PHYSICS OF END CORRECTION IN ORGAN PIPES

by Dennis Hedberg

I have always been cognizant of end correction in organ pipes but never really understood the physics behind it. I acknowledge there is little practical application, but for the benefit of readers who may have had similar experience I undertook the research and writing of this article. The further I researched the more I realized the complexity of the involved physics and how much additional research is needed.

Have you ever noticed two labial ranks, like a string and diapason, planted note for note and adjacent to one another, and asked yourself why the string pipe is longer than the diapason pipe when they both are tuned to the same pitch? The simple reason is *end correction.* It is the difference in pipe length required for a desired pitch and the actual physical length of that pipe. It is affected by the scales or diameters between the two ranks with the larger-scale diapason requiring more end correction than the smaller scale string pipe. Hence the diapason, requiring greater end correction, is shorter than the string but still sounds the same pitch. That is the simple reason but does not address the 'why.' Having a lifelong fascination about such things I wanted to demonstrate this phenomenon. A physics teacher long ago told me a scientist does not ask why a phenomenon occurs but rather under what conditions does it occur?

What we organ people refer to as an open pipe is an open-open tube to a physicist, meaning the tube/pipe is open at both ends. One of those open ends represents the pipe's mouth. Each end has an end correction to be dealt with. Their effects combine and are recognized together at the pipe's open top end.

The usual textbook model for describing standing waves is to visualize running waves on a stretched string, but sound waves in an organ pipe are invisible. In this case we look at an organ pipe as if it were a simple tube open at both ends. Most standard college physics text books do not discuss organ pipe physics with any detail. That leaves us with Figure 1 below, where Z_{IN} represents the input impedance at the open end where the mouth would be located at distance x=0 and Z_L represents the radiation impedance at the pipe's open top at distance x=L, where L is the actual length of the pipe[1].

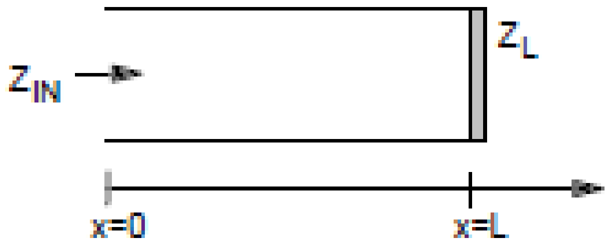


Figure 1

Rather than getting caught up in a real organ pipe, we substitute a short duration air pulse at the left end, x=0, where the mouth used to be. A small air mass whose pressure is slightly higher than atmosphere propagates towards the pipe's right end. Exactly at the end, because this mass is no longer confined within the pipe's walls, it rapidly expands and falls to atmospheric pressure creating a node, meaning zero pressure differential. But this node is not really at the pipe's end—it is further away. If this node had occurred exactly at the pipe's end there would be no sound. Remember this is an air mass and it is moving, so its momentum carries the node several millimeters beyond pipe's physical end. The distance the air mass travels between the pipe's physical end and the zero pressure node is 'end correction.' Within the end correction the plane wave exiting the pipe transforms into a spherical wave radiating in all directions. In doing so, a slight negative pressure (lower than atmospheric pressure) or rarefaction zone trails behind. The math handling that transformation is beyond the scope of this article.

The suction created draws air from farther back up the pipe, and that in turn repeatedly draws air from even farther up the pipe. This results in a low-pressure pulse having been reflected at the pipe's open end from the original high pressure pulse and reversing its phase or polarity 180° (or π radians). One can think of the high-pressure pulse as the positive half cycle and the reflected low pressure pulse as its negative half. When the reflected pulse returns to the pipe's left end, the mouth, it is reflected again and the whole process can repeat itself.

Figures 2 and 2a below graphically depicts the movement of air particles and the pressure amplitude that moves them. Notice pressure amplitude and particle movement, that while synchronous, are not time aligned. They are offset by 90° (π/2 radians), or a quarter cycle. It makes perfect sense if you stop and think about it. Take a sounding pipe. Remove it from the wind chest and place your finger over the pipe hole. Now there is no air flow but static pressure is still there

In Figure 2 the red waveform represents pressure variance over the 7.64ms period of one full cycle of Tenor C at 130.81Hz. The right cursor is positioned exactly at the half wavelength period of 3.82ms where the pressure waveform crosses zero.

Look at the green waveform representing particle volume flow which maximizes at the left cursor, 1.904ms, when it crosses zero. This is where its slope is maximum, also the red pressure waveform's amplitude is at its maximum. The concept may be hard to grasp because you cannot think of particle volume flow in terms of the waveform's amplitude. You have to look at its slope. Where it looks like it is at its maximum or minimum amplitude, its slope is flat, meaning zero particle volume flow.

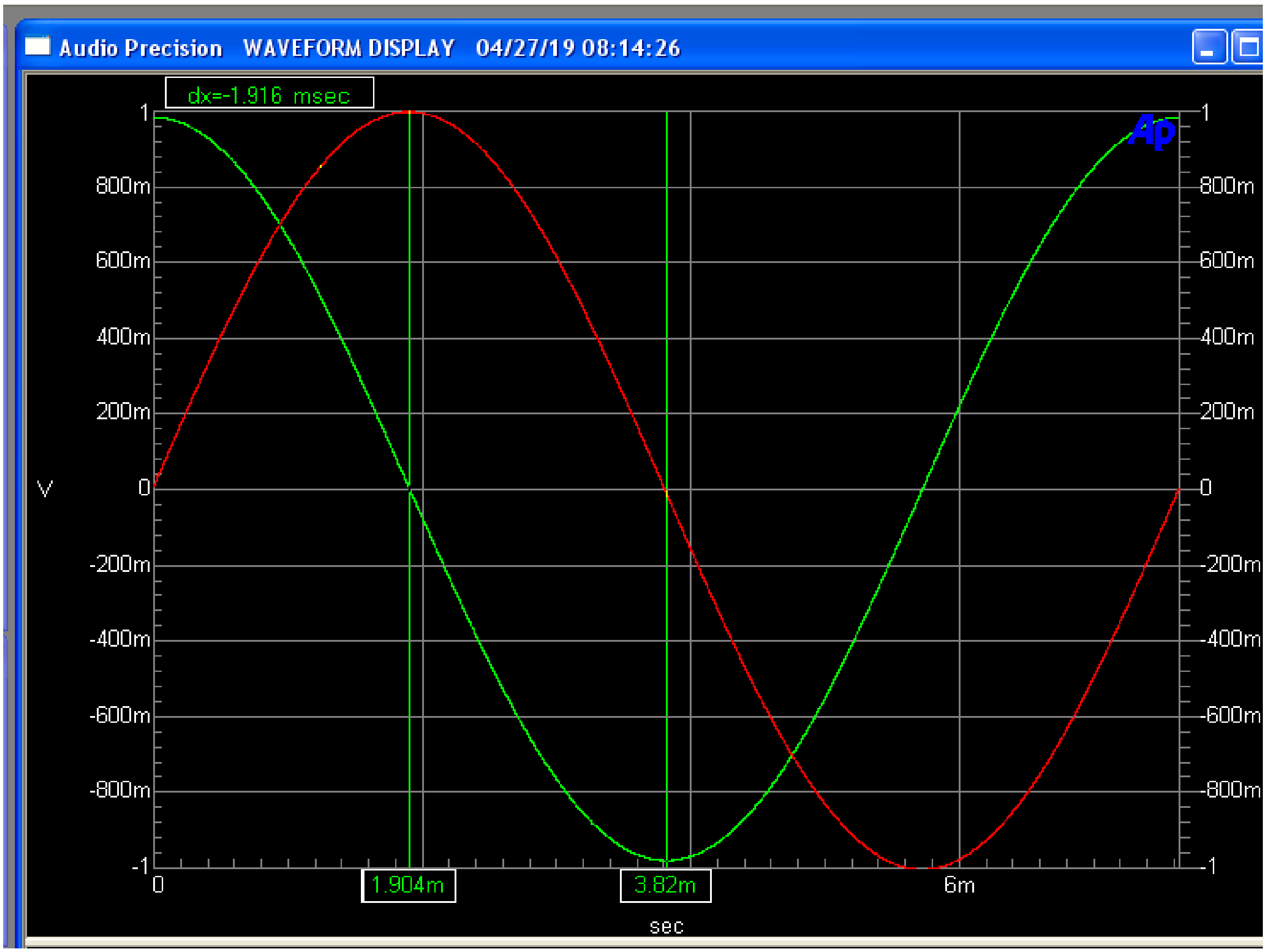


Figure 2

In Figure 2a the density of the black dots is indicative of a compression/condensed zone, (high density) or a rarefaction zone (low density). The "A's" and "N's" indicate antinodes and nodes respectively[9].

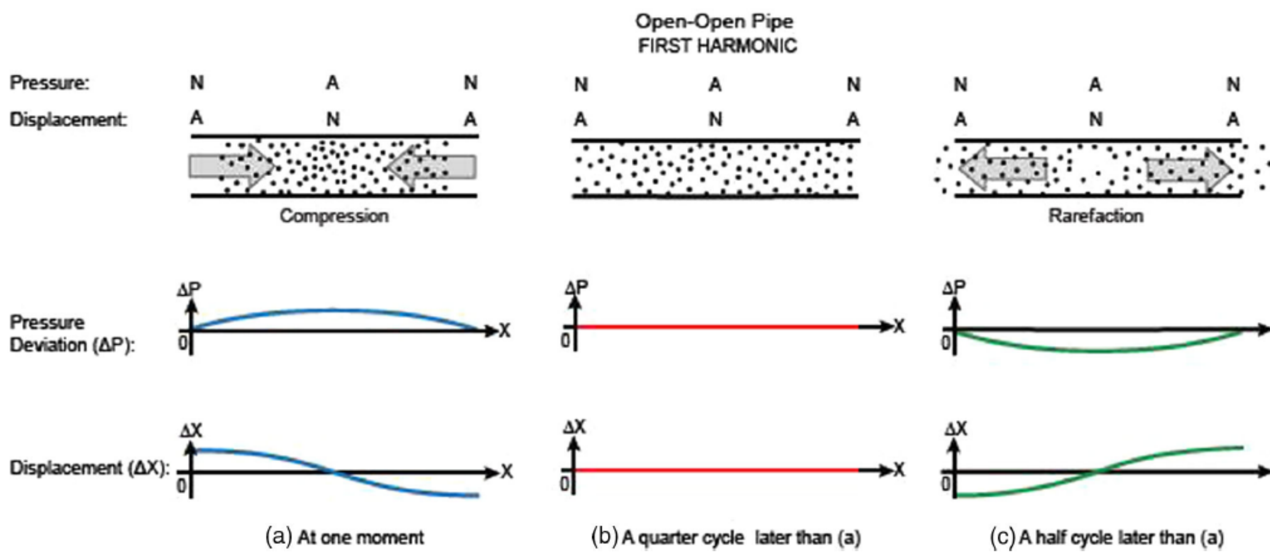


Figure 2a

A stopped pipe with only one open end speaks differently. See Figure 3 below. As with the open-open pipe the high pressure pulse travels down the pipe (first transit) and bumps into the pipe's rigid stopper and is 100% reflected (second transit), but this time there is no phase reversal. Returning to the open end the pulse is again reflected (third transit) with phase reversal. The final reflection at the stopped end without phase reversal (fourth transit) returns the pulse to the pipe's mouth where again the pressure node is some distance from the mouth. This distance is the 'mouth end correction[2]'.

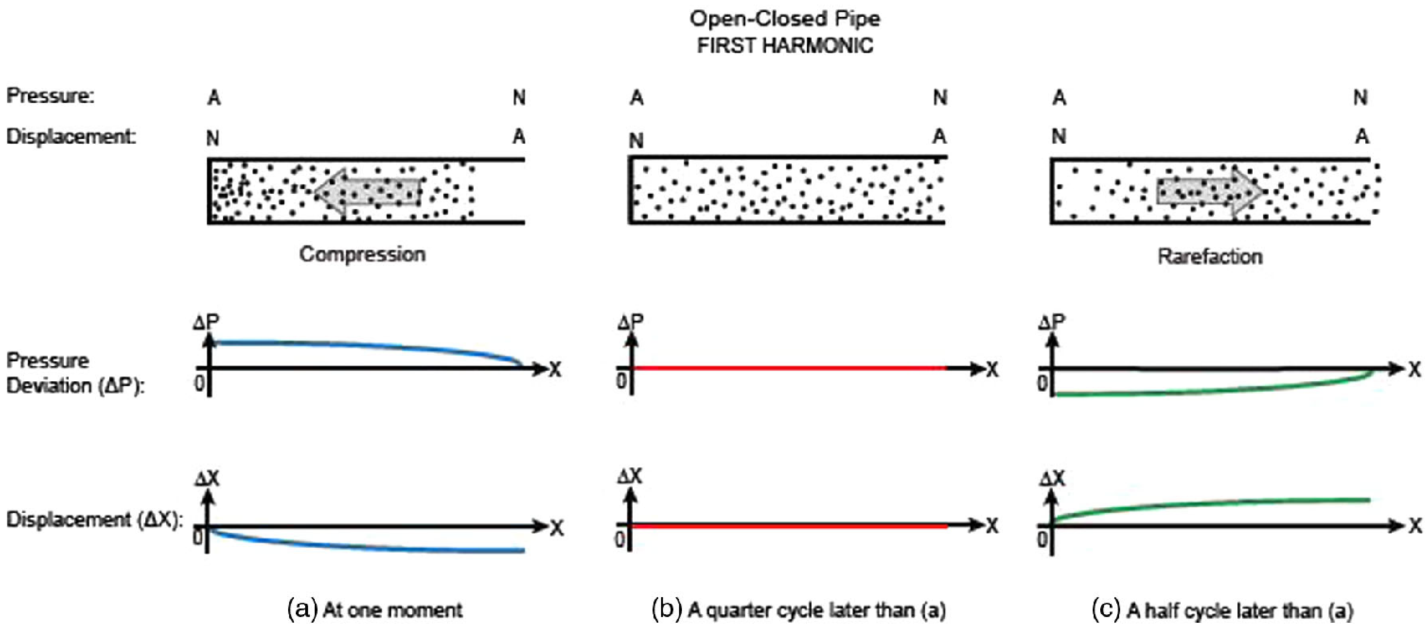


Figure 3

Regardless of whether the pipe is open-open or open-closed we have incident and reflected waves moving simultaneously in opposite directions. These waves add together; this adding is called *superposition.* If the timing between the superimposed pulses is just right, the resulting wave is referred to as a *standing wave* and causes the pipe to resonate at its fundamental frequency, which in this case is Tenor C.

> A downloadable zip file is available on the website, www.atos.org, containing animations illustrating particle movements in both open and stopped pipes as well as wave superposition and standing waves. Since Adobe™ no longer supports .swf files a stand-alone flash player executable is also included. Unzip its contents to your desktop. Install and launch the flash player then open the animations within the player.

It is understandable that an object can reflect or bounce off a solid object. But what if that object is just a mass of air bouncing off another mass of air? What conditions makes that possible?

In electrical engineering, Ohm's Law states one volt of electro-motive force (V) will cause one ampere of current (I) to flow through one ohm of resistance (R), or V=IR. Rearranging this equation we have R=E/I. Analogous to organ pipes, this expression can be rewritten as Impedance (Z), in acoustic ohms, equals pressure (Pa) in pascals, divided by particle volume flow (U), in cubic meters per second (m^3/sec). Impedance is a variant of resistance in that it addresses some imaginary property like *reactance* (X) or some other time determinant (ωt) or relative position (ωx) varying parameter. Imaginary numbers exist in an alternate plane offset by 90° or $\pi/2$ radians from the plane of real numbers. In Cartesian coordinates they equate to real numbers on the abscissa (x axis) and imaginary numbers on the intercept (y axix). Taken together, real and imaginary numbers are referred to as *complex numbers.*

As another example in electrical engineering, power is the product of voltage and current, provided voltage and current are time synchronous. In DC circuits they are synchronous, but frequently this is not true in AC circuits when inductance and/or capacitance are taken into consideration. Simply multiplying voltage times current yields *apparent* power referred to as volt-amperes (VA), not real or *effective* power (Watts). It is the imaginary component, usually represented by theta (θ), that when included in the expression for the apparent power equation that identifies the time difference or phase between voltage and current. Therefore effective power equals voltage times current times θ, or *power factor* as it is usually called.

In this discussion of organ pipes, we have pressure, particle flow and impedance. Because air particles have mass they cannot be instantly accelerated to their maximum flow rate. It is impedance that is responsible for slowing particle flow and it would then be said pressure leads particle flow by 90° or $\pi/2$ radians. (See Figure 2)

Air at standard conditions has impedance and it is found by multiplying the density by the speed of sound. The result, expressed as acoustic ohms, equals 1.204 kg/m^3 x 343.8 m/s = 413.9352 kg/m^2 seconds. When we take this quantity and divide by our pipe's cross sectional area of 0.00693978 square meters, it results in *specific characteristic impedance* of 59,646 acoustic Ohms. It is unique and constant for any given pipe.

Radiation Impedance is given by superposition pressure divided by the superposition acoustic volume flow. The principle of superposition is the phenomenon where two or more sound waves can travel through a common medium at the same time and not interfere with one another. The ratio between radiation and characteristic impedances is key to determining how much of the incident sound pressure level is radiated into the atmosphere and how much is reflected back to the source. Another term for this is *Standing Wave Ratio*. When these impedances are equal, all available power is transmitted or radiated. (When I say "all available power" I mean most of the power initially generated by the pipe is dissipated as heat through friction against the pipe walls and air viscosity.) This is a desirable situation for ham radio operators but not so good for an organ pipe. If all the sound power were radiated there would be nothing remaining to be reflected back to the pipe sustaining its standing wave. That would render the pipe speechless.

In part, standing waves are possible only because a portion of the incident wave propagating the pipe's length and exactly at its boundary with the open atmosphere has an impedance different from that of the open atmosphere.   The laws of continuity dictates pressure and flow must be equal on both sides of this boundary. But clearly they are not. It is their differing impedances that cause some of the incident wave to return to the source from whence it originated thus preserving continuity. What is not reflected is transmitted across the boundary and radiated into the atmosphere. The summation of reflected and transmitted sound power must equal incidence sound power.

The transmitted power must be replenished by some mechanism in order for the pipe to maintain stable speech. That brings us back to the pipe's mouth where the real action is.

The actual computations are complex and beyond the scope of anyone without advanced studies in higher mathematics and physics—and that is definitely not this author. In spite of my academic shortcomings, I still have the audacity to attempt description of what happens when chest wind is applied to a labial organ pipe.

Wave reflection in an organ pipe also occurs at the mouth, and with that, another end correction occurs. Rather than speaking in terms of impedance, the resources I investigated seem to universally write in terms of volume flow *acceptance* rather than impedance. Acceptance is the reciprocal of impedance. In electrical engineering *conductance*, measured in Siemens, is the reciprocal of impedance. (When I first studied electronics in the 1950s, vacuum tubes were king and conductance was stated in *mhos* which is ohms spelled backwards.)

As the plane air jet (windsheet), driven by pressurized air from the wind chest emerges from the pipe's flue slit it develops into an exponentially growing sinuous wave as it traverses the mouth's cutup to the upper labium at a speed approximately equal to half the speed of the jet as it emerges from the flue. That speed is dependent on chest wind pressure.

..   . See Figures 4 and 5 below.

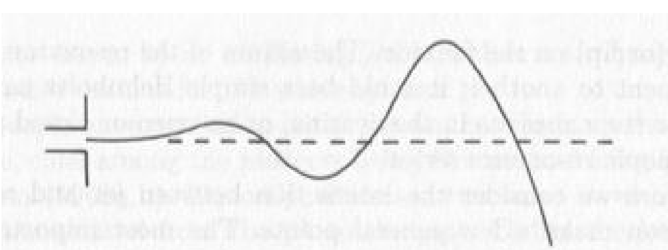


Figure 4

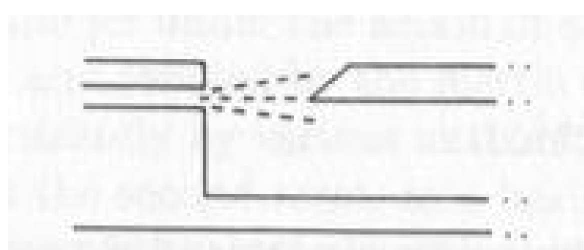


Figure 5

In figure 6, we see the jet flowing at a “steady velocity of V meets the edge of the resonator so that a fraction of the cross section S_j enters the resonator. This blends with an acoustic flow of average velocity v_m into the mouth area S_m of the resonator and, after a small mixing length Δx, becomes an acoustic flow velocity v_p into the main pipe of the resonator, the area of which is S_p.” S_m represents the part of the mouth not inside the jet. See Figure 6 below.

Note, the preceding description is a basic distillation of what is really a much more complex interplay between the jet stream and the pipe resonator.

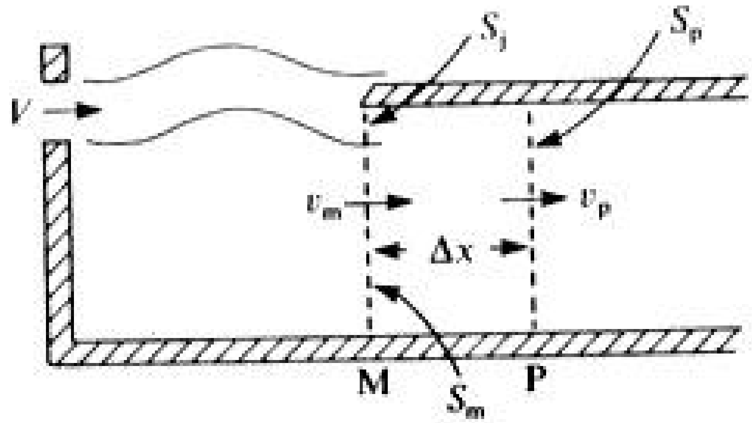


Figure 6

Figure 7 below is graphical representation of interaction between the jet and air column within the pipe. The text I bolded is the description of how the sound energy dissipated through radiation is replenished so the pipe can continue sounding.

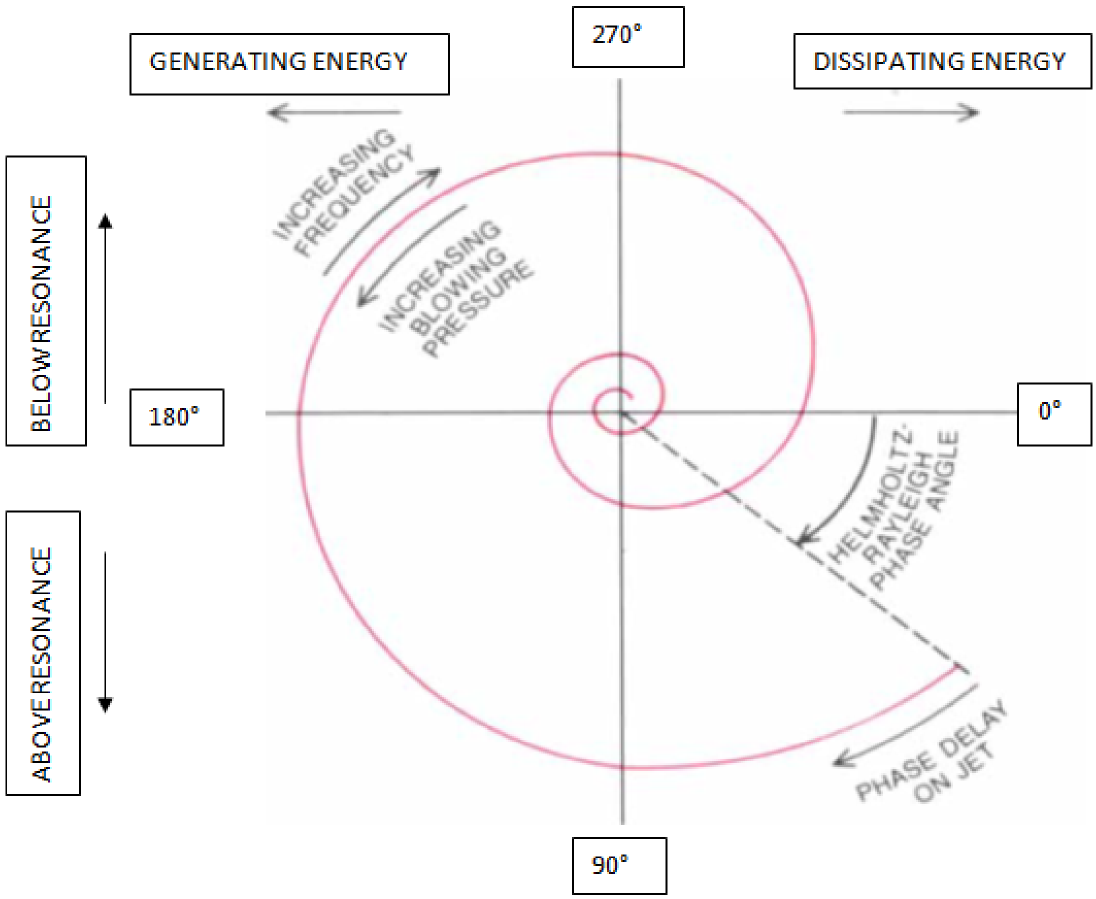


Figure 7

*Acoustic admittance of the jet as a function of frequency or of blowing pressure takes the form of a spiral in which the distance from the origin represents the magnitude of the admittance and the angular position represents the phase relation between the acoustic flow out of the mouth of the pipe and the pressure just inside the mouth. When the outflow is in phase with the pressure, the admittance lies in the right half of the spiral and the energy of the jet is being dissipated****. For the jet to act as an acoustic generator the admittance must lie in the left half of the spiral, which requires that the back-and-forth displacement of the jet be offset, or delayed, in phase with respect to the pressure inside the mouth of the pipe****. The wave reflected from the jet is then larger than the incident wave. When the admittance falls in the* *upper half of the spiral, the jet lowers the natural resonance frequency of the pipe; when it falls in the lower half of the spiral, the jet raises the resonance frequency.*

For a given blowing pressure, harmonics created of the pipe's fundamental frequency are dependent on how the jet impinges upon the upper labium, its cutup and the ratio of pipe length to cross sectional area… its scale.

We all understand stopped pipes only generate odd order harmonics but an open pipe can also generate odd order harmonics if the oscillating jet equally flows into or out of the pipe body. By slightly raising or lowering the languid the jet's trajectory can be biased to blow into the pipe body with more or less amplitude. Refer to Figure 5. Asymmetry fosters even order harmonics as well as odd order in the flow waveform[3]. See Figure 8.

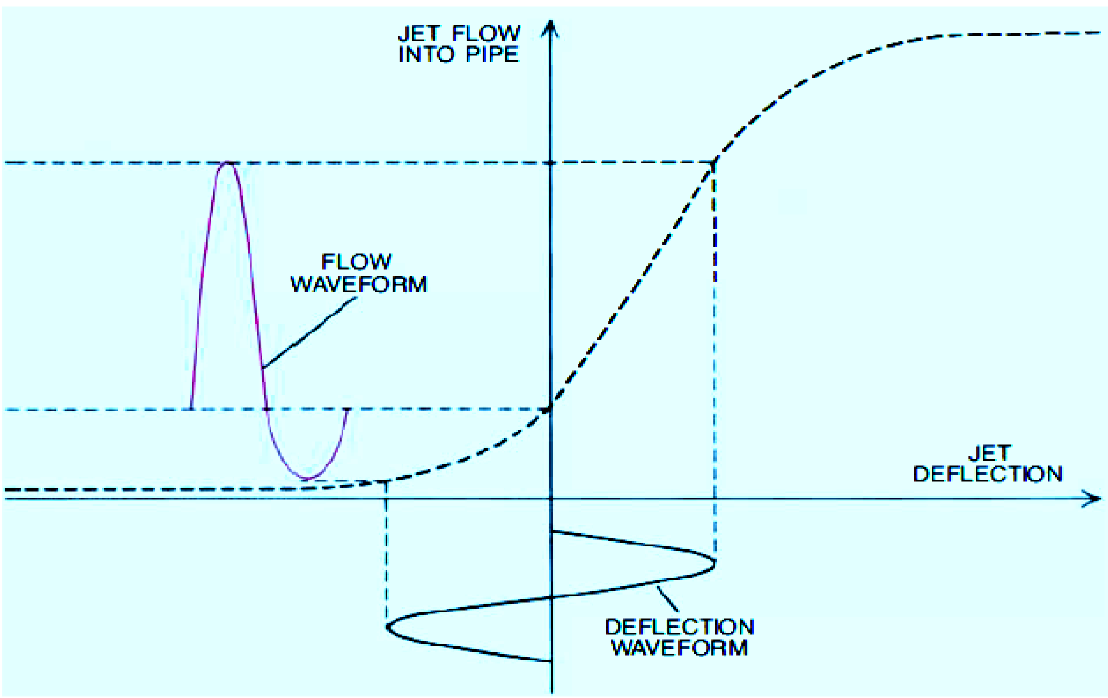
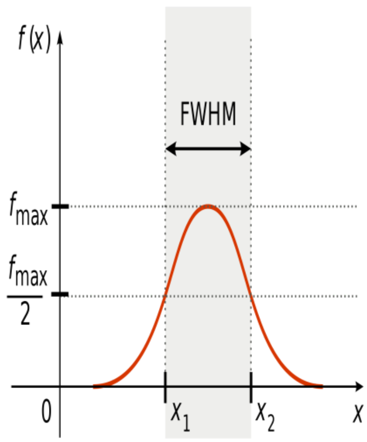


Figure 8

Larger scale pipes have greater end correction than smaller scales because of their lower "*Q*." Q is the ratio of the power at the pipe's resonant frequency to frequencies both above and below the resonant frequency power which are half the power of the resonant frequency. Notice x_1 and x_2 (high Q) are closer together in figure 9 than in figure 10 (low Q) [11].



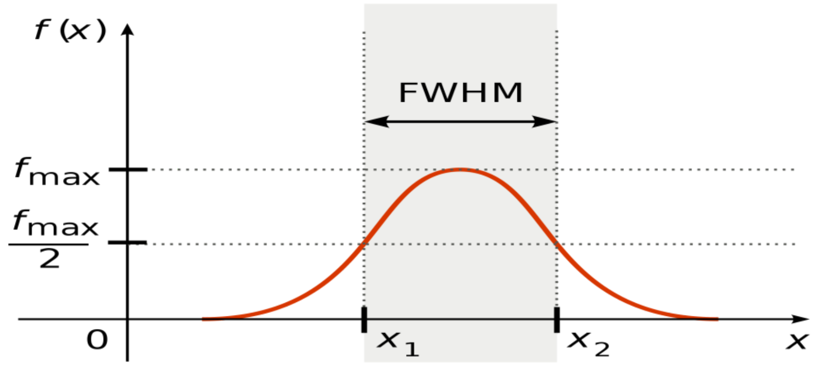


Figure 9

Figure 10

In organ parlance Q is a parameter indicating how well a pipe holds its pitch against any number of disturbances. This is why low-Q large scale pipes like diapasons and tibias have greater vibrato under the same varying wind pressure than smaller scaled high-Q strings. Furthermore, it is the reason smaller scaled pipes are preferable as tuning references.

Larger scaled pipes are louder and have a strong fundamental but end correction rapidly attenuates their harmonic development resulting in a powerful but relatively dull tone.

In figure 11 below where the fundamental frequency is the tallest peak. The dashed lines are at exact harmonic modes in the pipe's air column. In the figure's (b) section each of the succeeding harmonics' amplitudes rapidly attenuate because each peak is further delayed from its natural harmonic. This is known as *inharmonicity* and is the reason behind the concept of note stretching in stringed instruments' tuning. Because each peak is further delayed or separated from its associated natural harmonic resonance it receives ever less reinforcement.

By comparison in the figure's (a) section the smaller scaled string pipe with less end correction (higher Q) has more of its harmonic train falling almost exactly on the pipe's natural harmonics resulting in a long slow attenuation and thus a harmonic rich tone[4].

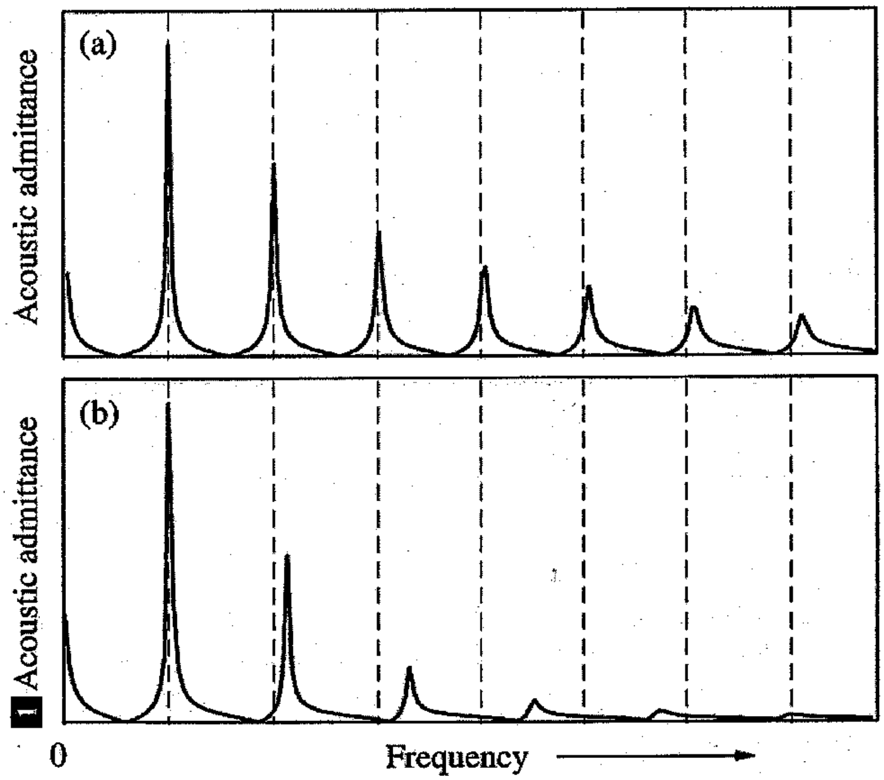


Figure 11

Previously we discussed differences between characteristic (pipe) and radiation (mouth) impedances being responsible for how much wave power is reflected. In the electrical analogy of part (a) of Figure 12 we see the sum of those impedances expressed by their reciprocal conductances ($1/Z_p + 1/Z_m$). In part (b) we see Δp varying indirectly proportional with the pipe's cross sectional area S_p.

Two simplistic electrical analogs first proposed by Helmholtz[7], then Rayleigh[8] present the interaction between the pipe's air column and its mouth's jet from two points of a symbiotic relationship. *Part (a) "Volume drive involves the injection of the jet fluid into the standing wave on or about times of maximum compression at the driving point. As such, the jet "sees" the parallel impedance of the pipe Q_p and of the mouth Z_m, and the particle flow in the pipe Q_p is simply the sum of the jet flow Q_j and the mouth flow Q_m". Part (b) "For Momentum drive the pipe is driven by the pressure Δp, generated by the jet as it slows and spreads in the pipe the jet, transfers its momentum to the pipe flow. The pressure created just inside the mouth by the jet is given by Δp and the pipe flow equals the mouth flow. The accepted general form of Δp is given in the figure where S_P is the cross sectional area of the pipe, S_j is the jet area in the pipe, v_o is the jet efflux velocity, and p is the density of air"* [5].

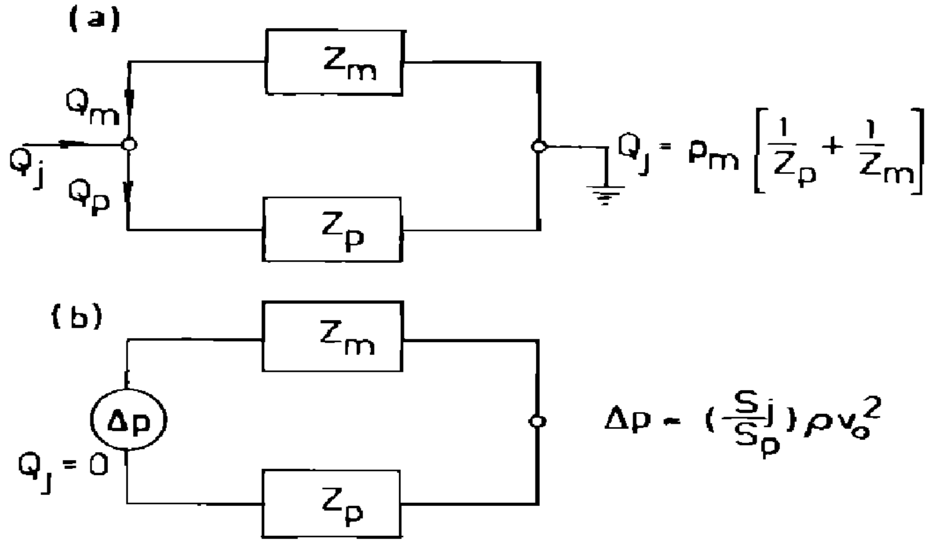

(a)
Z_m
Q_m
Q_j
Q_p
Z_p
$Q_j = p_m \left[\frac{1}{Z_p} + \frac{1}{Z_m}\right]$
(b)
Z_m
Δp
$Q_j = 0$
Z_p
$\Delta p \sim \left(\frac{S_j}{S_p}\right) \rho v_o^2$

Figure 12

PART 2

THE SPREADSHEET PART ONE

Part one relates to the role standing waves play in how a labial organ pipe develops its speech (Lines 1-29). The Excel formulae in column F are translated from physics equations in column G, and used in column B. The formulae in columns C and D are essentially the same as column B excepting for changing the column designators.

The goal of Part 1 is to establish coefficients of Reflected Power (B25), Transmitted Power (Cell B26 (subsequent cell references drop the word "Cell" for convenience), Reflected Flow (B27) and Transmitted Flow (B28). Also, values for Load Impedance (B17) and Input Impedance (B21).

The S.I. unit for pressure is the *pascal* (Pa). The pressure at sea level and 25° C is 1.01352×10^5 Pa (or equal to 760.2mm Hg or 0.0001450377 lbf/inch^2). Any of these converts to 101352 Pa. The pressure exerted by a sound wave is much, much less… I mean really, really, microscopically less!! Audiologists and physicists express sound pressure in pascals but more commonly used units include atm (atmosphere) and mm of Hg (Mercury).

Sound pressure is more commonly expressed in decibels, a relative scale. Consider that the minimum Sound Pressure Level (SPL) normal human hearing can detect is 20 micro pascals. 0 dB SPL is referenced to this pressure. Since the decibel scale is a logarithmic scale of measure, 94 dB Sound **Pressure** Level is required to equal one pascal. 94dB SPL is fairly loud but not dissimilar to a theatre organ diapason in close proximity to that which a tuner would encounter. At the opposite end of the scale 120dB SPL is considered the threshold of pain corresponding to 20 Pa. If Sound **Power** Level is of interest, 0 dB is referenced to 10^{-12} watts. Consequently 94dB Sound **Pressure** Level is approximately equal to 2.5 milliwatts Sound **Power** Level.

The equation in G11 describes the instantaneous pressure of the incident wave moving left to right whose peak amplitude is one pascal in B9. Look again at G11 and notice the imaginary exponents indicated by "*j*", $-jkx$, $j\omega t$ and θ, that occur here and also appear in several other equations. Analyzing $-jkx$, the minus sign indicates the wave is moving left to right. If the minus sign is absent, it indicates the wave is moving right to left. k is the wave number derived in B31, and x specifies the position of the measurement relative to the wave's origin. To the textbook equations in B11-B14, I added θ to those equation's exponents, also sine operators.

Describing sound waves often involves time and sine in some manner. I chose to divide Tenor C's 7.64 ms, 360° period into five degree increments. That requires converting degrees to radians (degrees x $\pi/180$ = radians) and does so at G26 and G27, with the results in G27 (θ) imported by formulae in F11-F14. The results of interest to me are the coefficients of Load Impedance (B17), Input Impedance (B22), Reflected Power (B25), Transmitted Power (B26), Reflected Flow (B27) and Transmitted Flow (B28).

For the moment let $x = 0$ as in E8. In Figure 1 see that x=0 is where the mouth normally is. Exponent $j\omega t$ establishes the time base representing the period of one Tenor C cycle, B35.

Equation G12 describes the speed at which wave air particles are moving left to right due to the instantaneous pressure of B11. It differs in that it incorporates air's density and speed of sound which taken together define air's impedance.

Now we consider the reflection wave represented by equations G13 and G14. They are almost identical to the incident wave equations discussed above except there is no negative sign in the *jkx* exponents indicating the particle flow velocity is now moving right to left. Also reflection wave amplitude is *B* (B13) instead of incidence wave amplitude *A* (B11).

The next two equations, G15 and G16, combine equations G11 and G12, and G13 and G14 respectively in superposition. The significant differences are that *A* and *B* pressures are added together in G15, but in G16 particle volume flow *B* is subtracted from particle volume flow *A*.

Examining the true open end of the pipe, x no longer equals 0 but rather *L,* B38, the actual measured length of the pipe. At x=*L* we also find radiation impedance Z_L, mentioned early in this article. Equation G17 finds Z_L by dividing superposition pressure G15 by superposition velocity G16 and changing their exponents from *jkx* to *jkL*.

THE SPREADSHEET PART TWO

Part two shows my process to calculate end correction and validate it against actual and theoretical measurements (Lines 30-71).

To begin, we need actual dimensional measurements of the pipe being studied. These include pipe length, pipe diameter, pipe width, mouth width and cutup, and depth if applicable. This information is entered into the grayed cells. For demonstration purposes I entered data for a diapason, string and stopped flute in columns B, C and D respectively

A Tenor C diapason pipe correctly tuned to 130.81Hz (B34) has a wavelength of 2628.24mm (B36) at 343.8 meters/second (speed of sound) (B32). The pipe's internal diameter is 94mm (B40).

Stipulating diapason pipes are half wavelength resonators and ignoring losses due to fluid viscosity and wall friction, it follows the length of this particular diapason pipe should be 1314.12mm (B37). But when making internal measurements from top to languid, the pipe was actually 1140mm long (B37). That was 174.12mm (B49) shorter than simple physics says it should be. Furthermore, at this length the pitch should be 150.79Hz (B50), but still resonates at 130.81Hz.

For comparison the same measurements taken of the violin pipe found it to be 1280mm long (C39) and 27mm in diameter (C40). This has only a 34.12mm (C49) difference compared to its theoretical 1314.12mm length (C37). So what is going on here?

Getting past the physics and math of standing waves, impedance and wave reflection we can look at the practical steps to quantify end correction. The term 'End Correction' is misleading because it is incomplete. There are actually two end corrections—one at each end. The pipe's mouth **is** the other end and its correction is greater than the more obvious one at the top of the pipe.

The mouth is more than just the other end of the pipe because of its shape and possible accoutrements such as ears, bridge, roller, or beard. Centuries ago no one was thinking about the math and physics. Organ builders just knew that beyond scale, a set of pipes' mouths had to have certain, shall we say, modifications, to achieve the tonality they were seeking. What has always irritated me is that applying the common formula of end correction equaling the pipe's diameter multiplied by anywhere from 0.3 to 0.8 depending on whether the pipe is open or closed. That is easy enough to do except that the pipe's actual length always turns out to be longer than this formula says it should be. On end correction Wikipedia writes, "There is no scientifically proven and accepted value for the end correction of a resonant tube, various values ranging from 0.3r to 0.6r, where r is the pipe's radius, have been suggested from numerous disparate experiments[6]." For an un-flanged pipe, researchers Levine & Schwinger (1948) settled on 0.6133*a,* where *a* is the pipe's radius[10] (B55).

A basic relationship for mouth correction is the pipe's cross section area divided by the square root of the mouth area[10] (B54). However it is only reliable with pipes having simple, sliding tuning sleeves at the pipe's open top end. Accuracy suffers with pipes employing slot tuning using either sleeves or scrolls. An alternative equation for mouth correction is found at B55. Its result is very close to that of B54.

The width or nodes of the Diapason waveform displayed in Figure 13 below is 3.82 msec (B38), which is the half-wavelength period of 130.81 Hz (B34). The left cursor is positioned at 399.8 usec which is as close to 0.41 msec as my Audio Precision instrument can resolve. The right cursor is positioned at 3.731 msec (B68). The span between the two cursors is 3.731msec-0.41msec = 3.32msec (B51) (corresponding with the pipe's true length of 1140mm) and multiply by 2 = 6.64msec Take the reciprocal of 6.64 msec and multiply by 1000 = 150.6Hz, B50, which is the frequency of the Tenor C pipe if there were no end corrections.

One other observation about Figure 13: The red trace is the left to right moving wave and the green trace is the reflected right to left moving wave with 180° phase reversal.

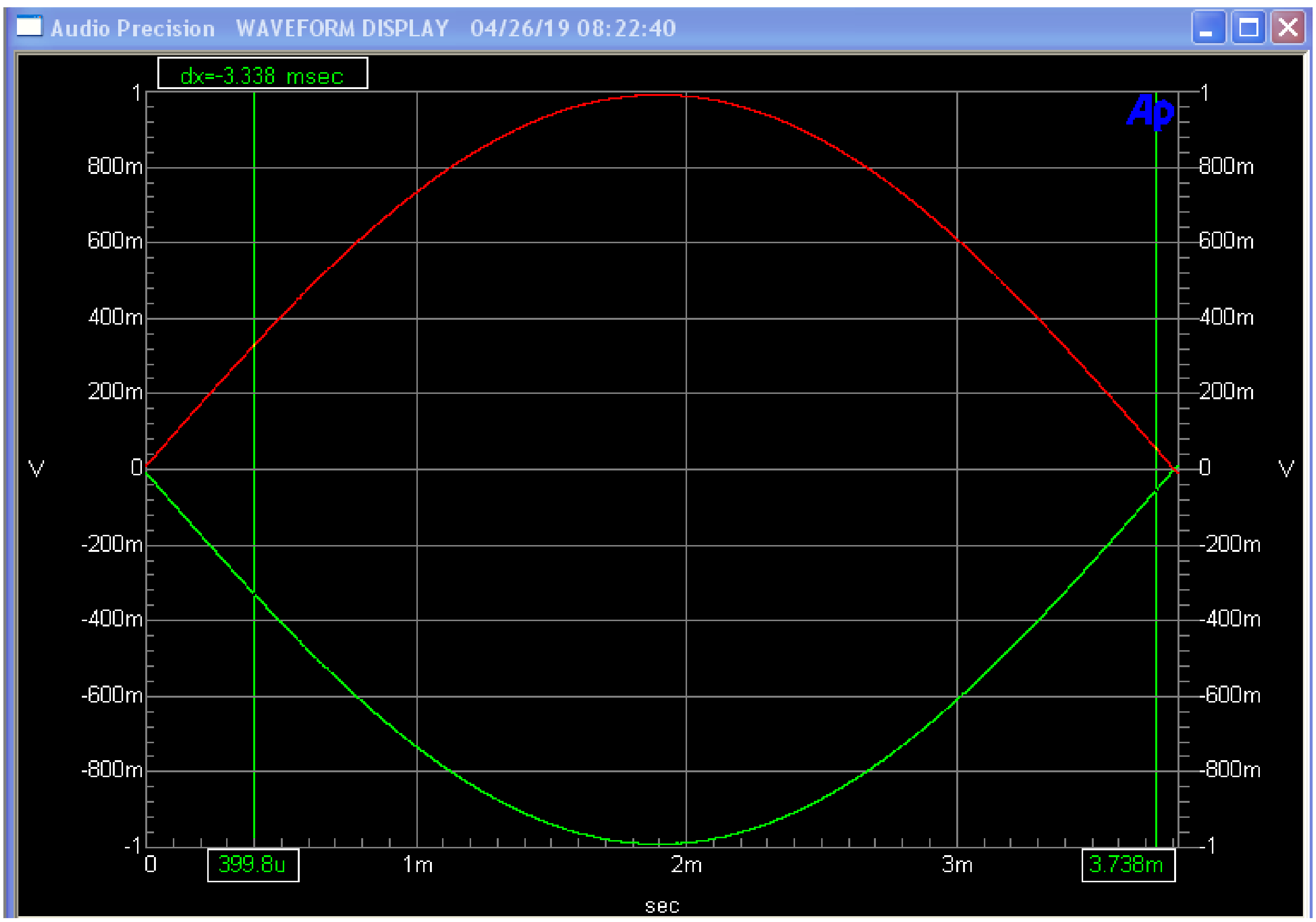


Figure 13

So after all this end correction discussion and the mechanics making a pipe speak, what is the outcome?

GRAPHS

Graph 1 (Diapason), Graph 2 (Violin), and Graph, 3(Stopped Flute) are derived from B24-B27, also B16 and B21. In spite of the Diapason and Violin pipes being open-open pipes differing only by their lengths and diameters, I find it curious that their respective graphs are so different. The Stopped Flute, an open-closed pipe, as expected, is still quite different from the previous two.

Some graphs look incomplete because I scaled the graphs to show the most revealing information. There is such a large range of y-axis values that if the peak values of impedances and peak values of power and flow were shown, the important data would not amount to anything more than a flat line. Therefore I graphed load and input impedances separate from power and flow and aligned the two graphs.

Abscissa values are in degrees. One complete cycle is 360° but in order to graph an uninterrupted single cycle I extended abscissa values to 720°. If I had done that with the Stopped Flute I would have had to extend the abscissa to 1440°.

Look at Diapason Graph One and notice that in the first and third segments load impedance (orange) is slightly greater than input impedance (purple). This means most of the wave's incident power is transmitted into the atmosphere and little is reflected. To the contrary, in the middle-third segment a very large difference in impedances exists meaning that essentially all the incident wave's power is reflected back into the pipe.

CONCLUSIONS

- Mouth end correction has a greater effect than top end correction.
    - Diapason mouth end correction was calculated to be 141.06mm (B52), while top end correction was calculated to be 28.83mm (B51). Total end correction, 169.83mm.
        - Graph 1, Diapason, identifies total end correction maximum at 170mm and actual pipe length at 1140mm.
    - True wavelength, 2628.24mm (B34). Calculated wavelength based on pipe half-wavelength including both mouth and top end correction, 2619.78mm, B58.
    - Frequency of Tenor C, 130.81Hz (B32). Calculated wavelength based on pipe half-wavelength with both mouth and top end correction, 131.23Hz (B59).
    - Percent error between true and calculated wavelength was 0.32% (B61).
    - Percent error between true and calculated frequency was -0.32% (B60).

- Similar data can be found in Graph 2, Violin and Graph 3, Stopped Flute
- Having made the case that the ratio of reflected waves to transmitted waves varies with the ratio of input impedance to load impedance, these statements can be made.
    - o If input impedance z2 > load impedance z1, then reflected wave is in phase with incident wave and a pressure maximum is reflected as a maximum.
    - o If input impedance z2 < load impedance z1, then reflected wave is 180° phase shifted relative to incident wave and pressure maximum is reflected as a minimum.
    - o If input impedance z2 >> load impedance z1 or input impedance z2 << load impedance z1 then reflection is nearly total and transmitted intensity is nearly zero.

ACKNOWLEDGEMENTS

My primary reference for this article was *The Physics of Musical Instruments, Second Edition* authored by Neville H. Fletcher and Thomas D. Rossing. (Figures 4-8) I feel compelled to acknowledge Dr. Fletcher and inquire if he was known to any of our Australian readers. Dr. Fletcher passed in 2017 and hailed from Armidale, New South Wales, Australia. Among his many topics of research and writings most significant to *Theatre Organ* readers was Musical Acoustics, where he authored or co-authored 71 articles and academic papers. Dr. Fletcher played the organ in his church for 20 years. His interest in musical acoustics led him to ask the question, how do organ pipes work?

…I had the same question.

I also must acknowledge Dr. Shannon Mayer, Chair, Physics Department, University of Portland. Her counsel was invaluable.

1 "Lecture Notes on Acoustics 1".Kurt Heutschi, Swiss Federal Institute of Technology, August 8, 2016, pp 42-43.

2 http://www.animations.physics.unsw.edu.au/waves-sound/standing-waves/index.html
(This URL works with Internet Explorer but may not work with Google Chrome.)

3 "The Physics of Organ Pipes", Neville Fletcher and Suszanne Thwaits. SCIENTIFIC AMERICAN, Vol. 248, No. 1(January 1983) pp 94-103.

4 “ORGAN PIPES—A PHYSICIST’S VIEW”, Neville Fletcher, ISO Journal, November, 1998, page 37.

5 “Acoustic Admittance of Organ Pipe Jets”, Neville Fletcher and S. Thwaites, JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, Volume 74, Issue 2, August, 1983, pp 400-408.

6 https://en.wikipedia.org/wiki/Acoustic_resonance

7 “ON THE SENSATIONS OF TONE”, Hermann Helmholtz, 1877, pp 88-93.

8 “THE THEORY OF SOUND”, Lord Rayleigh, Vol. 2, 1896, pp218-220.

9 http://newt.phys.unsw.edu.au/jw/flutes.v.clarinets.html

10 “Aerodynamics Of Flue Organ Pipe Voicing”, https://logosfoundation.org/akoestiek/Aerodynamics%20of%20flue%20organ%20pipe%20voicing.pdf page 3

11 https://en.wikipedia.org/wiki/Full_width_at_half_maximum