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Pitch and level changes in organ pipes due to wall resonances

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Abstract

The resonating air column in a thin-walled metal organ pipe was observed to interact with a wall resonance. Effects became audible when a wall resonance frequency was nearly the same as that of the air column. Level changes of 6 dB and frequency shifts of 20 cents were found. Instabilities similar to the wolf-tone on string instruments could occur: the air column oscillations switched between closely spaced frequencies. It was observed that the cross-section of the organ pipe was slightly elliptical and could deform under influence of the pressure inside the tube. Based on this mechanism, a phenomenological model is proposed. It qualitatively explains the observed changes in resonance behaviour of the air column. It allows identification and verification of the parameters governing the interaction. The results suggest that similar effects might occur in other wind instruments such as saxophones, bassoons and trumpets.

1. Introduction

In a wind instrument a column of air oscillates. An excitation mechanism (vibrating reeds or a vibrating jet of air) compensates the losses by radiation to the outside and by dissipation along the wall boundary. Usually the walls are stiff as compared to that of the enclosed air. Nevertheless, they vibrate. But since the amplitude is in the order of micrometers, the acoustic power radiated by the wall is negligible as compared to that from the openings of the air column. Despite that the influence of wall vibrations on playing properties and sound quality has remained subject of discussions over a long period of time [1–3]. Musicians and instrument builders are convinced that wall vibrations can be important, though they usually are unable to explain (to a scientist) what they do and what causes them.

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Scientific investigations have produced mixed results. In 1966, Backus and Hundley [4,5] published a historical overview and investigated some aspects of wall vibration effects. They found that wall vibrations of organ pipes with non-cylindrical cross-sections could influence the tuning. The resonance frequency of a square section copper tube with hollow walls could increase a semitone when the hollow walls were filled with water. They measured wall vibrations of organ pipes and clarinets and found amplitudes between 1 and 10 μm. The sound power radiated by the walls appeared to be at least 25 dB below that radiated by the air, and thus can be considered insignificant. They supposed that the wall vibrations of organ pipes are due to the forces exerted on the lip by the vibrating air stream from the flue and not to the standing wave inside the pipe. They mentioned that organ builders test malfunctioning of an organ pipe by grasping it, though alterations of pipe tone due to this are not mentioned. Further back in history, Miller [6] reported experiments where different organ pipes of rectangular cross-section were compared. They had the same inner dimensions, but one was made of 1 cm thick wood and another of 0.5 mm thick zinc sheet. He found that resonance frequencies could differ up to two semitones. Grasping the thin-walled pipe with the hand brought about changes in resonance frequency. Putting the thin-walled pipe inside a larger one and filling the hollow walls with water also gave a great variety of changes in frequency and tone quality. Ellerhorst [7] reported experiments with a square section organ pipe with hollow walls, where the frequency changed as much as a semitone when the hollow walls are filled with gypsum. Coltman studied the effect of the material on the flute tone quality and found no effect [8]. From their contacts with Hungarian organ builders, Angster and Miklós learned that wall vibrations in organ pipes are important and they started measuring these [9]. Recently, changes in harmonic content and pitch of organ pipes are reported [10–13]. Sometimes level changes in the fundamental as well as slight frequency shifts were found. Gibiat et al. [14] found overtone changes in the saxophone spectrum of 3–6 dB as a result of clamping the tube over its entire length. Pyle measured influences on the sound of brass instruments due to lacquer [15,16] or due to minute changes in the mechanical construction [17]. Present authors have reported pitch and level changes when grasping a thin-walled organ pipe [18–20].

The present paper describes experiments on a thin-walled organ flue pipe. Changes in frequency and level were observed during changes in blowing pressure or wall damping. Resonances of the wall were separately measured and compared with theory. A phenomenological model is proposed for a qualitative explanation of the observed phenomena.

2. Observations

A thin-walled organ pipe, which was kindly lend to us by Judit Angster, was found to exhibit unexpected loudness and pitch changes when grasping its wall. This had been reported earlier [18–20]. Frequency shifts of 20 cents and level changes of 6 dB were observed. This is clearly above the detection thresholds for changes in frequency and level, 3 cents and 1 dB respectively [2,21,22].

The pipe was blown by compressed air, the pressure of which was adjusted by a valve. Threshold blowing pressure was about 0.3 kPa, steady sound occurred at 1.5 kPa and overblowing at 4 kPa. In the experiment the blowing pressure started at a low value while being gradually increased. The frequency gradually increased, as expected. At a certain blowing pressure, however, resonance frequency and level changed suddenly. The behaviour could be

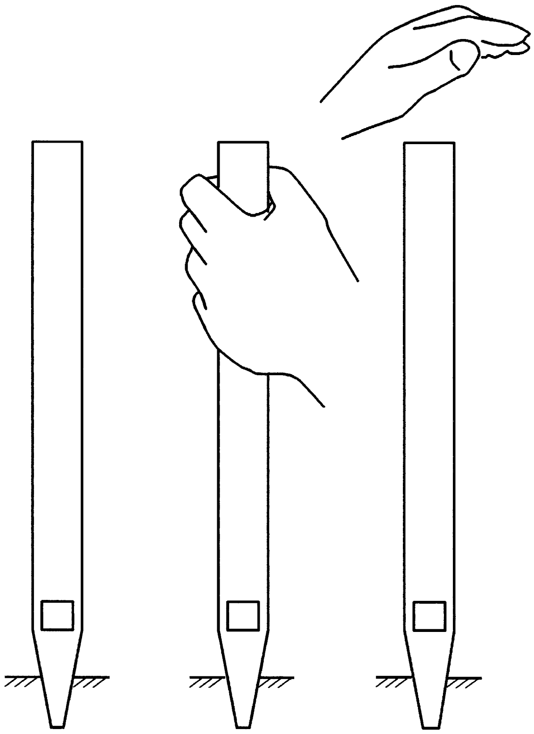

Fig. 1. Ways to change level and frequency of the organ pipe.

influenced by grasping the pipe or by holding a hand close to the open top (see Fig. 1). The first action changes resonance frequency and damping of the wall, the second action changes the air resonance frequency by changing the open end correction of the pipe [3,23]. It also was possible to change the behaviour by increasing the air temperature, and consequently the air resonance frequency, by blowing hot air in the pipe. Sometimes beatings occurred with varying rates, sometimes they alternated with a stable, "regular", pipe resonance. It resembled wolf-note-type oscillations as found in string instruments, which are ascribed to a coupling of string and soundboard resonances.

Fig. 2 shows the recorded spectrum of two situations. In the first situation the sound is stable, represented by the central peak at 259.7 Hz. In the second situation the sound is quasi-periodic (beatings). This is represented by the curve with the two adjacent peaks, which can be interpreted as a splitting of the stable resonance, resulting in a beating.

The wall vibrations were measured with a laser vibrometer. The free end of the pipe appeared to vibrate in the same manner as the lowest mode of a church bell. Dotted lines in Fig. 3 sketch the extremes of the wall shapes. The rest shape (drawn line) was slightly elliptical, semiaxes being $a = 24$ and $b = 22$ mm. The frequency was the same as that of the air, with a maximum amplitude of 20 μm at the open top end. Fig. 4 shows the amplitude of the first mode as a function of the position from the free end, measured at different angles. Amplitudes diminish toward the labium. Amplitudes at 0° and 90° were approximately alike but opposite in phase, at 45° the amplitude

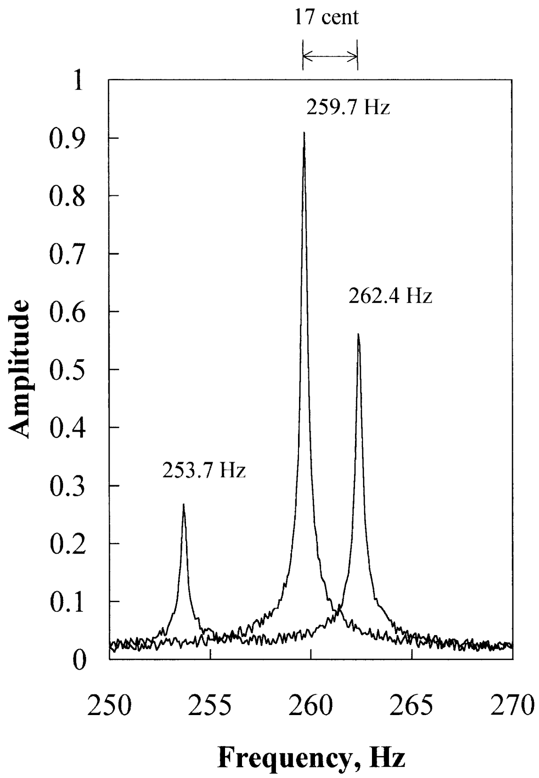

Fig. 2. Spectrum of the organ pipe, the middle peak for the stable resonance, the double peak for the beating behaviour.

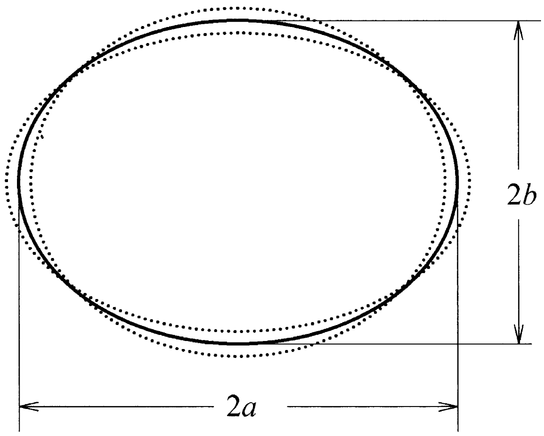

Fig. 3. Motion of pipe cross-section, in rest position semiaxes are *a* and *b*.

was much less, though not completely zero, probably due to the shape of the pipe not being completely regular. It is noted that the shape of the curves is similar to those of the lateral deformations of beams clamped at one end and free at the other end. This is shown in Fig. 4 for

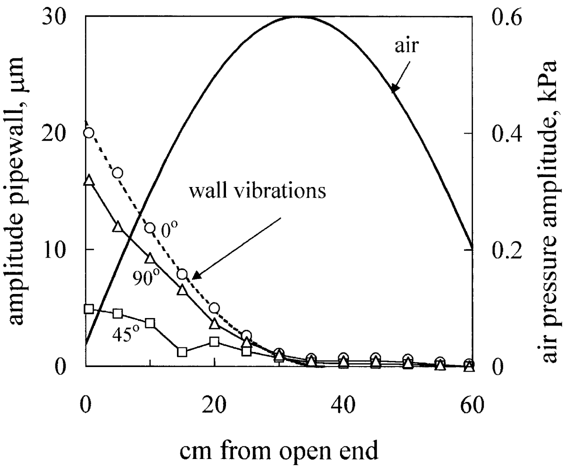

Fig. 4. Wall and pressure amplitudes of the fundamental.

the 0° curve: the dotted line is a theoretical one for a beam clamped at 35 cm from the open end, fitted to the measurements. It is not clear whether this is significant, and if so, why the tube vibrates as if clamped at this point; one would expect it to behave as if clamped near the labium. Irregularities in the ellipticity may be the cause. This varied over the length of the tube.

The character of the wall vibrations was investigated by exciting the tube with a shaker near the labium and measuring the maximum and the width of the resonance curve. Without touching the pipe the resonance frequency was 259.5 Hz, very close to the frequency of the stable resonance of the air, 259.7 Hz. The resonator quality Q was approximately 60. When grasped by the hand the frequency became 263 Hz and Q went down to about 12. The amplitude of the vibrations diminished 13 dB. Air had no influence on the quality factor of the pipe, which was verified by putting absorbing material not touching the walls in the pipe.

In the same Fig. 4, the amplitude of the air pressure of the first mode, calculated from one measurement inside the pipe, 20 cm from the open end, is plotted.

Fig. 5 shows measurements of air and wall vibrations of the second mode, in both cases amplitudes were much less. Note that the absolute values of the amplitudes are plotted, so adjoining peaks in the figure are opposite in phase. The pattern of the wall vibration is more complicated, but in the circumference also of the church-bell type. It is analogous to that reported in the literature: many oscillating patterns can occur, some of these closely spaced [9,10,24,25].

3. Pipe wall resonances

The organ pipe wall resembles a cylindrical shell. For some simple end conditions, such as clamped at one or both ends or simply supported at both ends, theory is available to calculate its resonance frequencies. However, the end conditions for the organ pipe are certainly not simple; in particular the situation at the labium is complicated. To investigate this, and to explain the vibration behaviour as shown in Fig. 4 in detail would necessitate a separate study. This goes

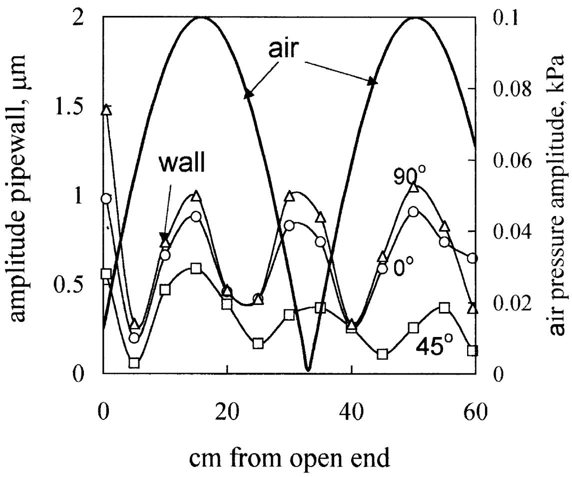

Fig. 5. Absolute values of wall and pressure amplitudes of the second harmonic.

beyond the present goal. The deformations shown in Fig. 4 would indicate the study of the resonance of a cylindrical shell clamped at one end, or a freestanding smokestack. As long it is small, an ellipticity of the cross-section will not influence the vibrational pattern. Formulas for various situations can be found in the literature, an overview is given by Soedel [26]. For a harmonic oscillation of a closed thin-walled cylindrical shell, the deformation amplitude as a function of position x and angle θ, $U(x, \theta)$, will be

$$U(x, \theta) = U_x(x) \cos n(\theta - \Phi), \tag{1}$$

where Φ is an arbitrary angle. The x dependent term of the solution is of the form

$$U_x(x) = \exp(\lambda x / L). \tag{2}$$

Inserting this into the equation of motion gives (see [26, Eq. 6.9.6])

$$\frac{Eh^3}{12(1-\nu^2)}\left[\frac{n^2}{r^2} - \left(\frac{\lambda}{L}\right)^2\right]^4 + \frac{Eh}{r^2}\left(\frac{\lambda}{L}\right)^4 - \rho h \omega^2 \left[\frac{n^2}{r^2} - \left(\frac{\lambda}{L}\right)^2\right]^2 = 0, \tag{3}$$

where E is the Young's modulus, ν the Poisson ratio, L the tube length, r the tube radius, h the wall thickness, and ρ the density. When $\lambda/L \ll n/r$, the expression is simplified; the frequency $f = \omega/2\pi$ then can be calculated from

$$f = \frac{1}{2\pi}\sqrt{\frac{E}{\rho}\left(\frac{h^2 n^4}{12(1-\nu^2) r^4} + \frac{r^2 \lambda^4}{L^4 n^4}\right)}. \tag{4}$$

From the boundary conditions for the smokestack the characteristic equation for λ becomes [26]

$$\cos\lambda \cosh\lambda + 1 = 0. \tag{5}$$

This condition is identical to the one for a bar clamped at one end and free at the other end. The first root $\lambda = 1.875$. Inserting numerical values, $L = 600$ mm, $r = 23$ mm, and for the first circumferential mode $n = 2$, it can be verified that indeed $\lambda/L \ll n/r$, confirming the validity of the simplified expression (4). Taking $h = 0.5$ mm, estimating Young's modulus of the pipe material $E \approx 20$ GPa, its density $\rho = 8500$ kg/m^3 and Poisson's ratio $v = 0.3$ [27], the resonance frequency calculated by Eq. (4) is found to be $f = 280$ Hz. This is close to the observed frequency, which speaks for the validity of the theory for this situation. Although the measurements showed the vibrating part of the tube to be less than 600 mm, the influence of this length on the resonance frequency is small, as appears from Eq. (4): the second term is small.

For higher modes, formulas are similar to or extensions of Eq. (4), depending on the boundary conditions. The roots λ become larger and the corresponding terms are no longer negligible. With the proper choice of λ it is possible to find a resonance frequency and wavelength close to the measured values of Fig. 5, but the many uncertainties, the irregular pipe and its unusual boundary condition at the labium render calculations insecure. Suffice to conclude that the description of wall resonances appears to be qualitatively correct.

4. A phenomenological model

4.1. The model

Since air and wall are coupled over their entire length of the pipe, a correct description is likely to be complicated [28]. Instead, a simple phenomenological model is proposed similar to the one given by Gough [1,29] for the coupling of a string and a soundboard on string instruments. It describes qualitatively the behaviour of the air–wall system.

The model is inspired by the observation that the cross-section of the pipe was not perfectly circular and that changing this ellipticity could cause the effect to diminish or to disappear. This also corresponds with actions organ builders take when they have difficulties with wall resonances: they put a stiff ring around the pipe or fix opposite sides by putting a thread across the diameter. These results suggest that tube area changes due to pressure changes cause the effect. The results of Miller and Ellerhorst on the square-section organ pipe point in the same direction [6,7]. Miklos and Angster also report couplings with higher air modes due to wall deformations [12]. The influence in a pure cylinder can be expected to be much less, since its extensional stiffness is much larger than its bending stiffness and correspondingly the area changes are much smaller. This also appears from a study determining the influences due to wall extensions: only small influences were found and only at high frequencies [28].

Fig. 6 shows the model. A Helmholtz resonator, subscript 1, represents the air column. A mass–spring element, subscript 2, represents the wall. This element is in parallel with the compliance of the resonator. Assuming harmonic motion, exp(jωt), the input impedance of the resonator, Z_1, can be written as

$$Z_1 = R_1 + \mathrm{j}\omega M_1 + 1\bigg/\left(\mathrm{j}\omega C_1 + \frac{1}{(R_2 + \mathrm{j}\omega M_2 + 1/\mathrm{j}\omega C_2)}\right), \tag{6}$$

where R is the resistance, M the inertness and C the compliance of the enclosed air (subscript 1), or the wall (subscript 2). The angular resonance frequencies of air and wall are ω_1 and ω_2,

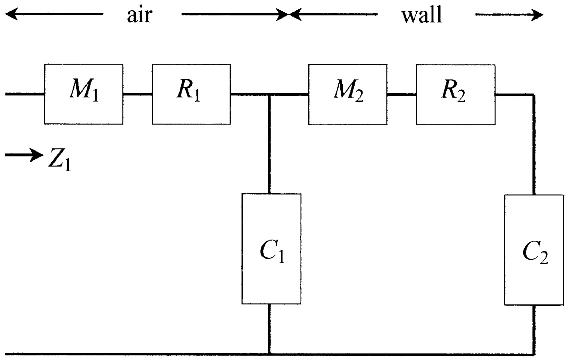

Fig. 6. Model for coupled air and wall vibrations.

respectively. The resonator volume is V, so its compliance is

$$C_1 = V/\rho c^2, \tag{7}$$

where ρ is the air density and c is the velocity of sound. Setting $\omega_1^2 = 1/M_1C_1$, $Q_1 = 1/\omega R_1 C_1$, $\omega_2^2 = 1/M_2C_2$, and $Q_2 = 1/\omega R_2 C_2$, Eq. (6) can be written as

$$Z_1 = \frac{1}{j\omega C_1}\left[\frac{1}{(1 + C_2/C_1 T)} - \left(\frac{\omega}{\omega_1}\right)^2 + \frac{j}{Q_1}\right], \tag{8}$$

where

$$T = 1 - (\omega/\omega_2)^2 + j/Q_2. \tag{9}$$

When $C_2 \ll C_1$ and $\omega_2 \neq \omega$, the first term between square brackets of Eq. (8) is unity and the wall has a negligible influence on the input impedance. However, this term can become large and have a marked influence on Z_1 when T becomes small which happens when $\omega_2 \approx \omega$.

4.2. Wall compliance

The wall compliance is proportional to the change in cross-section due to a pressure change. To calculate its value, we first observe that in the present case the half-axes of the ellipse, a and b, are approximately the same. The exact value for the circumference is $4aE$, where E is the complete elliptic integral of the second kind. A good first order approximation is $\pi(a+b)$. After deformation a and b become $a + \Delta a$ and $b + \Delta b$ respectively. Since the circumference of an ellipse is independent of small changes of its ellipticity; it follows that $\Delta b = -\Delta a$. The area of the undeformed ellipse is $S = \pi ab$, when deformed, $S + \Delta S = \pi(a + \Delta a)(b + \Delta b)$, approximately $\Delta S \approx \pi(b - a)\Delta a$. Considering that the pressure over the length of the tube is varying, we postulate a "coupling" constant $g < 1$ to allow for this. A rough approximation of this constant is obtained by taking the mean value of the product of both curves in Fig. 4, both normalized to unity at their maximum; this gives $g \approx 0.2$. So the volume change ΔV caused by the area change is found by multiplication by gL instead of by L:

$$\Delta V = \pi g L(b - a)\Delta a. \tag{10}$$

The change in a due to an internal pressure increase Δp is given by [30]

$$\frac{\Delta a}{\Delta p} = \frac{b - a}{2(p_{cr} - \Delta p)}, \tag{11}$$

where the "critical" pressure p_{cr} (= negative pressure causing buckling) is

$$p_{cr} = \left(\frac{h}{r}\right)^3 \frac{E}{4(1 - \nu^2)}. \tag{12}$$

Inserting the values given above it is found that $p_{cr} = 57$ kPa. This is much larger than Δp (see Fig. 4), so with sufficient accuracy one obtains from Eq. (11)

$$\Delta p = \frac{2p_{cr}\Delta a}{(b - a)}. \tag{13}$$

From Eqs. (10) and (13) the compliance of the wall, C_2, is obtained:

$$C_2 = \frac{\Delta V}{\Delta p} = \frac{\pi g L(b - a)^2}{2p_{cr}}. \tag{14}$$

This formula shows that the magnitude of the out-of-roundness has a strong influence: the difference of the semiaxes appears in the second power.

Some organ pipes are made of wood and, for constructional reasons, have a rectangular cross-section. Here the out-of-roundness of the cross-section is large. To keep the area change due to pressure changes small in this case demands a large bending stiffness, or thick planks.

4.3. Comparison with experiment

An important parameter for the description of the system is the ratio of the two compliances, C_2/C_1. From Eqs. (7) and (14), using $V = \pi a^2 L$, it follows

$$\frac{C_2}{C_1} = \frac{g\rho c^2(b - a)^2}{2p_{cr}a^2}. \tag{15}$$

Inserting all values previously mentioned one finds $C_2/C_1 \approx 0.002$

An estimate of the quality factor Q_1 of the air column is obtained from $Q = k/2\alpha$, where $k = 2\pi f/c$ is the wave number and the attenuation coefficient $\alpha \approx 3.0 \times 10^{-5} f^{0.5} a^{-1}$ [1,31,32]. For a frequency of 260 Hz this gives $Q_1 = 120$. Because losses at the walls tend to be somewhat larger than according to theory and there also will be radiation losses, a convenient value of $Q_1 = 100$ was chosen. For the quality of the pipe resonance the value was chosen found from the measurements, $Q_2 = 60$. The impedance now is calculated with Eq. (8). The absolute value of its reciprocal, the admittance, which is proportional to the air amplitude, is multiplied by $j\omega C$ and plotted in Fig. 7, for three values of the parameter $\varepsilon = \omega_2/\omega_1$, $\varepsilon = 0.95$, 0.97 and 0.99. The results show a great similarity with the curves in Fig. 2.

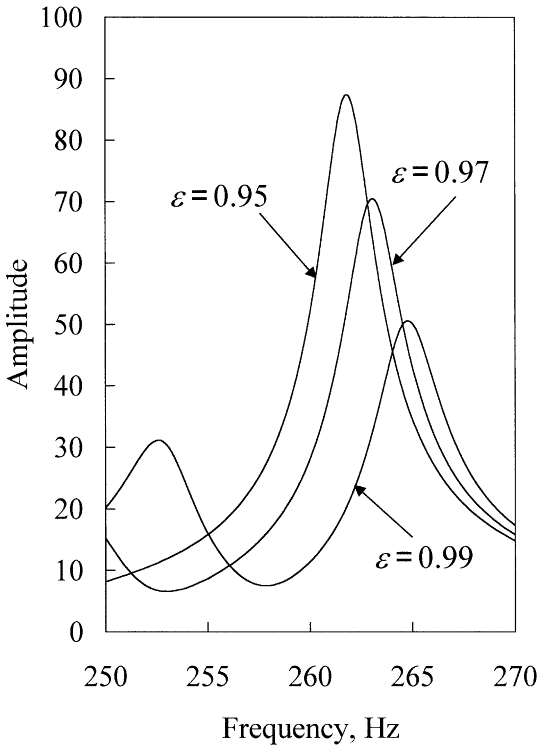

Fig. 7. Calculated amplitudes of air pressures in the tube, for three values of the ratio of resonance frequencies of wall and air, ε. Wall resonator quality $Q_2 = 60$.

Fig. 8 shows results for the same situation, only with a higher wall damping, $Q_2 = 15$, the value found when the hand grasped the pipe. The levels diminish, the resonance peak broadens, the curve shift diminishes and the peak splitting is undone.

5. Discussion and conclusion

Although the model is a great simplification of reality, the phenomena are described qualitatively quite well and to some extend also quantitatively. The presence of a non-circular cross-section is essential. A cursory inspection of many other thin-walled instruments reveals that their cross-sections usually are not exactly circular. Brass instruments and saxophones belong to this class. Also, it can be imagined that other types of asymmetries, intrinsically present in these instruments, cause a similar coupling of wall and air vibrations. For example, toroidal bends tend to straighten due to internal pressures. Trumpet players and builders claim that the positions of braces influence the playing of the trumpet. Pyle found influences of the plating of the bell of a trumpet [15,16]. Gibiat et al. [14] reported 6 dB variations in the harmonic spectrum of the saxophone, when the pipe was grasped or clamped.

Intuitively one would expect that compliance ratios of 500 or higher would not result in any effects: in a spring–mass resonator a 0.2% shift in mass results in a 0.1% shift in frequency, which

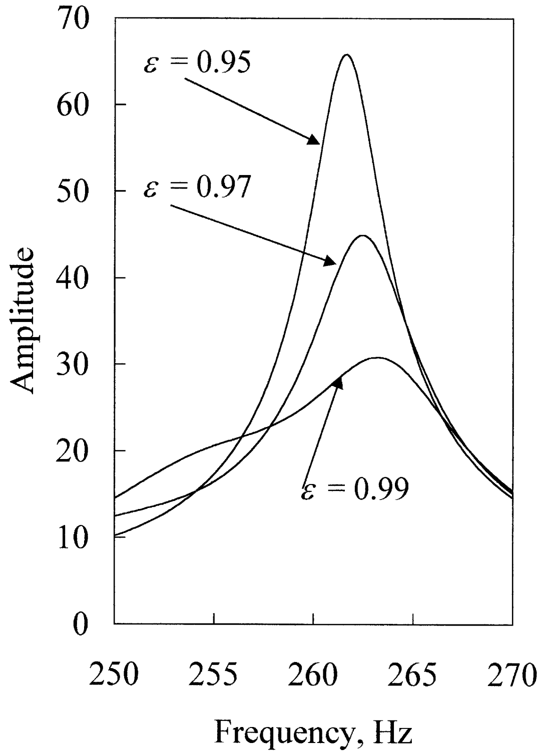

Fig. 8. Calculated amplitudes of air pressures in the tube, for three values of the ratio of resonance frequencies of wall and air, ε. Wall resonator quality $Q_2 = 15$.

is not detectable. However, as appeared from above, when this is combined with out-of-roundness or asymmetry, and a wall resonance is very close to one of the air, the effects can be much larger. On most instruments there are many possibilities of mechanical resonances that can be imagined to cause trouble. In practice this situation seems to be rare, not in the least because builders try to avoid interactions with wall vibrations. As in string instruments, small adjustments may prevent unwanted vibrations.

Some preliminary investigations into wall vibration influences in other instruments were carried out. For example it was observed that during playing the bocal (crook) of a bassoon vibrated vertically, in bending. The amplitude of the tip, near the reed, was 10 μm. The reed, attached to this tip, vibrates vertically with an amplitude of about 0.5 mm. This is about 50 times that of the tip. Considering the crook to have a resonance frequency in the 400 Hz range (this can be heard by hitting it), it can be imagined that in this frequency range there can be a coupling between the reed oscillations and a crook resonance (this coupling may not be based on out-of-roundness of the cross-section). This could influence the bassoon sound, especially interesting since the formant of the bassoon is in the 400 Hz range. However, preliminary experiments (gripping the bocal) did not reveal any effects.

Another preliminary study concerned the clarinet. From measurements, the mouthpiece of the clarinet close to the teeth was found to vibrate about 10 μm, sometimes in a double frequency [33].

This too can be considered sufficiently large to cause a coupling with reed deformations, but here too, any effects on the air sound could not be established.

Wall vibrations remain a subject of controversial discussions and many investigations have to be done to settle the debate.

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References

[1] N.H. Fletcher, T.D. Rossing, *The Physics of Musical Instruments*, 2nd Edition, Springer, New York, 1998.
[2] M. Campbell, C. Greated, *The Musician's Guide to Acoustics*, Schirmer, New York, 1987.
[3] C.J. Nederveen, *Acoustical Aspects of Woodwind Instruments*, 2nd Edition, Northern Illinois University Press, De Kalb, IL, 1998.
[4] J. Backus, Effect of wall material on the steady-state tone quality of woodwind instruments, *Journal of the Acoustical Society of America* 36 (1964) 1881–1887.
[5] J. Backus, T.C. Hundley, Wall vibrations in flue organ pipes and their effects on tone, *Journal of the Acoustical Society of America* 39 (1966) 936–945.
[6] D.C. Miller, The influence of the material of wind-instruments on the tone quality, *Science* 29 (1909) 151–171.
[7] W. Ellerhorst, *Handbuch der Orgelkunde*, Benziger, Einsiedeln, 1936; Reprint: Frits Knuf, Hilversum, 1966, p. 258.
[8] J.W. Coltman, Effect of material on flute tone quality, *Journal of the Acoustical Society of America* 49 (1971) 520–523.
[9] J. Angster, I. Bork, A. Miklós, K. Wogram, The investigation of the vibrations of an open cylindrical organ flue pipe, *Nineth FASE Symposium and 19th Hungarian Conference on Acoustics*, Balatonfüred, Hungary, 1991, pp. 143–754.
[10] L. Zipser, H. Franke, Vibration behaviour of organ flue pipes, *Proceedings of the Institute of Acoustics* (*ISMA 1997*), Vol 19, Part 5, Edinburgh, pp. 359–366.
[11] J. Angster, G. Paál, W. Garen, A. Miklós, The effect of wall vibrations on the timbre of organ pipes, *Proceedings of the 16th International Congress on Acoustics*, Seattle, WA, 1998, pp. 753–754.
[12] A. Miklós, J. Angster, Properties of the sound of flue organ pipes, *Acustica/Acta Acustica* 86 (2000) 611–622.
[13] M. Kob, Influence of wall vibrations on the transient sound of a flue organ pipe, *Acustica/Acta Acustica* 86 (2000) 642–648.
[14] V. Gibiat, M. Bouche-Pillon, S. Perrot, T. Vandenbogaerde, J. Roumaire, Influence des résonances mécaniques sur l'émission acoustique d'un instrument à vent simplifié, *Proceedings of the Fourth Congress on Acoustics*, Marseille, France, 1997, pp. 585–588.
[15] R.W. Pyle Jr., The effect of lacquer and silver plating on horn tone, *Horn Call* 11 (2) (1981) 26–29.
[16] R.W. Pyle Jr., The effect of wall materials on the timbre of brass instruments, *16th International Congress on Acoustics*, Seattle, WA, 1998, pp. 751–752.
[17] R.W. Pyle Jr., Personal communication, 1998.
[18] C.J. Nederveen, J.-P. Dalmont, *Experimental Investigation of Wall Influences on Woodwind Instrument Sound*, Forum Acusticum, Berlin, 1999, p. S76 (Abstract).
[19] C.J. Nederveen, J.-P. Dalmont, Influence of wall vibrations on organ pipe sound level and pitch, *The Physics of Musical Instruments*, Vol. 2, Brighton, 2000 (Abstract POMI2.4.6).
[20] C.J. Nederveen, J.-P. Dalmont, Wolf notes in organ pipes due to wall resonances, *Proceedings of the ISMA*, Perugia, Italy, 2001, pp. 345–348.

[21] W. Hartmann, Pitch, periodicity, and auditory organisation, *Journal of the Acoustical Society of America* 100 (1996) 3491–3502.
[22] J.W. Coltman, Just noticeable differences in timbre of the flute, *Catgut Acoustical Society Journal, Series II* 3 (1) (1996) 26–33.
[23] J.-P. Dalmont, C.J. Nederveen, N. Joly, Radiation impedance of tubes with different flanges: numerical and experimental investigations, *Journal of Sound and Vibration* 244 (2001) 505–534.
[24] A. Runnemalm, L. Zipser, H. Franken, Structural vibration modes of a blown organ pipe, *Acustica/Acta Acustica* 85 (1999) 876–881.
[25] M. Kob, Eigenmodes of a flue organ pipe, *Acustica/Acta Acustica* 86 (2000) 755–757.
[26] W. Soedel, *Vibrations of Shells and Plates*, Marcel Dekker, New York, 1993, p. 144.
[27] P. Svensson, M. Friesel, Influence of alloy composition, mechanical treatment and casting technique on loss factor and Young's modulus of lead–tin alloys, Report F99-04, Chalmers University of Technology, Göteborg, 1999.
[28] F. Gautier, N. Tahani, Vibroacoustic behaviour of a simplified musical wind instrument, *Journal of Sound and Vibration* 213 (1998) 107–125.
[29] C. Gough, The theory of string resonances on musical instruments, *Acustica/Acta Acustica* 49 (1981) 124–141.
[30] S.P. Timoshenko, J.M. Gere, *Theory of Elastic Stability*, 2nd Edition, McGraw-Hill, London, 1961, p. 295.
[31] L.E. Kinsler, A.R. Frey, A.B. Coppens, J.V. Sanders, *Fundamentals of Acoustics*, Wiley, New York, 1982.
[32] R. Caussé, J. Kergomard, X. Lurton, Input impedance of brass instruments—comparison between experiment and numerical models, *Journal of the Acoustical Society of America* 75 (1984) 241–254.
[33] C.J. Nederveen, T.D. Rossing, Personal communication, 1996.