small end of a conical duct rises rapidly from zero at low frequencies to a high-frequency value equal to that of a cylindrical pipe with the same diameter inlet. This rapid impedance variation at the small end combined with reflected wave behavior gives rise to resonance peak frequencies that are members of a complete harmonic series. These peak frequencies are smaller in amplitude that the ones present in flaring horns. To boost these frequencies a mouthpiece with a smaller taper than that of the main run of the air column.

In addition to this mouthpiece requirement for conical tubes, a mid-section cylindrical or mildl tapered tubing is included along with a flaring bell in order to get the needed cooperative effects between resonance. The fluegel horn, the alto, and the baritone are examples of conical brass instruments.

For flaring horns, the first resonance peak is not properly placed to join with other peaks in the pedal-note oscillation. On the other hand, a conical instrument has its first mode resonance peak very close to the desired pedal-note frequency, such that this note is easily produced. Because of this reason, the lower brass instruments tend to have conical shapes.

20.6 The Selection of Valve Slides to Give a Complete Scale

It can be intuitively understood that in order for a brass instrument needs to fill in gaps so that a complete scale is achieved, it is necessary to lengthen the instrument just a little bit to get a set of notes set a semitone lower, and a little more for another semitone, and so on. This is actually done, however the addition of tubing into the middle of the horn makes the average taper less than before; thus we can say that the average flare parameter is reduced. The addition of a piece of tubing to a horn will make a bigger percentage change in the frequencies of its lower modes that it will for the higher ones.

The frequency ratios between the various modes (which determine the effectiveness of any cooperations) are not drastically altered when reasonable amounts of tubing are inserted. The instrument works best with a particular set of proportions in which the addition of tubing extends the length of the instrument by 40%.

20.7 Further Properties of the Mouthpiece

We have seen the effect that the inclusion of the mouthpiece has on a flaring tube. Lets state some more mouthpiece features:

1. For a cylindrical pipe, the equivalent length L_e of a mouthpiece at low frequencies is equal to the length of cylindrical tube whose volume matches the total volume of the mouthpiece, regardless of its shape.
2. At the mouthpiece popping frequency F_p , L_e is the length of cylindrical tube (closed at one end) whose first-mode frequency equals F_p that is, $L_e = v/4\ F_p$
3. To a very great extent, the total volume and the popping frequency determine the variation of L_e by “anchoring” it at two points along the frequency scale. Subtle differences in the value of L_e at other frequencies are caused by variations in the proportions of mouthpiece cup and back bore.

4. The overall trend of L_e with frequency is a steady increase nearly to the top of the instrument's playing range. If two mouthpieces have the same volume, the one having lower popping frequency will show a greater total change in effective length as one goes up in frequency.

20.8 The Internal and External Sound Spectra of a Trumpet