THEORETICAL ASPECTS OF TRUMPET DESIGN ©

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Abstract

Trumpet makers have designed trumpets primarily by copying best available trumpets and by trial-and-error. As a result, a huge chasm exists between trumpet maker art and applicable technologies of acoustics, mechanical vibrations, metallurgy, and fluid mechanics. The complexity of the technologies is a communications barrier between theory and practice. This paper attempts to bridge such a gulf for selected theoretical aspects of trumpet design.

INTRODUCTION

Artisan trumpet makers bring many valuable attributes to their art, including: care, craftsmanship, extensive experience, specialized capabilities, and personalized service. Trumpet makers also learn what trumpeters seek in instrument performance. However, obtaining the ultimate in performance inherently requires additional expertise in mathematics, acoustics, mechanical vibrations, metallurgy, and fluid mechanics. It is extremely rare when the artisan trumpet maker has such proficiencies.

Using selected theoretical subjects in mathematics, acoustics, mechanical vibrations, metallurgy, and fluid mechanics, this paper provides scientific and engineering means for trumpet design and explains various trumpet phenomena.

WALL SHAPE, TAPER, FLARE, ACOUSTIC VELOCITY, AND DISCONTINUITIES

A cylindrical wall shape has a constant radius and a straight axis. The first and second derivatives of radius are zero for such a shape. A conical wall shape has a constant radial taper and a straight axis. The first derivative of radius is constant and the second derivative of radius is zero for such a shape. The second derivative of radius is the flare rate. Only cylindrical and conical wall shapes have a zero-flare rate. Within cylindrical and conical wall shapes, the acoustic velocity remains constant and is equal to the velocity of sound in still air for all frequencies. Within all other wall shapes, the acoustic velocity varies with both the flare rate and frequency.

An acoustic air column is defined by the wall shape. An abrupt change in the radius, taper, or centerline direction of the air column comprises a discontinuity. Discontinuities interfere with an attack, the starting of the note, and the ability to play softly. A large discontinuity returns a premature echo, or reflected pulse, to the lips. All discontinuities are to be avoided.

When an abrupt change in radius, taper, or centerline direction exists, the discontinuity is eliminated by using a transitional wall shape. At each end of the transitional wall shape, the radius, the first derivative of radius, and the second derivative of radius exactly match the corresponding values of the adjacent wall shape. The second derivative of radius is zero at each end of the transitional wall shape, it changes continuously over the length, and it reaches a maximum or minimum value at or near to the mid-length. The magnitude of the second derivative at or near to the mid-length is reduced as the length of the transitional wall shape is increased. It is necessary to use a transitional wall shape in the design of the mouthpiece and the leadpipe.

HARMONICS & TIMBRE

When a note is played very softly, the lips vibrate simply and only the fundamental tone is produced. When the note is played at a higher dynamic level, the lips vibrate in a more complex manner, and a disturbance is produced that contains harmonics. The number of harmonics present in the tone varies inversely with the fundamental frequency and increases with the playing volume. The frequency of each harmonic is an integer multiple of the fundamental frequency. Ordinarily, the relative amplitude of each higher frequency harmonic successively decreases.

French physicist, Henri Bouasse, (1929 and 1930) declared that the energy production in woodwind and brass instruments was not associated solely with the frequency of the fundamental, but also with the frequencies of the harmonics.

Benade's graduate student, Walter Worman, (1971) found that the total acoustic energy was distributed between the frequencies of all the harmonics (the fundamental and partials) and interacted with a set of air column impedance maxima (resonance modes). He found that when woodwinds and brasses were played softly, the fundamental frequency interacted with the impedance maximum associated with such frequency. However, when the instrument was played louder, harmonics interacted with the maxima associated with the harmonic frequencies. When played louder, each successive harmonic grew in strength much faster than the fundamental. At full volume, the strengths of the harmonics in the tone were in direct proportion to the height of the various impedance maxima that cooperate to generate the tone.

The timbre is the direct result of the relative amplitude of the harmonics. The relative amplitude of the harmonics depends upon the player's unique lip physiology, oral cavity and playing technique. When several trumpeters play the same trumpet, each produces a unique timbre.

Nevertheless, the timbre also depends upon the design of the trumpet air column and the trumpet structure. The mouthpiece cup volume and the design of the lead pipe affect the magnitude of the input impedance peaks, which affects the relative amplitude of the harmonics. The trumpet wall thickness, the metal wall acoustic velocity, and the trumpet mass affect the relative amplitude of the harmonics.

TRANSIENTS

Parts of this discussion are based upon information regarding acoustic transients, presented in The Physics of Musical Instruments, by Fletcher & Rossing (1998).

Luce and Clark (1967) measured transient properties of brass instruments and found that partials (harmonics other than the fundamental) below cutoff frequency built up together and reached their steady-state values nearly simultaneously. Partials with frequencies above cutoff built up in amplitude more slowly and reached their steady states at times that were longer the higher their frequencies lay above cutoff.

Risset and Mathews (1969) reached a similar conclusion both by analysis of instrument sounds and by subsequent synthesis of subjectively matched sounds using a computer. However, they found that for a short trumpet note, the first three harmonics reached their maximum values after only about 20 ms (milliseconds) while harmonics above the fifth took from 40 to 60 ms, with higher harmonics being longer delayed.

The Risset & Mathews finding that the first 3 harmonics reached maximum value in about 20 ms is corroborated considering 3 round-trips at about 6.7 ms per round-trip. Their finding that the first 6 harmonics reached maximum value in about 40 ms is also corroborated considering 6 round-trips at about 6.7 ms per round-trip. Reaching maximum value in 60 ms suggests 9 harmonics, and 9 round trips at about 6.7 ms per round-trip.

From the above, notes containing the first 3 harmonics reach maximum value in 3 round-trips. Notes containing the first 6 harmonics reach maximum value in 6 round-trips. And, notes containing the first 9 harmonics reach maximum value in 9 round-trips. Thus, the number of harmonics present requires an equal number of round-trips for those harmonics to become evident. Cutoff frequency is not relevant in such a process.

PLAYING THE INSTRUMENT

The acoustics and the transient process incurred in playing the instrument are now examined in detail. The player is assumed to play a Trumpet High C (acoustic resonance mode 8) at full dynamic volume.

The vibrating lips create a disturbance that contains many harmonics. At the start of a transient, only the fundamental is present in the pressure wave. The pressure wave travels from the lips toward the bell at a wave velocity determined by the fundamental frequency and the flare rate. Within the flaring bell shape, the pressure wave encounters an acoustic barrier and some of the pressure wave is reflected to the lips.

The time for such a round-trip is about seven milliseconds. The oscillation period for a trumpet High C is about one millisecond. For this note, the lips go through about seven oscillations before the lips receive any feedback from the instrument. For a Double C, the lips go through about fourteen oscillations before the lips receive any feedback. Upon receiving feedback, the player may adjust the lip vibration frequency if required.

At this point in the transient, the fundamental has excited air column mode 8 into resonance, and a standing wave has been established. The standing wave combines with the disturbance being produced by the lips, and the amplitude of the pressure wave is acoustically amplified.

In the next step in the transient, the second harmonic is added to the pressure wave. The pressure wave travels at the wave velocity, but the second harmonic travels at the group velocity. The group velocity depends upon the frequencies of the harmonics present and the flare rate. The pressure wave encounters an acoustic barrier closer to the large end of the flaring bell and some of the pressure waves are reflected back to the lips. The second harmonic has excited acoustic resonance mode 16 into resonance, and the amplitude of the standing wave has been increased. Air column modes 8 and 16 simultaneously resonate.

In the next step, the third harmonic is added to the pressure wave. The pressure wave travels at the wave velocity, but the second and third harmonics travel at the group velocity. The group velocity is changed because of the higher frequency of the third harmonic. Air column mode 24 is excited into resonance, and modes 8, 16 and 24 simultaneously resonate.

If ten harmonics are produced by the lips, the transient is completed in ten round trips, and air column modes 8, 16, 24, 32, 40, 48, 56, 64, 72, and 80 all simultaneously resonate.

The group velocity, affected by the frequencies of all the harmonics, is different from the wave velocity, causing the harmonics to have a different transit time than the fundamental. This difference in transit times is referred to as transit time dispersion.

Nevertheless, a bell shape that has near perfect harmonicity causes the reflection phase shifts at the open bell to vary with frequency in such way as to cancel the transit time dispersion.

Trumpet air columns that lack near-perfect harmonicity facilitate transit time dispersion and thereby create an incoherent reflected pressure wave. All commercially available trumpets have increasingly large harmonicity deviations beginning at about mode 30.

In this example, the reflected pressure wave is partially incoherent. The three lowest harmonics (with the largest acoustic energy) do not cause transit time dispersion, and the seven higher harmonics (with much smaller acoustic energy) cause transit time dispersion. The reflected pressure wave gets progressively more incoherent for higher notes. For a Double C, the reflected pressure wave is very incoherent because nine of the ten harmonics cause transit time dispersion.

THE MOUTHPIECE DESIGN

Most commercially available mouthpieces have some small discontinuities, which adversely affect the attack, the starting of the note, and the ability to play softly. To avoid discontinuities, a continuous mouthpiece wall shape is required.

A continuous mouthpiece cup wall shape is achieved by using tangent circular arcs and lines. A continuous mouthpiece cup throat is used to connect the continuous cup shape with the cylindrical bore. The ideal throat shape is a parabola with an exponent of two, or greater. The throat shape is tangent to both the cup shape and the cylindrical bore. Thus, a completely continuous cup wall shape is attained and no discontinuity exists at the cylindrical bore juncture.

Another transitional shape is used at the juncture of the cylindrical bore and the conical backbore. While a transition as short as about one-eighth inch can be suitable in avoiding a discontinuity, a longer transition can be more effective. However, a longer transition reduces the backbore average taper rate and thereby affects the timbre. To maintain the timbre, a longer transition requires that the appropriate average taper rate be preserved.

THE LEADPIPE DESIGN

Most commercially available lead pipes have small discontinuities, which adversely affect the overall response. While a conventional type lead pipe is very common, a reversed type lead pipe has more recently gained broad acceptance, as a result of improved performance.

An ideal reversed lead pipe shape is comprised of a transitional wall shape. Such a lead pipe is of the longest practical length. The initial taper rate is the largest value that is consistent with a transitional wall shape of such length, the end diameters, and the required cylindrical shape at the large end. The lead pipe tapers changes extremely gradually. The second derivative of radius is minimized near to the mid-length and has an extremely small value. Such a lead pipe design results in continuously changing input impedance peak heights.

THE BELL DESIGN

Bessel Horn wall shapes are commonly used in bell designs. Besson used Bessel Horn shapes and such bell shapes have since been copied by all trumpet makers. The Bessel Horn flare exponent values used range from about 0.500 to 0.650, and result in a variation in timbre. However, trumpets with Bessel Horn bell shapes are not acoustically ideal. The best of them has intonation flaws of about ± 20 cents and sharply increasing inharmonicity starting at about mode 30. As a result, trumpets with Bessel Horn bell shapes do not play easily in the higher register.

The Bessel Horn intonation flaws can be fully corrected using bell shape perturbations, as described in JASA paper, <u>Trumpet with near-perfect harmonicity: Design and acoustic results</u> (2011). The method developed by Macaluso requires the use of an acoustic simulation model and a powerful laptop computer.

The lack of ease of play can also be fully corrected using another complex mathematical technique developed by Macaluso. The technique is proprietary.

The immediate outlook for artisan trumpet makers to develop ideal bell designs is not very bright because complex technology is required. Eventually, trumpet makers will need to acquire the necessary mathematical and acoustic skills required to develop acoustically ideal designs.

AIR COLUMN ACOUSTIC DESIGN

The air column is designed using acoustically ideal designs for the mouthpiece and lead pipe, and designing the bell to attain near-perfect harmonicity to the highest modes. The mouthpiece, the lead pipe, and the bell can each be designed to achieve a desired timbre.

An acoustically ideal trumpet air column is discontinuity-free and has near-perfect harmonicity (harmonically related resonance frequencies). The resultant ideal air column has particularly desirable qualities: it provides for sure attacks, the notes start quickly, it can be played softly, the pitch does not change with playing volume, it has a clear tone full of harmonics, and it has excellent intonation. Further, and perhaps more importantly, the ideal air column returns a fully coherent reflected pressure wave to the player into the highest register. This provides a very easy playing instrument with excellent response.

An air column wall shape that produces near-perfect harmonicity has been unknowable until recently, when Macaluso discovered the mathematical means for determining such a shape.

Commercially available trumpets are designed by copying best trumpet designs, absent the application of acoustic criteria and principles. Consequently, such trumpet air columns have acoustic discontinuities and large variances from perfect harmonicity.

STRUCTURAL VIBRATIONS AFFECT RESPONSE

Good trumpet response requires starting the tone with minimum effort. The small airflow through the player's lips is the source of energy to create the acoustic resonances. A very small portion of the input energy necessarily is dissipated in viscous and thermal boundary layer losses within the air column. Any unnecessary structural vibration dissipates additional energy and is to be avoided.

Numerous modes of structural vibration can be excited by acoustic resonances. Such modes of structural vibration dissipate input acoustic energy and adversely affect response. The ideal trumpet structure is one in which only the relatively thin bell flare resonates at frequencies corresponding to those of most of the harmonics. The rest of the trumpet structure should have high natural frequencies that cannot be excited into resonance by the highest possible acoustic resonance. For a Bb trumpet, the highest frequency excitation source is selected as Triple C at 3,729 Hz. The natural frequency of any part of the structure should be 4.50 KHz, or higher.

TUBE LATERAL BENDING MODE OF VIBRATION

The design and location of braces is an essential mechanical consideration in achieving the best possible response. It is readily apparent that the valve cluster is inherently the stiffest portion of the entire trumpet structure. Therefore wherever possible, trumpet components should be braced directly to the valve cluster.

From information in the Mechanical Engineers Handbook, by Lionel S. Marks, a tube first natural frequency in the lateral bending mode is given by the following equation. The equation applies to end support bracing that provides either 'free-free' or 'clamped-clamped' conditions. While the equation applies to cylindrical tubing, it may be used for a conical tube of small-included angle, by using average outside and inside diameters over a selected portion of the length.

$$F_1 = 3.58 \times [(OD^2 + ID^2)^{0.5} /4] \times [E \times g/d]^{0.5} \times 1/ L^2$$

Where: F_1 = tube first natural frequency, in the lateral bending mode, HZ
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OD = tube outside diameter, inches
ID = tube inside diameter, inches
E = modulus of elasticity, pounds per square inch
d = specific weight, pounds per cubic inch
g = gravitational constant, 386 inches per second squared
L = bracing spacing, inches

A forced vibration with small amplitude occurs when the tube natural frequency is much lower than the excitation frequency. A resonance vibration with magnified amplitude occurs when the tube natural frequency is close to the excitation frequency. The amplitude is nil only when the tube natural frequency is much higher than the excitation frequency.

Brace spacing of about 4.40 inches is required to achieve a tube natural frequency of 4.50 KHz for brass trumpet tubing (0.460 ID & 0.500 OD). The required brace spacing for the small end of the conical leadpipe is somewhat less. The required brace spacing for the large end of the leadpipe is only slightly less. The required brace spacing for the larger diameter conical portions of the bell is somewhat greater.

The unbraced tuning slide bend, bell tail bend, and valve slide bends can readily vibrate in three different structural modes. Proper bracing can prevent such undesirable structural modes of vibration. An exact analysis of such structures and modes requires the use of more complex finite element analysis. However, for such modes, normal construction practices are quite satisfactory.

OSCILLATING MODE OF TUBE VIBRATION & EFFECT ON TIMBRE

From the Shock and Vibration Handbook, by Harris (p. 7-36), the natural frequency for a cylindrical tube excited by an internal oscillating pressure wave is given for various modes of vibration. For the lowest mode, the natural frequency, F, is given by the equation below, in Hz:

$$F = 0.12328\ (t/r^2)\ V_s$$

Where:
t = tube wall thickness, inches
r = tube outside radius, inches
V_s = velocity of sound, inches per second
$V_s = 19.657\ [E/d]^{0.5}$
E = modulus of elasticity, pounds per square inch
d = specific weight, pounds per cubic inch

For brass trumpet tubing (0.460-inch ID, 0.020-inch wall thickness), the natural frequency is 5,607 Hz, and the tubing will not resonate in that mode. The aforementioned computed natural frequency value was verified to within 0.5% by ANSYS finite element analysis.

Tubing with a 0.013-inch wall could be excited into resonance by acoustic resonance mode 32. However, tubing as thin as this is not commonly used.

The lowest trumpet wall system natural frequency affects the timbre. Such natural frequency can be determined using finite element analysis, but fortunately that is not required. The trumpet can be considered to be a straight-axis air column shape with an average value of wall thickness and an average value of metal acoustic velocity. The trumpet has a wall mass and a total mass. The non-wall masses consist of the valve section, valve caps, mouthpiece receiver, braces, hooks, rings, etc. and mouthpiece.

The unknown lowest trumpet wall system natural frequency affects the relative amplitude of the harmonics. An unknown high value of the lowest natural frequency selectively increases the amplitudes of the higher harmonics, thereby brightening the timbre. An unknown low value of the lowest natural frequency selectively reduces the amplitudes of the higher harmonics, thereby darkening the timbre.

For a change in average wall thickness of about 0.001-inch (5 percent change), the lowest trumpet wall system natural frequency is changed by about 7 percent. There is relatively little difference in the acoustic velocity for the common brass alloys used. Nickel Silver has an acoustic velocity about 7.7 percent higher than the brass alloys. So, any use of Nickel Silver will brighten the timbre. For a change in the total mass of about 0.175 pounds (5 percent change), the lowest trumpet wall system natural frequency is changed by about 2 percent.

TRUMPET BELL FLARE VIBRATION

A Bessel Horn trumpet bell flare shape with rim bead was analyzed using ANSYS finite element analysis (Yellow Brass, 0.020-inch wall). The lowest natural frequency for that shape was found to be 553 Hz. That is not the value for the Macaluso bell, but it is used to explain the flare resonances. Thomas Moore, et al, Vibrational Modes of Trumpet Bells (2002) measured trumpet bell flare resonance patterns, and showed that trumpet bell flares have resonance modes in which the bell rim is both a node and an anti-node. For both of those modes, with 1 to 3 axial nodes, and with 2 to 6 radial nodes, there are thirty modes of resonance. For the Bessel Horn bell shape used, the resonance frequencies range from 553 to 3,684 Hz. There are five more resonances for each additional axial node, and for each additional radial node, respectively.

The frequencies for acoustic resonance modes 6 to 32, with open valves, correspond closely to the frequencies of selected Bessel Horn bell flare resonances. See table below. The resonance frequencies for a bell flare wall thickness of 0.015-inch are about 75% of the values shown, and would allow mode 4 to also excite flare resonances. There are a sufficient number of bell flare resonances to closely correspond to the acoustic resonances for all of the notes in a chromatic scale, and for all of the harmonics of each of those notes.

The bell flare resonance frequencies vary directly with the wall material velocity of sound. Therefore, a bell made from lower velocity of sound material radiates a darker sound, and a bell made from higher velocity of sound material radiates a brighter sound.

As the bell flare vibration travels through the trumpet wall at about ten times the acoustic velocity of the air column, the response is sensed at the lips in a fraction of a microsecond.

Bells with very thick walls (about 0.125 inch) have natural frequencies that are above the range of the acoustic resonance frequencies, and bell flare resonances are precluded. While that improves the acoustic response slightly, it completely alters the traditional trumpet reaction.

Acoustic Resonance Mode Numbers Required for Trumpet Design	Acoustic Resonance Mode Frequencies Required for Trumpet Design Harmonic Series HZ	Selected Bell Flare Wall Vibration Resonance Mode Frequencies that are closest to Acoustic Resonance Frequencies HZ	Ratio of Acoustic Resonance to Bell Flare Wall Vibration Resonance Frequencies
2	233.082		
3	349.623		

4	466.164		
6	699.246	724	0.966
8	932.328	854	1.092
9	1048.868	1145	0.916
10	1165.409	1170	0.996
12	1398.491	1329	1.052
14	1631.573	1571	1.039
15	1748.114		
16	1864.655	1875	0.994
18	2097.737	2034	1.031
20	2330.819	2352	0.991
21	2447.360	2383	1.027
22	2563.901	2647	0.969
24	2796.983	2734	1.023
26	3030.064	2822	1.074
27	3146.605	3494	0.901
28	3263.146	3494	0.934
30	3496.228	3494	1.001
32	3729.310	3684	1.012

BELL WALL THICKNESS & RESPONSE

The previous equation for cylindrical tubing can be used to provide design guidance regarding the proper bell wall thickness. For a conical bell shape with a radius of 0.2500 at the small end and a radius of 0.6326-inch at 4.0-inches from the rim, the average cylindrical radius is 0.4413-inch. Using the average cylindrical radius and a wall thickness of 0.020-inch in the equation yields a natural frequency of 1,798 Hz. This value is inaccurate because the conical included angle is not very small. Therefore, there is risk that the bell could be excited into resonance by high acoustic frequencies within the playing range. Certainly, a much thinner wall should not be used as it could cause the sound to “break-up” at high dynamic volume.

The natural frequencies at the open end of the bell can be calculated using ANSYS finite element analysis. However, that is not required in view of the data from experiments.

The bell flare wall thickness can be gradually tapered from about 0.019-inch at 4.0-inches from the rim to about 0.014-inch at the rim. That will both improve the vibration response and better match the bell vibration resonance frequencies to those of the acoustic resonances.

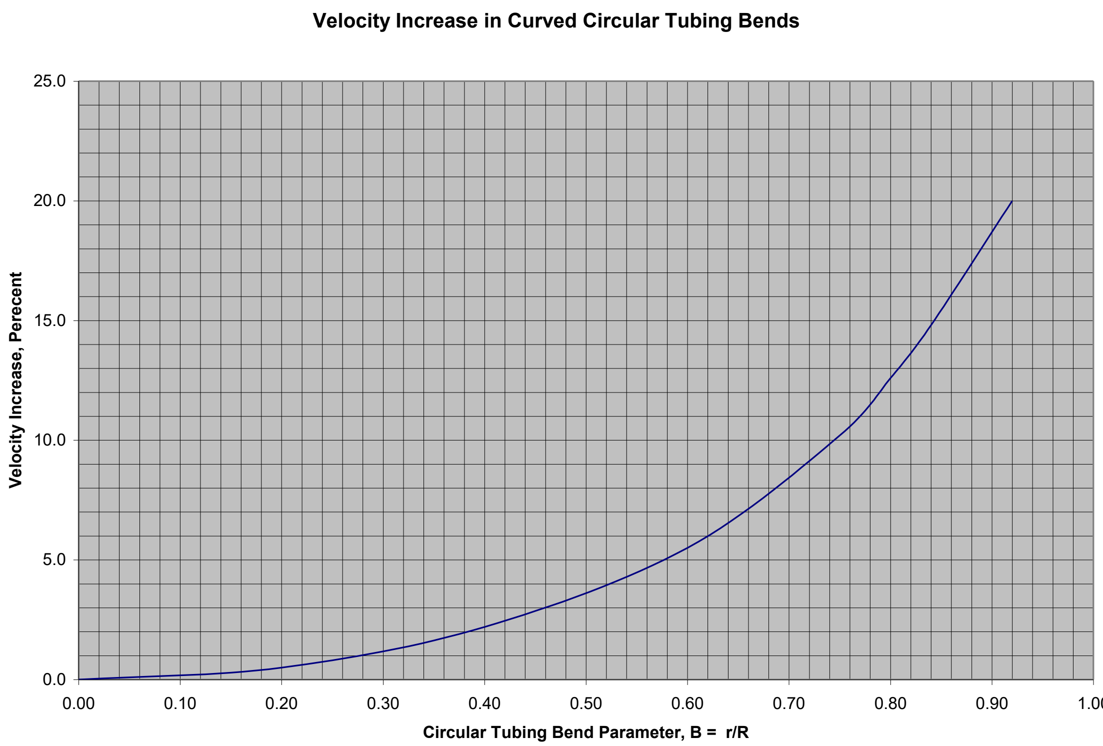
PRESSURE WAVE VELOCITY INCREASE IN TRUMPET BENDS

The trumpet air column has smoothly curved bends to achieve a practical trumpet length. A very good approximation of the bend effective length is the length of the curved centerline. This approximation is very accurate when the bend radius, R, is large in comparison to the tubing radius, r. For smaller radius bends, a careful analysis is required.

Keefe and Benade (1983) developed a mathematical analysis for acoustic effects in circular cross section curved bends. From their analysis, the pressure wave velocity increases within a curved circular pipe. Such wave velocity increases are a function of the Bend parameter, B, defined as the tubing radius, r, divided by the bend radius, R. See figure below.

The pressure wave velocity increases significantly within the bends of the valve slides. For example, the valve slide bend radius, R, is typically about 0.375-inch, and the tubing radius, r, is commonly about 0.230-inch, resulting in a corresponding value of the bend parameter, B = (r/R), of about 0.61. From the figure, this would result in an increase in wave velocity of about 6%. The trumpet maker can readily adjust the length of the valve slide to compensate for such effects within the bends.

The principal dimensions of the tuning slide bend and the bell tail bend are somewhat similar to each other. For a typical full-radius bend, the Bend Parameter, B = (r/R), is 0.160. From the figure shown below, the wave velocity increase in such a bend is only about 0.3 %. Therefore, the full-radius bends of the tuning slide and the bell have an insignificant increase in the wave velocity.



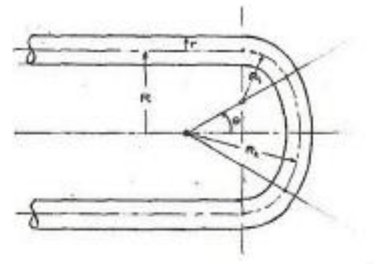
Keefe and Benade's analysis was not rigorous. Later in 1983, they conducted experiments with curved tubing in which the Bend parameter, B, was 0.728. For such a bend, the measured increase in wave velocity was 4.7%, while the theory predicted a 9.4% increase. The measured increase was about one-half that given by theory. While the cause of the discrepancy has not been determined, it is clear that the wave velocity effect is less than given in the figure. Therefore, the wave velocity increase for full radius tuning slide and bell tail bends is even more insignificant.

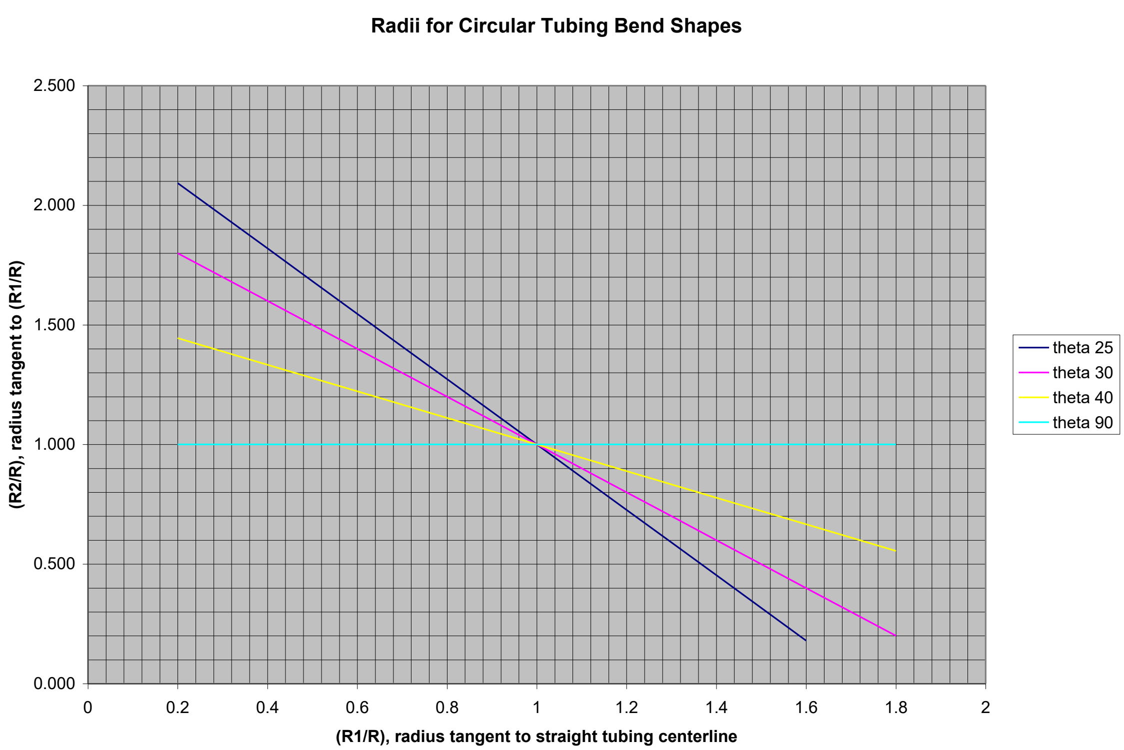
VARIOUS TUNING SLIDE BEND SHAPES

The full-radius bend is very commonly used. Some trumpet makers use a "bent-bow" design and a few use an "ovate" shape. In such shapes, two different radii are used to make the bend. One radius is smaller and one is larger than the value of the full-radius. It is necessary that such shapes be smooth and continuous.

The first radius used must be tangent to the straight tubing centerline, and the second radius used must be tangent to the first radius. The angle, theta, which defines the point of tangency between the two radii, is a design variable. There is a family of such bend shapes, in which the relationships between the two radii are functions of the angle, theta.

A sketch of a "bent-bow" bend, showing the design nomenclature, is presented below. The dimensionless radii for the complete range of both of the aforementioned bend shapes are shown in the following chart. While not rigorous, the velocity increases for such two-radius bends can be estimated. The velocity increase can be taken as about one-half of the values shown in the previous figure.





It has been found that the "bent-bow" tuning slide shape does produce acoustic reflections that affect the apparent response of the instrument. This phenomenon is due to a discontinuity created by a sudden rate of change in the direction of the tubing axis. It is relatively easy to compare the effect of such a "bent-bow" tuning slide vs. a full-radius tuning slide by play testing.

THE BELL TAIL BEND

While some trumpet makers incorporate "bent-bow" and "ovate" bends into the bell tail bend, a full-radius design for the bell tail bend is common. From the preceding data and analysis, no benefit can be expected from bell tail bends of other than a full radius. Additionally, two-radius bends may compromise the straight-axis bell shape acoustic calculations. Unlike the tuning slide bend, the bell stem inside diameter increases over the length of the tail bend. Therefore, the design of tail bend tooling is far simpler when the bell bend follows a full-radius bend rather than a much more complex two-radius bend. For all the above reasons, the bell tail bend should be full-radius.

THE MOUTHPIECE GAP

The mouthpiece gap geometry affects both the acoustics and the fluid mechanics within the gap. While acoustic simulations show that no acoustic effects exist, fluid mechanics considerations show that some very important effects exist. The gap length is therefore determined based upon fluid mechanics considerations.

The free air stream leaving the mouthpiece backbore tends to continue to expand at the backbore exit taper rate for a short distance after leaving the backbore; however, turbulence at the boundary of the free air stream causes the air stream to expand at a gradually increasing rate. Based upon this simple but important phenomenon, gap length considerations are discussed and the free airstream within the gap is illustrated in the following figure.

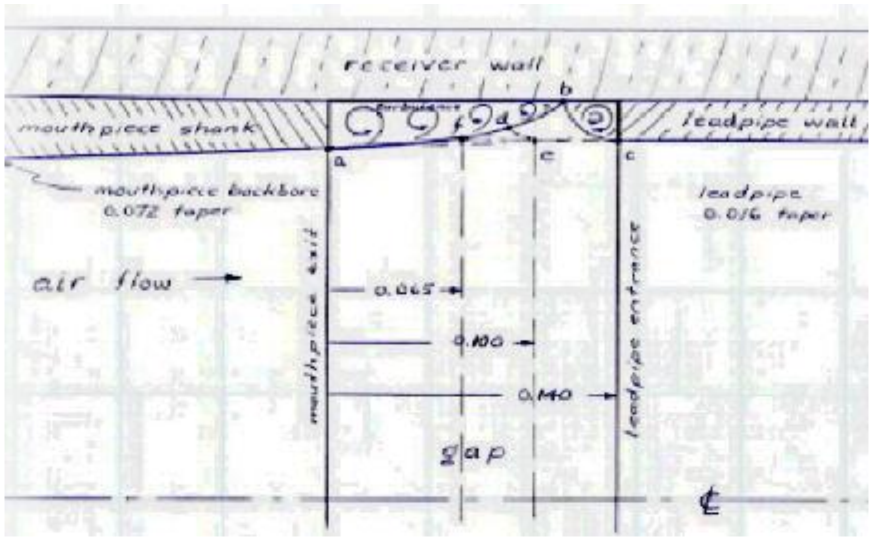
In an existing design, the receiver inside diameter is 0.382-inch, the mouthpiece backbore exit diameter is 0.3366-inch, the leadpipe entrance diameter is 0.345-inch, and the backbore exit diametral taper rate is 0.072.

If the air stream were to continue to expand at the backbore exit taper rate, a distance of 0.117-inch would be required for the airstream to attain the leadpipe entrance diameter. However, the air stream expands at a gradually increasing rate, and the required distance is considerably less than 0.117-inch.

The free airstream expanding at a gradually increasing rate might attain the lead pipe entrance diameter in a distance as small as 0.065-inch. However, there is no known way to calculate such a distance. Further, considering using such a small gap is very risky. For a gap length that is somewhat smaller, the free airstream will "jet" into the open lead pipe and be unattached to the lead pipe wall. This will result in a feeling that "the player cannot fill the horn with air", and the instrument will not "slot" properly. For a gap length that is somewhat larger, the free airstream will ram into the lead pipe end wall. This will result in a feeling that "the horn is extremely stuffy".

A gap length that is free of such undesirable risks is described. The air stream leaves the mouthpiece back bore taper and continues to decelerate at a gradually increasing rate until it reaches the receiver inside diameter. It is estimated that this occurs within an axial distance equal to about five times the mouthpiece exit wall thickness. The air stream subsequently accelerates into the lead pipe entrance. It is estimated that this occurs within an axial distance equal to about one-and-a-half times the lead pipe entrance wall thickness. Based upon these estimates for the example conditions, the required gap would be about 0.140-inch. Such a gap is illustrated as path *abc* in the figure below. For any larger gap, the air would flow along the receiver wall for the added gap length. There is no disadvantage to this, except for a slight added resistance.

While an ideal gap can be determined experimentally by systematically varying the gap, the gap obtained using the above method produces very good results.



BLOW RESISTANCE

An appropriate amount of trumpet blow resistance is essential to matching the instrument to the trumpeter. Many trumpeters are aware of the general effects that the mouthpiece bore diameter, the backbore taper rate, the leadpipe taper rate, the shape of the tuning slide bend, the tubing bore, and the valve port diameter have on blow resistance.

While the input impedance and resonance frequencies are determined entirely by the physics of acoustics, the blow resistance is determined solely by the physics of fluid mechanics. When a trumpet tone is produced, both a steady airflow at low velocity and an oscillating pressure wave, propagated at acoustic velocity, coexist. Those two entirely different regimes apparently simultaneously occur with no interactive effect.

Assuming that the blow resistance is unaffected by acoustic effects, a detailed fluid mechanics "pipe friction" model of the entire trumpet air column can be developed. Such a model facilitates computation of the air column input blow resistance, based upon the same dimensions that are used in the acoustical computations.

The blow resistance is expressed as a dimensionless number, the total head loss divided by the bore velocity head. In such a model, the air is assumed to be incompressible, and the Reynolds Number and the Friction Factor are variables throughout the air column. The well-established effects of tubing wall friction, sudden expansions, sudden contractions, conical shapes, and bends of various dimensionless curvatures are obtained from fluid mechanics textbooks.

MEANS OF TRUMPET TESTING

Trumpets are play-tested by trumpeters; and they are also acoustically tested using techniques to excite the air column resonances. Both means of testing have advantages and disadvantages.

Play testing by professional trumpeters readily reveals how the instrument performs musically. This type of testing can determine many subtle and important qualities of the instrument. However, the trumpeter play tester subconsciously compares the test instrument to the trumpeter's personal trumpet. While such tests are very valuable, they can be subjective and quantitative measurements are not obtained.

The acoustic tests measure the resonance frequencies very accurately and with complete objectivity. It is very important to accurately measure the resonance frequencies, as an excellent instrument should have near-perfect harmonicity. One limitation of such test means is that the trumpet isn't blown. In acoustic tests, the effects of the lips and the small airflow on the resonance frequencies are absent. While the impedance of the player's lips does affect the resonance frequencies, most musical acousticians feel that the effect is rather small. The small airflow is also considered by physicists to have an unimportant effect on resonances.

Neither test method, by itself, is perfect; therefore, using both test methods is preferred. By using both test methods, an increased amount of valuable data is obtained.

TABLE ! ©

Trumpet Chromatic Scale	Equal Percentage Scale Hz	Bb Trumpet Note	Acoustic Resonance Mode	Harmonic Series Hz	Cents Sharp	Cents Flat	Valve Fingering	Resulting Frequency Hz	Cents Sharp
C	3729.31	**Trip C**	**32**	**3729.31**	**0**		0	3729.31	0
B	3520.00						2	3520.00	0
Bb	3322.44		28	3263.146		32	1	3322.44	0
A	3135.96						**1&2**	3155.28	**10**
Ab	2959.96						2&3	2959.96	0
G	2793.83		**24**	**2796.98**	**2**		0	2796.98	2
F#	2637.02						2	2640.00	2
F	2489.02						1	2491.83	2
E	2349.32		20	2330.82		14	**1&2**	2366.46	**12**
Eb	2217.46						2&3	2219.97	2
D	2093.00		**18**	**2097.74**	**4**		0	2097.74	4
C#	1975.53						2	1980.00	4
C	1864.66	**DoubC**	**16**	**1864.66**	**0**		0	1864.66	0
B	1760.00						2	1760.00	0
Bb	1661.22		14	1631.573		32	1	1661.22	0
A	1567.98						**1&2**	1577.64	**10**
Ab	1479.98						2&3	1479.98	0
G	1396.91		**12**	**1398.49**	**2**		0	1398.49	2
F#	1318.51						2	1320.00	2
F	1244.51						1	1245.91	2
E	1174.66		10	1165.41		14	**1&2**	1183.23	**12**
Eb	1108.73						2&3	1109.98	2
D	1046.50		**9**	**1048.87**	**4**		0	1048.87	4
C#	987.767						2	990.000	4
C	932.328	**High C**	**8**	**932.328**	**0**		0	932.328	0
B	880.000						2	880.000	0

Bb	830.609		7	815.787		32	1	830.609	0
A	783.991						**1&2**	788.821	**10**
Ab	739.989						2&3	739.989	0
G	698.456		**6**	**699.246**	**2**		0	699.246	2
F#	659.255						2	660.000	2
F	622.254						1	622.957	2
E	587.330		5	582.705		14	**1&2**	591.616	**12**
Eb	554.365						2&3	554.992	2
D	523.251						**1&3**	528.562	**18**
C#	493.883						**1,2&3**	505.826	**41**
C	466.164	**Mid C**	**4**	**466.164**	**0**		0	466.164	0
B	***440.000***						2	440.000	0
Bb	415.305						1	415.303	0
A	391.995						**1&2**	394.411	**10**
Ab	369.994						2&3	369.994	0
G	349.228		**3**	**349.623**	**2**		0	349.623	2
F#	329.628						2	329.998	2
F	311.127						1	311.475	2
E	293.665						**1&2**	295.808	**12**
Eb	277.183						2&3	277.496	2
D	261.626						**1&3**	264.281	**18**
C#	246.942						**1,2&3**	252.913	**41**
C	233.082	**Low C**	**2**	**233.082**	**0**		0	233.082	0
B	220.000						2	220.000	0
Bb	207.652						1	207.650	0
A	195.998						**1&2**	197.205	**10**
Ab	184.997						2&3	184.997	0
G	174.614						**1&3**	176.187	**16**
F#	164.814						**1,2&3**	168.609	**39**

TWO TRUMPETS USING FILE 32.05 BELL ©

5/16/2018
6/26/2018 revised

For record purposes, the weights and wall thicknesses of components of the 0.460-inch bore Kanstul S/N 5927 trumpet are given below, in pounds and inches. Jennings JT-2 350 precision scale was used to weigh as many parts as feasible. Weights of other parts were calculated from part volumes and the density of yellow brass, based upon Starrett Dial Caliper (± 0.001" resolution) measurements.

Receiver/all braces	0.1400	(apparent weight)
Lead pipe	0.1250	weighed, approximate
Tuning slide	0.1381	weighed
Valve Slides	0.3219	weighed/calculated
Bell	0.4400	weighed, approximate
Valve Block	1.1504	weighed/calculated
Trumpet, Total	2.3154	weighed, as total
GR 64Z* Mouthpiece	0.2361	weighed

The lead pipe, tuning slide, valve slides and bell weigh about 1.165 pounds, about one-half the trumpet total weight. With lightweight valve slides, the total trumpet would weigh 0.0483 pounds less, or 2.2671 pounds. The leadpipe, tuning slide, valve slides and bell would then weigh about 1.1167 pounds, about one-half the trumpet total weight.

The drawn lead pipe wall is 0.019-inch, the inside tubing wall measures 0.019-inch, the outside tubing wall measures 0.021-inch, the specified bell wall thickness is 0.019-inch wall, except that the flare portion of the bell is 0.017-inch, and near to the bell wire the wall is 0.015-inch. As spinning is not precise, the actual thicknesses are likely to vary from specification.

I have two trumpets built on Kanstul valve-sections. As Kanstul confirmed they do not make lightweight valve-sections, they are standard-weight. Trumpet S/N 001 uses File 22.0795 bell, and Kanstul S/N 5927 uses File 30.00 bell. Either trumpet could be used to build a "standard-weight" trumpet with File 32.05 bell.

Because the Kanstul valve section cannot be safely rebuilt with lightweight valve slides, a "lightweight" trumpet with File 32.05 bell could be built using an existing Yamaha valve block (no S/N). Yamaha valve blocks and valve slides are available from on-line sources. The Yamaha valve block is essentially a copy of the Bach design. Yamaha, Kanstul, Blackburn, (and likely Getzen) reverse-engineered the Bach design. The 0.460 bore tuning slide could be made using lightweight tubing and the Bach "square" crook (balled-out to 0.460). The lightweight inside tubing used is 0.460/0.490 (0.015-inch wall) and the outside tubing used is 0.4915/.530 (0.01925-inch wall).

The objective for the "lightweight" trumpet was to obtain improved vibration response, using the same air column design. However, that was later determined to be incorrect. As the thinner tubing does not vibrate, there is no change in response. The response must be improved by reducing the wall thickness of the bell flare. The lightweight trumpet is expected to produce a darker sound at the same dynamic level and a brighter sound at a higher dynamic level.

Kanstul S/N 001 could become the new standard-weight trumpet and Yamaha (assigned S/N 002) could become the new lightweight trumpet. Ron Glynn will measure the wall thickness and weigh all bells, as received, and after polishing.

Both trumpets could be built at the same time and could be play tested by Ron Glynn against a leading professional model, giving me an immediate assessment of the File 32.05 bell. Both would require engraving and plating. To be most comparable to YTR9335NYS, the standard-weight trumpet should be used in the acoustic testing and the professional trumpeter play testing.

TRUMPET CONSTRUCTION ©

Charles A. Macaluso 6/6/2018
Revised 6/26/2018

Early American trumpet makers copied the coveted French Besson trumpets. Trumpet makers have lacked the requisite engineering and acoustic skills to improve the trumpet air column. As a result, the best of earlier designs have continued to be copied for almost a hundred years. While the required criterion of near-perfect harmonicity has been known for at least four decades, an air column wall shape required to satisfy the criterion has remained unknowable. Recently, the required air column wall shape was mathematically determined by Macaluso.

The Macaluso air column wall shape is acoustically ideal. The second derivative of radius is minimized within the mouthpiece and leadpipe, and the entire air column is discontinuity-free. More importantly, the air column has near-perfect harmonicity for all resonance modes to about 11 KHz. This assures both near-perfect intonation and an instrument that is easy to play, with good instrument response, into the highest register. These are the hallmarks of a fine trumpet.

Over the years, trumpet construction varied considerably. While this was done without using well-known principles of mechanical vibrations and fluid mechanics, the wide range of constructions used provided much valuable information. Thus, there is no need for construction innovation. Appropriate trumpet construction can be based upon earlier results.

Trumpet response is important to the player. The trumpet response depends upon both the acoustic response and the vibration response. The best acoustic response is assured by using the acoustically ideal Macaluso air column. As less energy is required for a thinner trumpet wall to vibrate, the vibration response is improved as the bell flare wall thickness is reduced.

Trumpet sound, or timbre, is important to the player. The number of harmonics and their relative amplitude determine the timbre. The player produces a number of harmonics that varies with the playing register and the dynamic playing level. The relative amplitude of the harmonics depends upon the unique physiology of the player's lips and oral cavity. In summary, the timbre depends upon dynamic playing level and the player's unique physiology and playing technique.

Nevertheless, the timbre is affected by the trumpet construction. The internal oscillating pressure wave excites the trumpet wall system. Such system is comprised of the surrounding wall and various non-wall masses (i.e. the valve section, valve caps, mouthpiece receiver, braces, hooks, rings, etc. and mouthpiece). The lowest natural frequency of the trumpet wall system affects the relative amplitude of the harmonics. A high natural frequency value selectively increases the amplitudes of the higher harmonics, thereby brightening the timbre. A low natural frequency value selectively reduces the amplitudes of the higher harmonics, thereby darkening the timbre. While the wall thickness for each component within the air column may vary, the trumpet timbre depends upon an equivalent trumpet wall thickness.

The lowest natural frequency of the wall system is directly proportional to the wall thickness and the value of acoustic velocity of the metal used. However, the total non-wall mass reduces the natural frequency of the wall system considerably. The wall thickness and the metal acoustic velocity can vary over the length of the instrument. The timbre is the collective result of single equivalent values of wall thickness, metal acoustic velocity, and non-wall mass.

As stated earlier, the wall thickness also affects the instrument vibration response. A thinner wall will improve the response, and at the same dynamic playing volume, the timbre will be darkened. However, at a higher dynamic playing volume, the timbre will be brightened.

A range of different metals, primarily copper alloys, are used in trumpet construction. Yellow Brass is the most common alloy used. Leadpipes are made of Rose Brass, Gold Brass, Yellow Brass, and Nickle Silver. Bells are made of Sterling Silver, Rose Brass, Gold Brass, Yellow Brass, and Beryllium Copper. All those metals have different values of the velocity of sound, which depends upon the values of Modulus of Elasticity and density. The timbre is darker for lower values of metal acoustic velocity and brighter for higher values of metal acoustic velocity.

A conventional leadpipe construction is commonly used. However, a longer, reverse-construction leadpipe (RLP) more recently has been used. The RLP is generally considered to be more open-blowing. A larger included-angle, longer leadpipe has uniformly increasing input impedance resonance peak heights. This facilitates increased accuracy in rapid register changes, but is not widely understood or appreciated. Such a leadpipe is also very open blowing. No specific major disadvantages can be attributed to the RLP. Nevertheless, choice of leadpipe design is still largely personal preference.

The tuning slide crook design varies from fully-round to a “square”, or D-shaped, bend. The D-shaped crook, with two sharp bends, is generally felt to be more acoustically responsive. The sharp bend causes a rapid increase in the local acoustic velocity. Such increase at the first of these bends causes a premature reflection, which is sensed by the player as improved acoustic response. The blow resistance of such a crook is slightly higher. A tuning slide with no brace has both quicker vibration response and a slightly brighter timbre.

The trumpet bore size affects the blow of the instrument. Trumpet bore sizes vary considerably. Some European designs have small bores. Around the world, the medium-large (ML) bore of 0.459 or 0.460 has become very common. A few custom makers have used a larger bore within the valves, and several makers advocate use of a varying bore size, a so-called poly-bore. Some powerful high-note players use a very small cup volume mouthpiece with a bore as large as 0.474, and other high-note-players select very open-blowing leadpipes. Those choices are made to reduce the instrument blow resistance to offset the increasing acoustic resistance encountered in the highest registers. Such increasing acoustic resistance is avoided in using the Macaluso air column design.

Based upon the above information and explanations, the following construction was chosen for the standard weight and lightweight Macaluso trumpets:

A 0.460-inch bore throughout
A 12.50-inch long RLP
Yellow Brass throughout
Bach-Copy two-piece valve section
Bach D-shaped Tuning Slide Crook
2 Bach water keys
Minimum bracing
Standard Weight Wall Thickness: Leadpipe 0.019, Tubing 0.019/0.021, Bell 0.019/0.015
Lightweight Wall Thickness: Leadpipe 0.016, Tubing 0.015/0.01925, Bell 0.016/0.015

TRUMPET BUILDER PLAY TEST RESULTS ©

6/26/2018

“My name is Ron Glynn. I earned a Bachelor Degree in trumpet performance from Western Illinois University and a Master Degree in the same discipline from Northwestern University. At Northwestern, I studied under Vincent Cichowicz, second trumpet in the world famous Chicago Symphony Orchestra (CSO) brass section from 1952 to 1974. ”

“I began playing at age 6 and am currently 49 years of age. My background in playing trumpet includes orchestral and solo playing, and an extensive history of playing lead in big bands and jazz groups.”

“In 1997, I took a job working at Schilke Music Products. For over 17 years I was trained and worked in every aspect of trumpet manufacturing, from design work to the implementation of new manufacturing processes. During that time, I personally made over 20,000 trumpet bells.”

“About three years ago, I started my own shop doing brass instrument repairs and building trumpets. I was recently commissioned by Mr. Macaluso to produce the tail bend of a trumpet bell of new acoustic design, and to install the new bell on an existing S/N 001 trumpet. After doing the work, I did a complete test of the instrument.”

"In play testing the Macaluso S/N 001 Bb trumpet, I began with arpeggios and lyrical passages. For direct comparison, I used a 1966 standard weight medium large bore Bach Stradivarius Model 37, which I have owned and played for 25 years."

"Simply put, the Macaluso trumpet has a middle register immediacy of response that the Bach never had. Tonal pitch centers are clearer and, as a result, are far more secure. Dynamic playing can normally expose a restrictive instrument, showing its inability to be resonant at soft volume levels as well as a tendency to be harsh and bright at higher dynamic volume levels. The Macaluso trumpet was easy to play at both ends of that spectrum. Soft dynamics were completely secure and louder passages were full and bold. Playing from a pedal C to middle C, all of the chromatic pitch centers are accurate, clear and secure. From middle C to high C, the trumpet remains extremely open, with almost no restriction. Normally, this is where every other Bb trumpet on the market begins to fight against the player because of poor harmonicity. Typically, as the player ascends, the trumpet pushes back until the player finally succumbs. In this regard, the Macaluso trumpet does not act like any other Bb trumpet on the market. As you go above F above High C, the trumpet just sings. Pushing on to Double C, it remains open and secure. The sound is very pure, clear, and full of harmonics. I have never play tested a Bb that played like this instrument."

"Because of the acoustic design work Mr. Macaluso has undertaken, the full potential of a Bb piston style trumpet has been realized. Simply put, the superior acoustic design of the Macaluso trumpet makes it much easier to play, and more accurate, than any other trumpet that I have ever played. It simply performed at a much higher level in every style and setting."