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The physics of the trumpet

Seminar

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Ljubljana, December 2013

Abstract

In this seminar we first take a look at the definition of acoustic impedance. Then we take a look at how the shape of the bell affects the transition between the high inner tube impedance and the low outside air impedance, and how to reach transition without reflection. Finally we briefly describe the basics of sound generation by lip vibrations.

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1 Introduction

The trumpet is a wind instrument of the brass family and is very versatile with a wide range of playing techniques. Sound is made by blowing air through pursed lips and into the mouthpiece. This vibration excites the air inside the trumpet, which then produces a pitch. A trumpet does not simply transmit sound into a room. Most of the sound stays inside where it forms standing waves that draw energy from the player's lips. The instrument basically amplifies the pitch produced by the embouchure. Like most brass instruments, the pitch is largely determined by the player's embouchure (the position and tension of the lips).

For real wind and brass instruments, the idealised model of cylindrical tube resonators is strongly perturbed by a number of important factors. These include [1]:

- the shape of the internal bore of an instrument, which is often non-cylindrical (it has a large effect on coupling with impedance at the end of the trumpet) including conical and often flared tubes with a flared bell on the radiating end,
- the finite terminating impedance of the reed or mouthpiece used to excite the resonances, no longer providing a perfect displacement node,
- radiation of sound from the end of the instrument, which is therefore no longer a perfect displacement antinode,
- viscous and thermal losses to the walls of the instrument, and
- bends and valves along the length of brass instruments, connecting additional lengths of tubing, which allow the player to play all the notes of a chromatic scale within the playing range of the instrument.

2 Construction

Trumpets are among the oldest musical instruments, dating back to at least 1500 BC [2]. The oldest surviving examples of trumpets are two instruments that were discovered in the tomb of Tutankhamun in 1922.

The trumpet is constructed of brass tubing bent twice into a rounded oblong shape. The modern trumpet has three valves and a bore that is partly cylindrical, partly conical. Careful design of these parts is critical to the intonation of the instrument. The trumpet and trombone have cylindrical section of considerable length, while the fluegelhorn, French horn, euphonium, and tuba, often referred to as instruments of conical bore, are tapered throughout much of their length.

The three valves of the trumpet add lengths of tubing to the instrument to lower the pitch. The segments of tubing that can be added by the valves lower the fundamental by a tone (1st valve), a semitone (2nd valve) and a tone-and-a-half (3d valve). Based on a length of about 140 cm [3], valve 1 would have to add 17.9 cm, valve 2 8.6 cm, and valve 3 would need to add 27.8 cm [4]. Used singly and in combination these valves make the instrument fully chromatic.

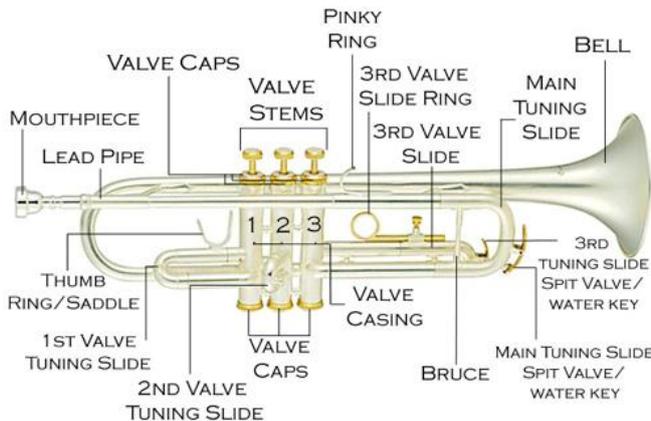


Figure 1: The figure shows all major parts of a trumpet: bell, valves, lead pipe, mouthpiece and others.

A musical wind instrument consists of a very nearly linearly-behaved resonator closely coupled to a nonlinear acoustic generator – the reed, lips or air jet produced by the player [5]. The resonator is usually a tube, in which a column of air is set into vibration by the player blowing into a mouthpiece set at the end of the resonator. The playing frequency is determined, to first order, by the resonances in the bore of the instrument and the frequency of the vibrating lips. Upstream from the lips lies the player's vocal tract with acoustic resonances that has a large effect on performance technique.

3 Acoustic impedance.

To decide for which frequencies the conditions for a sustainable standing wave are met for a trumpet, it is necessary to find the acoustical input impedance. Acoustic impedance, which has the symbol Z , is the ratio of acoustic pressure p to acoustic volume flow U [6]. So we define $Z = p/U$. The acoustic impedance at a particular frequency indicates how much sound pressure is needed to generate provided air vibration at that frequency in a specific point. So it tells us about the acoustic performance of the instrument, in an objective way that is independent of who might play it, and it allows us to compare subtle differences between instruments. The units for impedance are kg/m^4s , which we call the acoustic ohm Ω . The specific acoustic impedance z is the ratio of the sound pressure to the particle velocity:

$$z = \frac{p}{v} = ZS, \quad (1)$$

where Z is the acoustic impedance. At the trumpet each resonance of the air column within the bore of the instrument corresponds to a peak on the input impedance curve. This contrasts with both sides open instruments (e.g. flute), whose resonances are minima of the input impedance curve. Generally the playing frequencies of the trumpet are very close to one of those resonances, with the exception of the pedal note (figure 2), whose fundamental frequency does not correspond to a resonance of the instrument. What happens here is that the higher resonances ($2f$, $3f$, $4f$ etc) combine to help the lips establish a vibration at the frequency of the missing fundamental f .

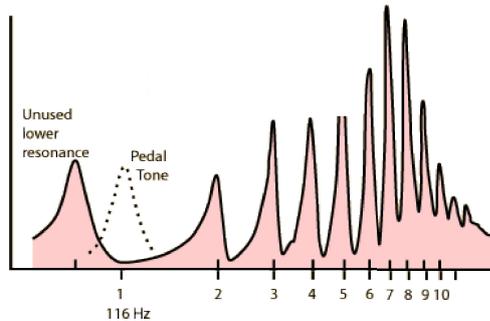


Figure 2: Input impedance curve for trumpet [7]. The pedal tone is at the fundamental of the harmonic series but which is not a resonant frequency of the air column. If the player's lips are vibrated at the frequency of the pedal tone, then the upper harmonics contribute so the listener perceives that the fundamental is being played.

4 Trumpet tube

In first order the trumpet consist of cylindrical pipe. At the far end, the pipe is open to the air, so the pressure there must be close to atmospheric at all times: in other words, the varying part of the pressure (what we call the acoustic pressure) is near zero. A node for displacement is always an antinode for pressure and vice versa. So, the displacement curve has an antinode at the bell: the air is free to move in and out at the bell (the acoustic flow at the end of the trumpet can be large). Thus the trumpet operates at minima of output impedance: a small pressure and a large flow. At the other end, the pipe is sealed from the atmosphere by the player's lips, and the pressure can vary maximally. So at this end we have a pressure antinode and displacement node. We must know that the trumpet is not completely closed by the mouthpiece. However, this average area is much less than the cross section of the trumpet so the reflection of the acoustic wave is almost complete, and the acoustic flow is very small, in spite of the large acoustic pressure produced by the vibrating lips. High pressure, low flow: it is a high value of acoustic impedance. The trumpet is considered in first order as tube closed at one end with a pressure antinode at the playing end. This results in standing-wave solutions with an odd number of $1/4$ -wavelength between the two ends, such that $k_n = n\pi/2L$, where n is odd integer value. The corresponding modal frequencies are therefore in the ratios 1:3:5:7: etc.

The assumption that $Z=0$ at $x=L$ is not perfect, because the open end of the pipe radiates into the surrounding air which has mass and also its own impedance. The impedance $Z=0$ at $x=L$ would be valid only when we have vacuum outside the instrument. So, in an actual pipe, the inside waves are coupled with output waves - acoustical radiation (surrounding air vibrate together with air inside the pipe). Thus the pipe appears to have an acoustic length that is slightly greater than its physical length. For a cylindrical pipe with one open end of radius r , the additional length, called the end correction, is at low frequency approximation $0.61r$ [8]. The end correction present the imaginary part of free-end impedance, while the real part present radiation losses.

4.1 The effects of the bell

The main function of the bell is to form more gradual impedance transition between the high inner tube impedance and the low outside air impedance. This impedance transition is more fatal for long wavelengths than short wavelengths. This is because for higher frequencies the bell is slowly changing impedance, thus the waves with high frequencies reflect less than low frequency waves. The primary purpose of the bell is the amplification of lower frequencies. The bell has also other effects on sound. It raises the frequencies of the lower modes because the flare makes the vibrating air column shorter at longer wavelengths. Thus, the air column is shorter for the lower modes, which will raise their frequencies. Physical insight into the influence of bore shape on the modes of typical brass instruments is given by the Webster's horn equation [1]:

$$\frac{1}{S(x)} \frac{\partial}{\partial x} \left(S(x) \frac{\partial p}{\partial x} \right) = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} \quad (2)$$

where $S(x)$ is a function that describes the variation of cross-section area with x . This equation we get from wave equation with plane-wave approximation. It gives one-dimensional approximation of sound waves along a rigid tube with a variable cross-section area $S(x)$. Provided the flare is not too large, the above plane-wave approximation gives a good approximation to the exact solutions and preserves the essential physics involved. If we make the substitution

$$p = \psi S^{-1/2}, \quad (3)$$

look for solution varying as

$$\psi(x) e^{i\omega t} \quad (4)$$

and write S in terms of a local equivalent radius a so that $S = \pi a^2$, then equation (2) can be written as

$$\frac{1}{\pi a^2} \frac{\partial}{\partial x} \left(\pi a^2 \frac{1}{\sqrt{\pi}} \left(\frac{1}{a} e^{i\omega t} \frac{\partial \psi}{\partial x} - \psi e^{i\omega t} \frac{1}{a^2} \frac{da}{dx} \right) \right) = \frac{i^2 \omega^2}{c^2 a \sqrt{\pi}} \psi e^{i\omega t}$$

$$\frac{1}{a} \frac{\partial}{\partial x} \left(a \frac{\partial \psi}{\partial x} - \psi \frac{da}{dx} \right) = -\frac{\omega^2}{c^2} \psi \quad (5)$$

$$\frac{\partial^2 \psi}{\partial x^2} + \left[\left(\frac{\omega}{c} \right)^2 - \frac{1}{a} \frac{d^2 a}{dx^2} \right] \psi = 0.$$

If we write the above equation as

$$\left(\frac{\omega}{c} \right)^2 \psi = -\frac{\partial^2 \psi}{\partial x^2} + \frac{1}{a} \frac{d^2 a}{dx^2} \psi, \quad (6)$$

we find that this equation is closely related to the Schrödinger wave equation

$$E\psi = -\frac{\hbar^2}{2m} \frac{\partial^2 \psi}{\partial x^2} + V(x)\psi, \quad (7)$$

with $1/a \frac{d^2 a}{dx^2}$ the analogue of potential energy and $-\partial^2 \psi / \partial x^2$ the analogue of kinetic energy $-\hbar^2 / 2m \partial^2 \psi / \partial x^2$, where m is the mass of the particle. So, we can consider propagation acoustic pressure in tube as particle in potential well by quantum mechanics. The shape of the horn is in this case some sort of "potential" of the tube, which affects on travel of acoustic pressure. We can express the "potential" of the tube with curvature. The curvature of a plane curve at a point, which is defined as

$$\kappa = \frac{1}{R} \quad (8)$$

where R is the radius of curvature, is measure of how sensitive its tangent line is to moving the point to other nearby points [9]. If t is tangent vector and s is arc length along curve from a fixed point on the curve, then curvature is

$$\kappa = \frac{dt}{ds} = \frac{d}{ds} \frac{da}{dx}. \quad (9)$$

The radius of curvature with approximation of small wall slope da/dx can be written as

$$R \approx \left(\frac{d^2a}{dx^2} \right)^{-1}. \quad (10)$$

The ‘‘potential’’ of the tube can then be written as $1/aR$. The solution of the equation (6) at constant R is of the form $e^{i(\omega t \pm kx)}$, so that

$$k^2 = \left(\frac{\omega}{c_0} \right)^2 - \frac{1}{aR}. \quad (11)$$

If $\omega > \omega_c = c_0/(aR)^{1/2}$, k is real, so that unattenuated travelling and standing wave solutions exist. However, when $\omega < \omega_c$, k is imaginary and waves no longer propagate, but are exponentially damped as $e^{-x/\delta} e^{i\omega t}$, with a decay length of a $c_0/(\omega_c^2 - \omega^2)^{1/2}$.

The propagation of sound waves in horn is therefore directly analogous to the propagation of particle waves in a spatially varying potential. If the curvature is sufficiently large sound waves will be reflected before they reach the end of the instrument. However, just like particle waves in a potential well, sound waves can still tunnel through the potential barrier and radiate into free space at the end of the flared section. For a horn with a rapidly increasing flare, the reflection point occurs when the wavelength

$$\lambda_{reflected} > 2\pi(aR)^{1/2}. \quad (12)$$

At this point we must tell that at brass instruments, the curvature of the tube increases faster than the radius of the tube. The effective length of an instrument with a flared horn on its end is therefore shorter for low frequency modes than for the higher frequency modes. We can say that the bell acts as a high-pass filter, because above a cut-off frequency no sound is reflected back to the lips. Equation 12 shows us that the cutoff-frequency is higher for a more rapidly flaring bell.

4.2 Shape of the bell

The shape of the bell is designed to transmit into the air as much of input energy, while making the instrument easier to play at the same time. As we mentioned before all this properties depend on impedance. Take a look at how to reach transition without reflection.

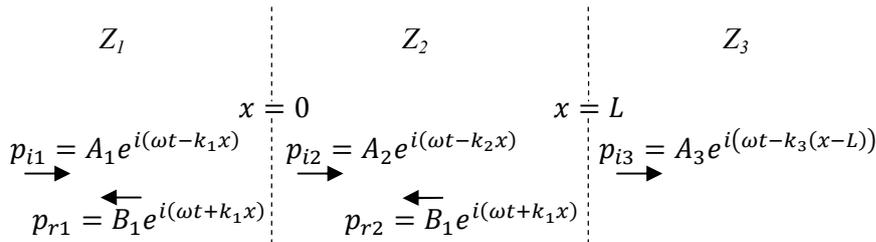


Figure 3: Let’s take a sound wave passage over three consecutive layers with different impedances Z_1, Z_2, Z_3

We seek to make the coefficient of reflection

$$R = \left| \frac{B_1}{A_1} \right|^2 \quad (13)$$

equal to zero. The boundary conditions are that p and U are continuous across the junctions $x=0$ and $x=L$. Between Z_1 and Z_2 the continuity of p gives

$$\begin{aligned} A_1 e^{i(\omega t - k_1 x)} + B_1 e^{i(\omega t + k_1 x)} &= A_2 e^{i(\omega t - k_2 x)} + B_2 e^{i(\omega t + k_2 x)} \\ \text{or} \quad A_1 + B_1 &= A_2 + B_2 \quad (\text{at } x = 0) \end{aligned} \quad (14)$$

between Z_2 and Z_3 continuity of p at $x=L$ gives

$$A_2 e^{-ik_2 L} + B_2 e^{ik_2 L} = A_3 \quad (15)$$

Similarly the continuity of U at $x=0$ gives

$$\frac{(A_1 - B_1)}{Z_1} = \frac{(A_2 - B_2)}{Z_2} \quad (16)$$

and at $x=L$ gives

$$\frac{A_2 e^{-ik_2 L} - B_2 e^{ik_2 L}}{Z_2} = \frac{A_3}{Z_3} \quad (17)$$

From the four boundary equations (14), (15), (16) and (17) we look for the ratio B_1/A_1 . If we take into account above equations, we obtain

$$\begin{aligned} \frac{B_1}{A_1} &= \frac{(r_{31} - 1) \cos k_2 L + i(r_{21} - r_{32}) \sin k_2 L}{(r_{31} + 1) \cos k_2 L + i(r_{21} + r_{32}) \sin k_2 L} \quad \text{where} \\ r_{31} &= \frac{Z_3}{Z_1}, \quad r_{21} = \frac{Z_2}{Z_1}, \quad r_{32} = \frac{Z_3}{Z_2} \end{aligned} \quad (18)$$

Hence

$$\left| \frac{B_1}{A_1} \right|^2 = \frac{(r_{31} - 1)^2 \cos^2 k_2 L + (r_{21} - r_{32})^2 \sin^2 k_2 L}{(r_{31} + 1)^2 \cos^2 k_2 L + (r_{21} + r_{32})^2 \sin^2 k_2 L} \quad (19)$$

If we choose $L = \lambda_2/4$, $\cos k_2 L = 0$ and $\sin k_2 L = 1$ we have

$$\left| \frac{B_1}{A_1} \right|^2 = \frac{(r_{21} - r_{32})^2}{(r_{21} + r_{32})^2} = 0 \quad \text{when } r_{21} = r_{32} \quad (20)$$

that is, when

$$\frac{Z_2}{Z_1} = \frac{Z_3}{Z_2} \quad \text{or } Z_2 = \sqrt{Z_1 Z_3} \quad (21)$$

We see, therefore, that if the impedance of the coupling medium is the geometric mean of the two impedance to be matched and the thickness of the coupling medium is

$$\frac{\lambda_2}{4} \quad \text{where } \lambda_2 = \frac{2\pi}{k_2} \quad (22)$$

all the energy at frequency ω will be transmitted with zero reflection.

Brass instruments are more complex than sequence of layers. Let's look for shape of horn, which makes the waves reflection small as possible (figure 4). What is the function that describes that shape? The problem is similar to the transition of waves over several consecutive layers. A way to eliminate reflections is to change the boundary conditions slowly compared with the wavelength [10]. One geometry that can be easily calculated is to assume that you can produce a whole series of quarter-wavelength plates.

Figure 4: The air inside the horn we divide into layers of width $\lambda/4$.

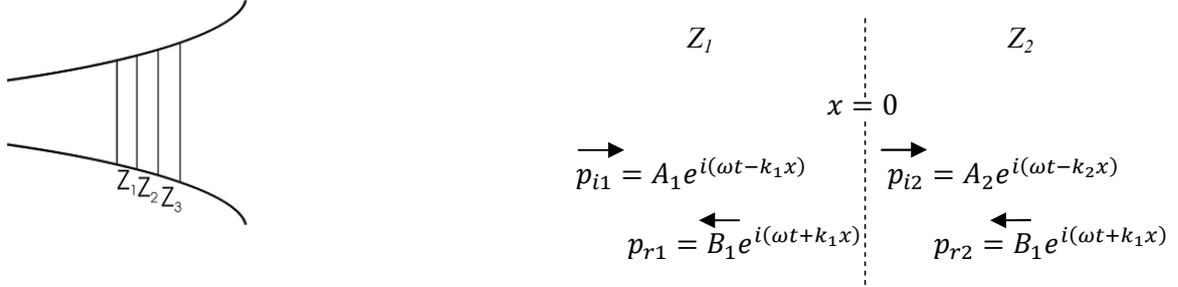


Figure 5: Sound wave passage over two consecutive layers with impedances Z_1 and Z_2 .

Between two layers the continuity of p at $x=0$ gives

$$A_1 + B_1 = A_2 \quad (23)$$

and continuity of U at $x=0$ gives

$$\frac{A_1 - B_1}{Z_1} = \frac{A_2}{Z_2} \quad (24)$$

The equation (23) and (24) can be solved to give

$$B_1 = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right) A_1 \quad (25)$$

So the reflection at one of boundary layer can we write with some approximations as

$$\Delta R = \frac{B_1}{A_1} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \approx -\frac{\Delta Z}{2Z} \approx -\frac{1}{2Z} \frac{dZ(x)}{dx} \left(\frac{1}{4} \lambda \right) \quad (26)$$

In order to have the reflection from each boundary cancel the one from the earlier boundary, ΔR must be small (when the difference of neighboring impedances is small) and independent from x , call it α . Then

$$\frac{dZ}{Z} = -\frac{8\alpha}{\lambda} dx \quad (27)$$

and

$$Z = Z_0 e^{-8(\alpha/\lambda)x} \quad (28)$$

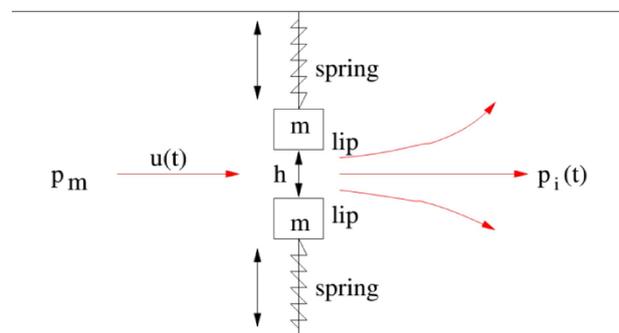
This tell us that impedance of instrument must exponentially decrease to get no reflection. This applies only to the high frequencies compared with the shape of horn.

5 Sound Generating by Lip Vibrations

5.1 Basic lip model

In many wind instruments, acoustic power is generated by airflow through a vibrating valve. In trumpets and other brass instruments, the valve is the player's lips which, when air passes between them, vibrate to modulate the airflow. By adjusting the tension in the lips, the shape of the lips within the mouthpiece (the embouchure), and the flow of air between the lips via the pressure in the mouth, the brass player forces the lip to vibrate at the required frequency of the note to be played. The frequency with which valve vibrates is controlled partly by its own natural frequency and partly by the resonances of the instrument air column to which it is connected. The nature of the lip motion is one of the most complex parts of a brass instrument system, and one of the most difficult to study. In many cases the lips have been modeled as a mass on a spring approximation (figure 6) The lips do not, however, move in just one dimension, as with a one mass/spring model, and it has been found that the lip motion is in all three dimensions. It can also be the case that simultaneously different parts of the lips are moving in different directions [11].

Figure 6: Basic one mass lip valve model, where the lips behave as masses on springs. P_m is the pressure inside the mouth, P_i is the pressure in the mouthpiece and the height of the lip opening is denoted by h .



5.2 Pressure controlled valves

We can think of a player's lips or a woodwind reed as a valve that is controlled by the pressure that is generated across it. In wind instruments, the player typically places the mouthpiece of the instrument in the mouth (or on the lips) and blows, creating a static overpressure upstream of the reed. This creates a pressure difference across the valve, which causes it to oscillate, creating an acoustic pressure signal at the input to the instrument. In order to precisely describe the physics of the valve it is necessary to describe its response to an increase in air pressure. Neville H. Fletcher and Thomas D. Rossing use a (σ_1, σ_2) [8] notation to classify valves into their various types, as shown in figure 7. σ_1 has classification +1 if a pressure excess p_0 at the inlet tends to open the valve, and -1 if it closes it. The symbol σ_2 refers similarly to the effect of an excess pressure p applied at the outlet.

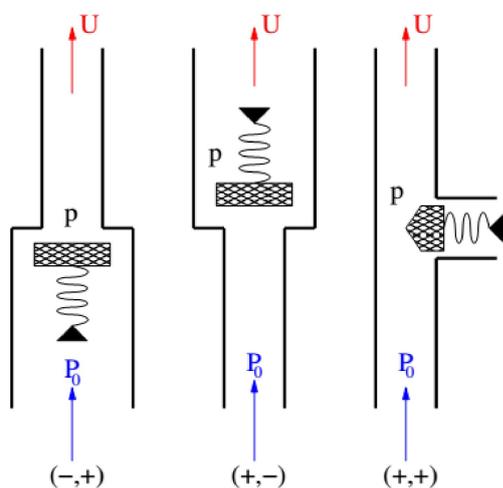


Figure 7: Simplified models of pressure controlled valves. Figure shows the three types of valves. From left to right: inward striking valve (woodwind reed and the reed pipes of the pipe organs), outward striking valve (simple models of the lip-valve driving brass family musical instruments and the valve in the human larynx), sideways striking valve (valve in the avian syrinx) [8]. The inlet pressure is p_0 and the outlet pressure is p . It is important to emphasize that, in reality, pressure controlled biological valves, such as brass instrument player's lips are much more complex than suggested in this figure and require more than one geometric parameter to specify their configuration.

In order to describe the flow of air through any wind instrument, it is necessary in principle to solve the Navier-Stokes equation. This equation is nonlinear, and the only way in which it can be solved is by numerical methods. Such a solution would not reveal a great deal about the general principles underlying the mechanism of sound generation and control except for specific limit cases. It is therefore appropriate to use much simpler models.

5.3 Single reed and lip valves

The common reed valves of woodwind instrument (clarinet, saxophone, oboe and bassoon) have classification $(-, +)$. The player does work to provide a flow of air at pressure above atmospheric: this is the source of energy, but it is more or less steady. What converts steady power (DC) into acoustic power (AC) is the reed. However, it is more than a single-way converter because it also interacts with the resonance of the air column in the instrument. Let us find the equation which describes the flow variation with pressure difference. Our discussion begin with a consideration of steady flow through a valve supplied from an infinite reservoir at pressure p_0 , while the outlet pressure is p . We can write the volume flow U as

$$U = Wxv, \quad (29)$$

where x measures the opening of the valve, assumed to be of width W . The pressure difference $(p_0 - p)$ across the valve is ordinarily large enough that we can assume Bernoulli's equation to apply, so that the flow velocity is [12]

$$v = \sqrt{\frac{2(p_0 - p)}{\rho}}, \quad (30)$$

where ρ is the density of air. The opening x of the valve we get from the force tending to open the valve. The force can be found by integrating the static pressure $p_0 - 1/2 \rho v^2$ over the whole valve surface. If S is the area of valve flap over which the upstream and downstream pressures act, then the Bernoulli term $1/2 \rho v^2$ can be taken into account by reducing these areas to effective values S_1 and S_2 . The force is then $(\sigma_1 p_0 S_1 + \sigma_2 p S_2)$. For simplicity we set $S_1 = S_2 = S$, which amounts to ignoring the Bernoulli term, which is in any case small for valve geometries where flow separation is clean. If the static opening is x_0 , then we can write

$$(x - x_0) = (\sigma_1 p_0 + \sigma_2 p)SC, \quad (31)$$

where C is the elastic compliance of the valve spring.

By inserting the expressions for the flow velocity and opening of the valve in equation (29), we can write the volume flow U as:

$$U = W[x_0 - (\sigma_1 p_0 + \sigma_2 p)SC][2(p_0 - p)/\rho]^{1/2}. \quad (32)$$

In case, for steady flow, with $\sigma_1 = -1$ and $\sigma_2 = 1$ (single reed valve), we can write

$$U = \alpha(p_0 - p)^{1/2} - \beta(p_0 - p)^{3/2}, \quad (33)$$

where α and β are positive constants. At this moment we must define the reed conductance G_r , to find under what conditions the reed acts as acoustic generator. At the low frequencies considered in quasi-static flow, conductance G_r , which is the real part of admittance, is given by [8]

$$G_r = -\frac{\partial U}{\partial p} \quad (34)$$

For sound generation the work done by the generator on the resonator must be positive. That means that U increase with increasing p . Following the literature, we define the conductance with negative sign because we look for output conductance of reed not input conductance of resonator. If we look at the figure 7, we see that the volume flow U and the pressure p downstream side of the reed, which causes the force, are opposite. So if we want that resonator receive work from generator, must be output conductance of generator negative. This is when the blowing pressure increases past the point A on figure 8 and the effect of the reed closing becomes dominant.

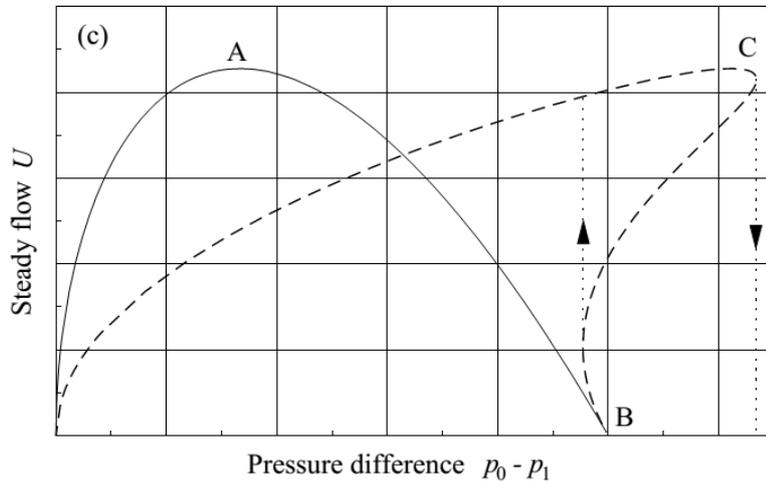


Figure 8: The quasi-static flow characteristic for a reed valve of configuration $(-,+)$ as in a clarinet (full curve) and of a double reed as in an oboe (broken curve).

Lip valves are more complex but, on a simple model, have classification either $(+,-)$ or perhaps $(+,+)$. When we come to consider lip valves the static flow characteristic is not very helpful. In each case the static flow simply increases monotonically with increasing blowing pressure and there is no negative region of real part of the admittance. To understand the operation of these valves as acoustic generators it is necessary to consider their behavior at frequencies close to their natural resonance. We must go back to Eq. (29) and insert the effective pressure driving the oscillatory flow without ignoring the Bernoulli term. A. Hirschberg has in *Mechanics of Musical Instruments* given a detailed discussion of the aerodynamic theory involved, and has pointed out that quite minor changes in the geometry of the valve can have large aerodynamic and acoustic consequences.

Conclusion

This seminar shows, that number of important factors affect on trumpet operating. To transmit into the air as much of input energy, while making the instrument easier to play at the same time is very dependent on shape of the bell. To investigate influence of the bell and other properties of the trumpet it is necessary to introduce the acoustic impedance. In this seminar we also found out that the impedance of brass instrument must exponentially decrease to get no reflection. This applies only to the high frequencies. Actually we want to have also some reflection to instrument act as a resonator.

Pressure-controlled valves are responsible for sound production in musical instruments of the woodwind and brass families. This seminar introduces various configurations of the valve defined by the couplet (σ_1, σ_2) and describes conditions under which the reed valve acts as an acoustic generator. That is when the real part of output admittance of valve becomes negative, which means that energy flows from generator to resonator.

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