Blowing pressure, power, and spectrum in trumpet playing

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Measurements of sound output as a function of blowing pressure are reported for a group of experienced trumpet players. The study identifies several common features, namely (1) a threshold blowing pressure approximately proportional to the frequency of the note being played, (2) an extended region in which the sound output rises by about 15 dB for each doubling of blowing pressure, and (3) a saturation region in which sound output rises by only about 3 dB for a doubling of blowing pressure. Some players are able to blow with maximum pressures as high as 25 kPa, which is significantly greater than normal systolic blood pressure. A simple theory is presented that provides a physical explanation for the acoustical behavior, but a detailed treatment requires solution of the nonlinear coupled equations both for the lip-valve mechanism and for nonlinear wave propagation in the instrument tube. Frequency analysis of the sound shows a basic spectral envelope determined by the resonance properties of the mouthpiece cup and the radiation behavior of the bell, supplemented by an extension to increasingly high frequencies as the blowing pressure is increased. This high-frequency behavior can be attributed to nonlinear wavefront steepening during sound propagation along the cylindrical bore of the instrument.
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INTRODUCTION

Blowing technique is a vital part of the playing of any wind instrument, and it is therefore rather surprising that the study of physical parameters such as blowing pressure has attracted so little attention. The foundations of such a study for many wind instruments were laid as long ago as 1965 by Bouhuys,[1] but the only subsequent detailed measurements of which we are aware are those on the flute by Fletcher[2] and on woodwind reed instruments by Fuks and Sundberg.[3] The only papers on trumpet performance technique of which we are aware are those of Luce and Clark,[4] who examined spectral properties of the sound, and of Bertsch,[5] who studied the sounds produced by different trumpet players but did not correlate these with blowing pressure. There have, of course, been many papers on various more mechanical aspects of sound production in brass instruments that will be referred to later.

Bouhuys' results for the trumpet are summarized as follows. The blowing pressure measured in the mouth ranged from about 30 to 100 mm Hg (4 to 13 kPa) for high notes played *pp* and *ff*, respectively. Corresponding figures for low notes are omitted from the graph. The acoustic power output ranged from about 20 μW to 1 mW for low notes and from 200 μW to 30 mW for high notes. The overall acoustic efficiency was 0.01% to 0.03% for low notes and 0.03% to 1% for high notes, the higher efficiencies applying to fortissimo playing. In each case only one note and two dynamic levels were measured, and the radiated sound power was estimated from on-axis measurements in a normal room.

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It is the purpose of the present paper to report more extensive measurements of blowing technique for a group of trumpet players, with detailed studies on one professional player, and to interpret these findings acoustically.

I. MEASUREMENTS

Measurements were made on three players: a professional orchestral trumpeter (GC), and two experienced amateur players (NH and KB). In the measurements to be reported, they all played standard B♭ trumpets, but some measurements were also made of GC playing a B♭ cornet, and a piccolo trumpet in A. A catheter tube, about 2 mm in external diameter, was inserted in one corner of the player's mouth and the blowing pressure was measured on one of two bourdon gauges that had been calibrated against a water manometer. Acoustic measurements were made at a distance of 1–1.5 m from the horn mouth on the axis of the instrument and later corrected to the equivalent level at 1 m distance. The A-weighted sound pressure level was noted and the sound itself recorded for later analysis. In the case of player GC, the measurements were made in an anechoic chamber, while for the other two players a normally furnished living room was used. Because the frequency response of the microphones used fell off above 16 kHz, the reported measurements extend only to this frequency.

The playing tests consisted of a series of steady notes of given pitch played with increasing loudness from pianissimo up to the fortissimo limit for the particular player. The note pitches covered the whole compass of each instrument in an appropriately transposed CFCF . . . sequence, or something close to that.

Figure 1 summarizes the measured results for professional GC playing a standard B♭ trumpet. Several points are

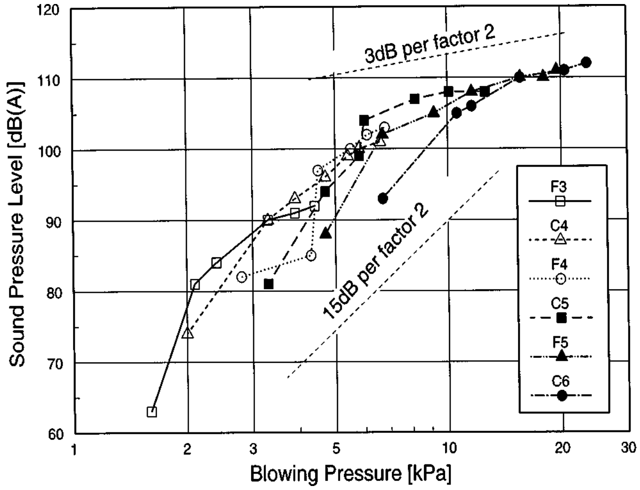

FIG. 1. Equivalent SPL at 1 m produced by player GC on a standard B♭ trumpet in an anechoic chamber, as a function of blowing pressure.

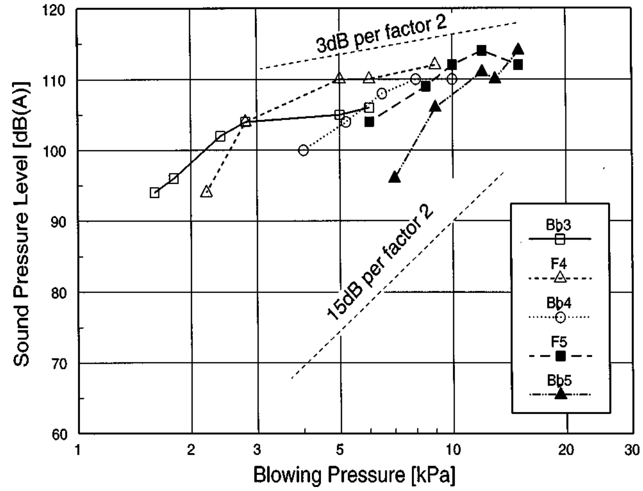

FIG. 2. Equivalent SPL at 1 m produced by player NH on a standard B♭ trumpet, as a function of blowing pressure.

worthy of immediate note. The first is that, in agreement with Bouhuys and the common knowledge of players, there is a threshold pressure required for the sounding of any note, and this threshold increases steadily with the pitch of the note. Second, there is an upper limit to the pressure that can be used for any note, and again this limit increases as we ascend the scale. It is noteworthy that the highest blowing pressure used by this particular player, who is of solid physique, is about 25 kPa. This pressure is much higher than the normal systolic (maximum) blood pressure, which is typically only about 18 kPa, so that it is small wonder that the player reported physiological difficulties when required to play at this level! To appreciate the magnitude of this pressure excess, the graph should be replotted with blowing pressure on a linear scale. Physiological measurements by Fiz *et al.*[6] on the maximum expiratory pressure that can be achieved by trumpet players—not while playing the trumpet, or indeed while actually expelling air—yielded a value of 23±5 Pa, in confirmation of the general level of this result, while they found that similarly fit young men who did not play any brass instrument were able to achieve expiratory pressures of only 19±1 Pa. Presumably muscle training accounts for this difference.

Figures 2 and 3 show similar measurements for players NH and KB. If the two figures are superimposed, then they roughly replicate the measurements in Fig. 1, but player NH, who had a stocky physique similar to that of GC, used only the louder part of the range, while KB, who was much slighter of build and had been criticized by his teacher for not playing vigorously enough, used only the quieter part. The maximum blowing pressure used by KB was only about 7 kPa while NH used pressures up to about 15 kPa.

The professional player GC thus had a much greater range of dynamics and employed a much greater blowing-pressure range than either of the other players, a conclusion that is perhaps not surprising. The measured sound pressure levels should not be compared between players more closely than ±3 dB, because the acoustic environments were somewhat different, but the maximum A-weighted level of about 110 dB for high notes is in good agreement with the maximum measured by Bertsch,[5] as also is the dynamic range.

Figure 4 shows the threshold pressure required by each of the three players to produce notes of various pitches. In all cases, the threshold pressure is very nearly proportional to the frequency of the note being played, but there is a range of about a factor of 2 in the slope of this characteristic, with the professional player GC having threshold pressures within the range spanned by the other two players.

During the course of the study, similar measurements were made of the playing technique of GC on a B♭ cornet and a piccolo trumpet in A. In each case the blowing pressures and sound pressure levels were very similar to those measured for the same notes on the trumpet, with the threshold pressures for the highest notes on the A trumpet appropriately extrapolated upwards.

II. SPECTRAL ANALYSIS

To supplement the measurement of sound pressure level, a recording was made, at a distance of about 1.5 m on the instrument axis, of the sound produced by professional player GC for each note. It is well known that the upper

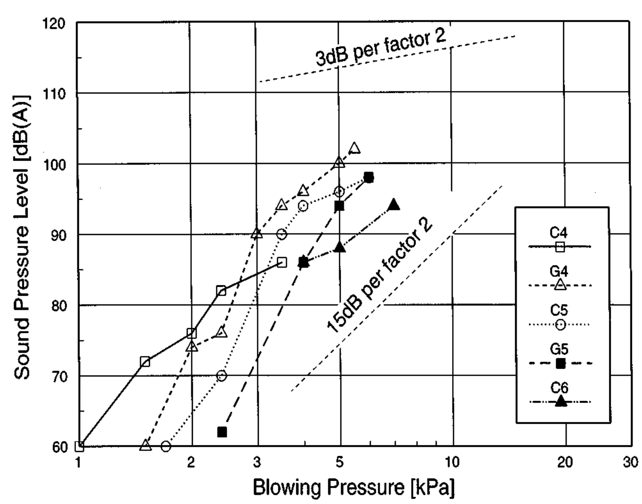

FIG. 3. Equivalent SPL at 1 m produced by player KB on a standard B♭ trumpet, as a function of blowing pressure.

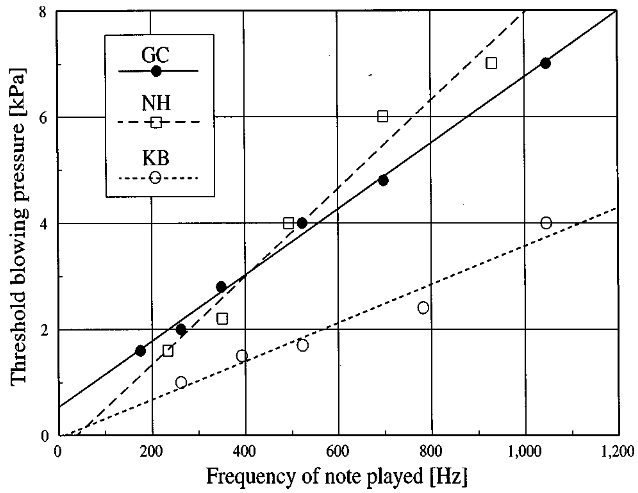

FIG. 4. Threshold blowing pressure used by players GC, NH, and KB to produce notes of various pitches. The sequence of notes played by each player is not exactly the same.

partials of the trumpet sound increase in level relative to the fundamental at high loudness levels, giving incisive brilliance to trumpets in the orchestra. The object here was to investigate this change in timbre over the whole range of playing levels.

Investigations of the envelope of the trumpet spectrum by Luce and Clark[4] characterized it as consisting of two frequency regions. Below the radiation cutoff of the bell, typically about 1000 Hz, the radiated power rose slowly with frequency, typically at 2 to 4 dB/octave, while above cutoff the envelope fell at 15 to 25 dB/octave. They found that the slope below cutoff increased and the slope above cutoff decreased as the intensity level was increased. These measurements apply, not to individual notes, but rather to the average spectrum over the entire instrument.

The present measurements broadly confirm these results, but introduce new detail because they relate to individual notes rather than to the overall spectral envelope. Figure 5

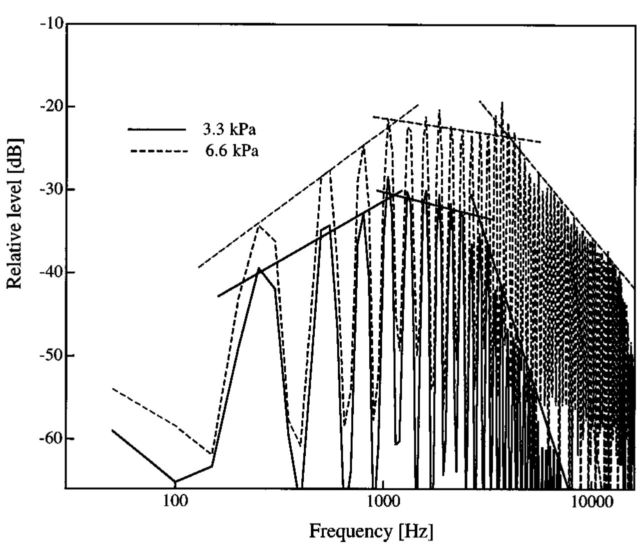

FIG. 5. Spectrum of the note C4 played softly and loudly on a B♭ trumpet. The three slope regions and their transitions are clearly evident, as is the shift with playing level.

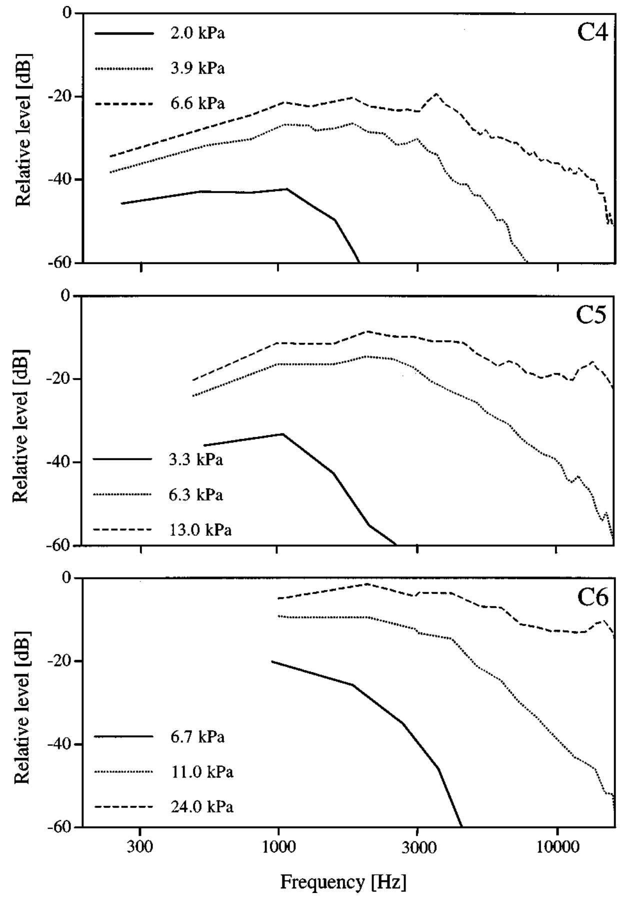

FIG. 6. Spectral development of the noted C_4, C_5, and C_6 as functions of blowing pressure, as played on a B♭ trumpet by GC.

shows typical acoustic spectra for the low note C_4 played softly and loudly on a B♭ trumpet. It is clearly tempting to characterize these spectra in terms of three slopes: a rise of about 6 dB/octave below about 1000 Hz, a nearly constant slope from 1000 Hz to an upper transition at 2–3 kHz which increases with dynamic level, and an upper section with slope about −30 dB/octave at low levels and only about −10 dB/octave at the higher level shown. It is more realistic, however, to examine the spectral envelopes for a wide range of notes and dynamic levels, as shown in Fig. 6. This makes it clear that it is difficult to assign these slopes in an unambiguous manner. What does seem clear, however, is that there is a basic low-level spectral envelope with a characteristic that rises towards a maximum near 1000 Hz and then declines at higher frequencies, as shown by the full curves. On top of this is some other mechanism that extends the envelope to increasingly higher frequencies as the dynamic level is increased. We see below that there is a simple theoretical justification for this interpretation.

III. DESCRIPTIVE THEORY

The sound generation mechanism in brass instruments depends upon the motion of the player's lips, which constitute a pressure-controlled valve. The actual behavior of the lips is certainly complex, for they consist of soft tissue that can support various types of wavelike oscillatory behavior,[7] rather as can the human vocal folds. For our present purposes, however, such detail is not required, and we can use a simple mass-and-spring model. The operation of such simplified valves has been discussed in detail in several publications—for a detailed exposition and list of references the reader is referred to the book by Fletcher and Rossing.[8] The particular case of brass-players' lips has been investigated by Martin,[9] by Elliott and Bowsher,[10] by Yoshikawa,[11] by Adachi and Sato,[12] and by Copley and Strong.[13]

The essence of this mechanism is that the player's lips are driven open and closed by the oscillating sound pressure in the instrument mouthpiece. Details depend upon whether the valve is of the "outward-swinging door" $(+,-)$ or "sliding door" $(+,+)$ type, or something in between.[11–15] Unlike the "inward-swinging door" $(-,+)$ reed valves in woodwind instruments, a brass-player's lips can act as an acoustic generator only within a narrow frequency band quite close to their natural mechanical resonance frequency.[14] This resonance frequency is determined by their vibrating mass and their muscle tension. There is a threshold blowing pressure necessary to initiate the lip vibration that is determined by the lip tension (and is thus related to the lip vibration frequency) and by the acoustic impedance of the instrument and of the player's mouth cavity.[14]

We can put together a simple theory to describe the operation of this lip-valve generator. Suppose that $p_0(f)$ is the threshold gauge pressure in the mouth for excitation of the lip valve when producing a note of frequency f. If it is assumed that the lips are initially held closed, then to a first approximation this pressure will be that which is needed to force the lips open against the lip tension force T, and so will be proportional to T. If the vibrating mass m of the lips were independent of their tension, then their resonant frequency f would be proportional to $(T/m)^{1/2}$, so that we should expect $p_0(f)$ to be proportional to f^2. The structure of the soft tissue in the lips, however, is such that their vibrating mass m decreases markedly with increasing muscular tension. The measurements of Elliott and Bowsher[10] suggest that $m \propto 1/T$, so that it is a better approximation to write

$$p_0(f) = Kf, \tag{1}$$

where K is a constant. This expression agrees well with the experimental data in Fig. 4, which gives a value of about 7 Pa/Hz for K in the case of player GC, 8 Pa/Hz for NH, and 4 Pa/Hz for KB.

Once the lips are forced open by a blowing pressure p greater than p_0, they oscillate in resonance with the instrument horn, because the skilled player has chosen the tension to match the note he wishes to play. The lip vibration is approximately sinusoidal, because the frequency is near resonance, and the vibration amplitude is about equal to the equilibrium lip opening, so that the lips just close once in each cycle.[9] It is thus a reasonable assumption to write the linear opening x of the lips as

$$x = A(p - p_0)(1 + \cos 2\pi f t), \tag{2}$$

where p is the blowing pressure in the mouth and A is another constant, the magnitude of which is inversely proportional to lip tension, and thus to the frequency of the note being played. A is typically about $10^{-7}\ \mathrm{m\,Pa^{-1}}$ for a high note, so that the lip opening would reach 1 mm for a blowing pressure 10 kPa above p_0 if it behaved linearly. It should be recognized, however, that the relation (2) cannot hold for very high pressures. Instead, the lip opening x will saturate, because of tissue nonlinearity and also the constraining effect of the mouthpiece, at a value not much more than 1 mm. This can be added as an upper limit to the relation (2).

Equation (2) actually conceals a great deal, for it does not show how the oscillating mouthpiece pressure actually leads to regeneration and thus to vibration of the lips. For this detail, the reader is referred to one of the more complete treatments of brass instruments.[8,10] In brief, however, the oscillating mouthpiece pressure is the main driver of lip motion, and the sounding frequency may be either a little above or below both the lip resonance and the horn resonance, depending upon the geometry of lip motion. For our present purposes, consideration of these details is unnecessary.

The lip opening is typically elliptical, but the axial ratio decreases as the lip opening increases. It is not feasible to model this exactly, but an interpolation is adequate. If the axial ratio of the ellipse remained constant, then the opening area S would vary as x^2, while if the width of the opening remained constant, then S would be simply proportional to x. It is therefore a reasonable approximation to take the area of the opening to be

$$S \approx C x^{3/2}, \tag{3}$$

where C is a constant, the magnitude of which can be estimated to be about $0.05\ \mathrm{m}^{1/2}$ for typical lip-opening shapes.

At any instant, the quasi-static Bernoulli flow through the lips is then

$$U = (2/\rho)^{1/2}(p - p_1)^{1/2} S = B(p - p_1)^{1/2} x^{3/2}, \tag{4}$$

where p_1 is the back-pressure in the instrument mouthpiece, and B is another constant, of magnitude about $0.06\ \mathrm{m^2\ kg^{-1}}$, as can be seen from (2) and (3). This back-pressure can be evaluated from the fact that the instrument operates at a resonance, so that its input impedance is nearly purely resistive and has a magnitude R that is typically of order $10^8\ \mathrm{Pa\ m^{-3}\ s}$, allowing a bore diameter of about 8 mm and an effective Q-value of around 10 for the resonances. We consider later a refinement in which the magnitude of R varies with frequency. In any case, the back-pressure is $p_1 = RU$. Substituting this in (4), and squaring, leads to the quadratic equation

$$U^2 + B^2 R x^3 U - B^2 p x^3 = 0, \tag{5}$$

which has the solution

$$U = \frac{B^2 R x^3}{2}\left[\left(1 + \frac{4p}{B^2 R^2 x^3}\right)^{1/2} - 1\right]. \tag{6}$$

A. Power and efficiency

Equation (6) can be solved to find the component $\tilde{U}(nf)$ of the flow at the frequency nf of the nth harmonic by substituting (2) for x, performing a Fourier transform numeri-

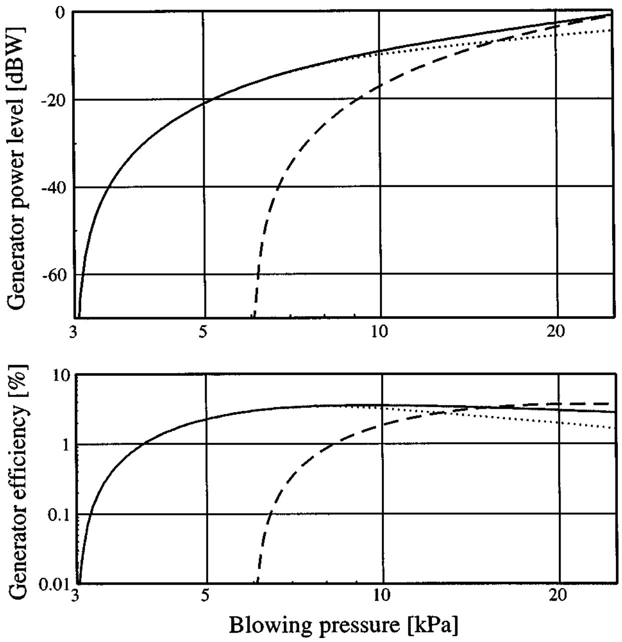

FIG. 7. Calculated acoustic power (in decibels relative to 1 W) produced by the lip generator, and the overall pneumatic efficiency of this generator, both as functions of blowing pressure. Two cases are plotted, corresponding to two notes an octave apart. In the case of the lower note, the dotted curve shows the behavior if the lip opening is limited to 1 mm.

cally, and retaining just the term at this frequency. The acoustic power supplied by the generator to the instrument is then

$$\Pi = \frac{1}{2} R \sum_n \tilde{U}(nf)^2. \tag{7}$$

Figure 7 shows the result of two such calculations for notes an octave apart, 250 and 500 Hz, using the parameter values given in the text and assuming $K = 7$ Pa/Hz in (1), as for player GC. Quantitative details of this calculation should not be given much attention, because the parameters involved were only roughly estimated and only terms up to $n = 3$ were included in the summation, but the overall behavior is significant. The acoustic power supplied by the lip generator rises sharply from zero as the blowing pressure exceeds the threshold value p_0, and settles down to a slope of about 5 to 15 dB per doubling of blowing pressure. If the lip aperture is limited by nonlinearity, however, then the characteristic turns over to a smaller slope at high blowing pressures as shown by the dotted portion of the curve for the lower note. For the higher note, the lip displacement reaches this limit only at about 20 kPa. These curves are individually very similar to the measured curves for individual notes in Fig. 1, though the quantitative agreement is not particularly good. The maximum calculated generator power is about 1 W at a blowing pressure of 25 kPa for no lip motion limitation, and about 0.3 W if the opening is limited to 1 mm. No upper limit to the blowing pressure appears in the case of the lower of the two notes.

Actually the consideration of terms up to only $n = 3$ in (7) is an adequate approximation, because we are dealing with the acoustic power supplied by the lip generator to the mouthpiece, not with the radiated sound. As discussed in the next section, the relative levels of upper harmonics in the mouthpiece flow, and thus in the mouthpiece pressure, are small compared to their relative levels in the radiated sound.

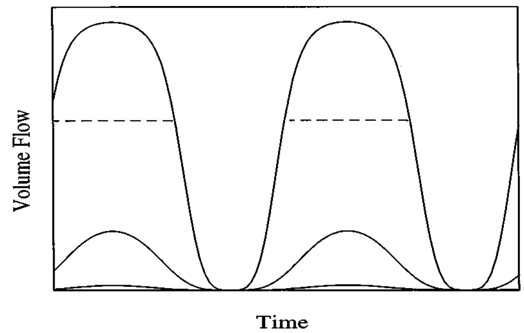

FIG. 8. Calculated lip flow waveforms for a trumpet at low, medium, and high playing levels. The broken curve shows the behavior if the lip opening is limited to 1 mm. The waveforms of the mouthpiece pressure are identical under the assumptions of the calculation.

The quantity plotted in Fig. 7 is not, as we have noted, the radiated acoustic power, but rather the acoustic power produced by the lip generator. Much of this power is dissipated in viscous and thermal losses to the walls of the instrument, and typically less than 10% is radiated as sound. The radiation efficiency itself behaves like the radiation resistance at the open bell of the instrument, and so rises at 6 dB/octave up to the radiation cutoff frequency, which is typically about 1000 Hz for a trumpet, above which it remains constant. We discuss the development of the radiated spectrum in the next section, but for the present we accept that the calculated maximum generator power of 1 W for high notes is therefore expected to result in only about 100 mW of acoustic output power. The measurements in Fig. 1 show a maximum sound pressure level of 110 dB at 1 m, which would correspond to about 1 W of radiated power from an isotropic radiator, since the A-weighting has little effect on total power measured over the frequency range of the trumpet. The trumpet radiation pattern is, however, far from uniform, so that the total radiated power is probably not much more than 100 mW. For lower notes, the transfer efficiency to radiation will be even smaller and, in particular, the lower-frequency full curve of Fig. 8 should be depressed by 6 dB relative to the higher-frequency curve because of the frequency dependence of the radiation resistance. The calculations are thus in better agreement with experiment than might have been expected from their approximate nature.

We might note the implications of this analysis for total acoustic efficiency, as measured by Bouhuys.[1] The total input pneumatic power is approximately $\Pi_0 = pU_0$, where U_0 is the zero-frequency flow component in the Fourier transform calculation above and we have neglected oscillations in mouth pressure. The generator efficiency is then simply Π/Π_0. This efficiency is also plotted in Fig. 7, and ranges from about 0.1% for very soft playing up to about 3% for loud playing, though this efficiency decreases slightly if the lip aperture is limited. Reducing these figures by a factor of about 10 for high notes and as much as 100 for low notes to convert them to radiated acoustic power gives overall efficiencies in remarkably good agreement with those measured by Bouhuys.[1]

B. Spectrum

Solution of Eq. (6) for the flow through the lip valve shows that it has the form in Fig. 8. Since we have assumed a constant value for the input resistance R at the harmonic resonance peaks, the mouthpiece pressure has the same form. For very soft playing the waveform is reasonably sinusoidal, but at higher levels it has a markedly distorted shape, with a plateau for large lip opening, when the flow is limited by the resonant horn resistance and the consequent mouthpiece back-pressure, and a rather sharp decrease to zero as the lips close. This calculation is in good qualitative agreement with the mouthpiece pressure measurements of Elliott and Bowsher.[10]

A flow with this shape has a spectrum that is nearly constant up to a frequency about n times that of the fundamental, where n is the mark/space ratio of the waveform when it is approximated by a rectangular wave. This conclusion, however, derives from the unduly simplified assumption that the resistive part R of the input impedance is the same at all the low resonances of the instrument. For a real trumpet this is not so, for the Helmholtz-type resonance of the volume of the mouthpiece cup, vented through the constricted back-bore and loaded by the characteristic impedance of the instrument bore, produces a resonant envelope to the input impedance, as investigated by Benade.[16] This leads to an envelope for R that rises to a broad peak with a Q value around 5, typically at 500–1000 Hz, and then decreases, and we should expect to find evidence of this in the spectrum. It is not difficult in principle to substitute such a frequency variation for R back into Eqs. (5)–(7), but we shall not bother to do this in detail. It suffices to note that such a procedure would certainly modify the spectrum of the power supplied by the lip-valve generator to reflect a similar mouthpiece resonance. This then explains the common envelope feature seen in all the low-level curves of Fig. 6.

We must now seek to explain the origin of the increased level and apparent actual power gain in the high-frequency components observed in loud playing. That there is indeed a discrepancy between the spectrum measured in the mouthpiece cup and that of the radiated sound is well known, and part of the explanation lies with the radiation behavior of the instrument horn. This is not entirely simple, as discussed by Benade and Jansson,[17] but the general conclusion is that there is a cut-off frequency, around 1 kHz, below which the radiated sound level rises at 6 dB/octave relative to the internal sound pressure, and above which the relation is flat. These considerations, together with the mouthpiece resonance, have been built into a generalized linear model for the transfer function between mouthpiece pressure and radiated sound by Elliott *et al.*[18] They conclude that, above the radiation cutoff, there is little if any power loss, at least for small signal levels where the linear approximation is valid. While this consideration is clearly important in determining the balance between low-frequency and high-frequency components of the radiated sound, it fails to explain the apparent power gain at high frequencies observed in loud playing.

This high-frequency discrepancy in the spectrum has been investigated by Beauchamp.[19] He reported that there is indeed a marked excess in the level of high-frequency components in the radiated sound, particularly above the radiation cutoff frequency, and that this level varies greatly with playing conditions, often appearing as an actual power gain. The explanation of this behavior has been given by Hirschberg *et al.*[20] who showed that it arises from nonlinear acoustic propagation behavior, particularly in the long cylindrical part of the instrument bore. Such nonlinear propagation behavior has been discussed in detail by Beyer,[21] but a brief semiquantitative discussion will be adequate here.

As we have already seen, the mouthpiece pressure p_0 rises each cycle to nearly the blowing pressure in the player's mouth, and thus perhaps as high as 25 kPa or about 180 dB relative to the normal reference level. While the pressure in the main bore is probably lower than this by a factor of at least 3, the level is sufficiently high that the propagation behavior is significantly nonlinear. This can be seen from an examination of a wave of even 2 kPa amplitude, in which the peak acoustic particle velocity is about 5 $\mathrm{m\,s^{-1}}$. Since the cylindrical part of the bore is around 1 m long, this leads to a convective transit-time gain of perhaps 0.05 ms for the high-frequency components in the compressive part of the propagating wave. The result is a steepening of the leading edge of this wave that increases as the pressure amplitude increases. In extreme cases a shock wave may even develop. Adiabatic temperature rise in the wave enhances the effect.

The result of this nonlinear propagation behavior is a transfer of energy from the low-frequency components of the mouthpiece waveform to higher harmonics, the extent of this transfer increasing as the blowing pressure is increased. Because of the initial rise of radiation resistance below cutoff, this transfer increases the radiated sound energy as well as providing an apparent power gain at high frequencies. This leads to an even greater increase in the subjectively perceived loudness, because the wider sound spectrum has less auditory masking, as discussed by Plomp.[22]

While we shall not attempt to investigate these phenomena in any detail in the present paper, it is possible to draw some semiquantitative conclusions from the experimental data. Referring to Fig. 6, we see that, while fitting straight lines as in Fig. 5 is not generally convincing, it is possible to describe the high-frequency extent of each curve by giving the frequency above which the harmonics are more than 20 dB below the spectral peak. This information is plotted in Fig. 9. The highest frequency measurements are limited by the frequency response of the microphone, and points shown as 16 kHz may well be higher. These results show that the high-frequency extension of the spectrum, and by implication wavefront steepening, increases about linearly with blowing pressure, which is what we should expect from the discussion in the previous paragraphs. For a given blowing pressure, the effects of wavefront steepening are less pronounced for higher notes.

It is not difficult to see the general reasons for this behavior, if we make the assumptions that extension of the spectrum above the frequency determined by the mouthpiece resonance and the radiation cutoff, namely about 1000 Hz, is caused almost entirely by nonlinear propagation effects, and that the magnitude of these nonlinear effects is proportional to the pressure amplitude in the propagating wave. Both

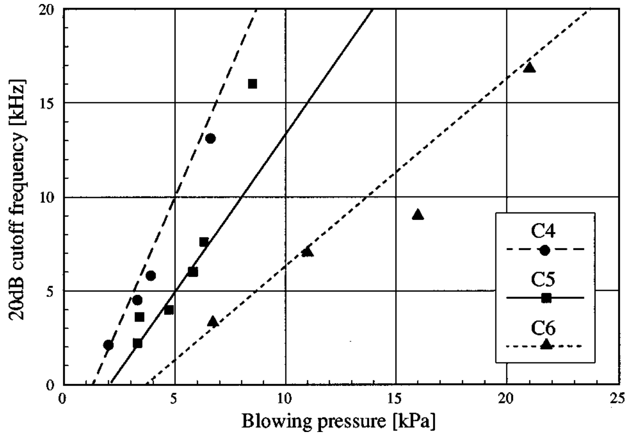

FIG. 9. Frequency at which the spectral envelope falls 20 dB below its peak value, as a function of blowing pressure, for three notes played on a B♭ trumpet. The lines have been drawn according to the prescription discussed in the text.

these assumptions are reasonable in terms of the discussion above, but require detailed justification.

Since the pressure in the instrument bore is proportional to the pressure $p_1 = RU$ in the mouthpiece, it is necessary first to examine the flow U through the lips, as given by (6), with the lip opening x given by (2). It is not possible to derive simply an expression for the extension of the spectrum as a function of blowing pressure for a given note pitch, but we seek rather to see how this extension, whatever it is, scales with pitch and blowing pressure. Suppose therefore that the flow $U(f,p)$ refers to a note of fundamental frequency f played with blowing pressure p. We seek to know the flow $U(\alpha f, \beta p)$ for a note of fundamental frequency αf played with blowing pressure βp. To increase the lip vibration frequency by a factor α requires an increase in lip tension and a decrease in lip moving mass by the same factor α, as discussed in relation to Eq. (1). This increases the threshold pressure p_0 by a factor α and changes the constant A in (2), and thus the value of x at a given pressure, by a factor α^{-1}. Similarly, to a reasonable approximation, increase in the blowing pressure by a factor β increases x by a factor β if the threshold is ignored.

Returning to (6), we find that the expression $4p/B^2R^2x^3$ is typically of order unity for $x \approx 1$ mm, which makes approximation difficult. If x is a good deal larger than this, then $U \approx p/R$, while if x is smaller, then $U \approx Bp^{1/2}x^{3/2}$. Adopting the latter expression and using the argument in the previous paragraph leads to the result

$$U(\alpha f, \beta p) \approx \beta^2 \alpha^{-3/2} U(f,p). \tag{8}$$

This means that, if the note frequency is raised by a factor α and the blowing pressure by a factor $\beta = \alpha^{3/4}$, then the flow, and hence the pressure and the spectral result, are all unchanged. This argument ignores the niceties of threshold pressure, and so holds only well above threshold. The upshot of this simplified argument is to suggest that, whatever the harmonic development curve for a note of sounding frequency f played with pressure p, this can be transformed to the corresponding curve for sounding frequency αf by increasing all the plotted blowing pressures by a factor $\alpha^{3/4}$. The exact value of the exponent in this prescription depends upon the behavior of lip opening shape embodied in Eq. (3). This may vary a little from player to player, but the extreme values are 0.5 and 1.

Referring to Fig. 9, we have a reference curve for the lowest frequency f that is a straight line not passing through the origin. The approximate relation given above then suggests that the curve for frequency $2f$ can be derived by simply multiplying all the pressures in the reference curve by $2^{3/4} \approx 1.7$, and the curve for frequency $4f$ by multiplying all the pressures in the reference curve by $4^{3/4} \approx 2.8$. The lines in the figure have been drawn to this prescription, and fit the experimental data quite well, which gives some measure of confirmation to the assumptions. For much larger blowing pressures and lip openings, we must turn to the result $U \approx p/R$, which suggests that all curves tend to the same asymptote in the limit of high pressures. It does not appear that this asymptote has been reached in the experimental data.

It must be emphasized that this argument is lacking in rigor and serves simply to provide a possible basis for explanation for the observed behavior. A proper analysis clearly requires explicit consideration of the pressure waveform and frequency and quantitative treatment of the nonlinear propagation.

IV. CONCLUSIONS

This experimental study has established, in a general way, the blowing technique used by typical trumpet players. In particular, we recognize the following features:

(1) a threshold blowing pressure for sounding of each note, this pressure rising linearly with the frequency of the note to be played;

(2) a rapid rise of radiated sound output for blowing pressures above threshold, settling down to a regime in which sound output power rises about 15 dB for each doubling of blowing pressure, the sound power for a given blowing pressure being nearly independent of the pitch of the note being played;

(3) a saturation regime, in which the sound output power rises only slowly with increasing blowing pressure, a doubling of blowing pressure increasing the sound level by only about 3 dB.

While this represents the general pattern of performance technique, there is a good deal of variation between individual performers in relation to the pressure range used, and thus the tone quality produced. At a more detailed level, these differences may also depend upon lip shape and musculature and upon learned playing technique. Some variation is also to be expected between trumpets with different mouthpiece sizes and bore diameters, though the range of variation among standard instruments is not large.

A first-order theoretical consideration suggests the underlying physics responsible for these results, in terms of the flow behavior of the vibrating lip-valve generator and nonlinear wave propagation in the main bore of the instrument. These considerations give expressions for the acoustic input power at the instrument mouthpiece, the spectrum of which is then modified by nonlinear propagation behavior in the instrument bore, which steepens the wavefronts and transfers acoustic energy from low to high harmonics. These high harmonics are more efficiently radiated, produce a narrower radiation pattern, and enhance both the subjective loudness of the tone and its ability to rise above the general orchestral background.

Although manifestly incomplete in many details, the theoretical treatment outlined does appear to capture the essence of the performance technique used by trumpet players and to provide a skeleton upon which a more detailed understanding could be built.

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