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Non-linear behavior of tone holes in musical instruments: An experimental study

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Typical pressure amplitudes observed in woodwinds correspond to acoustic oscillation in open-tone-hole with large displacements involving flow separation at sharp edges. For high Strouhal numbers, fluid particle displacements small compared to the tone-hole diameter, one observes local vortex shedding near the edges. At low Strouhal numbers the formation of free jets alternatively leaving and entering the pipe is observed. The resulting nonlinear contribution to the resistance and reactance of the tone-hole impedance depends on the ratio of tone-hole diameter and the Stokes layer thickness (Shear number Sh). High Shear numbers $Sh = O(10^2)$ are typical for musical instruments. At high Shear numbers ($Sh > 14$) and intermediate Strouhal numbers ($Sr = O(1)$) one observes positive contribution to the end-correction (reactance) due to local vortex shedding near the edges. A negative contribution to the reactance end-correction is observed at low Strouhal numbers ($Sr < 1$). Undercutting of tone-holes is common practice when tuning musical instruments. This involves chamfering of the edges on the inner pipe side. It does significantly reduce the nonlinear resistance end correction at high Shear numbers. This effect is not sensitive to the size of the chamfer.

1 Introduction

The typical amplitude A_0 of the standing acoustic wave corresponding to the fundamental oscillation frequency $\omega_0 = 2\pi f_0$ of a clarinet is in the range 1 kPa $\leq A_0 \leq 5$ kPa [1]. At a pressure node in the pipe this corresponds to acoustic flow velocities with an amplitude in the pipe of the order of $|u'| = A_0/(\rho_0 c_0) \leq 10$ m s^{-1} with ρ_0 the air density and c_0 the speed of sound. For a pipe diameter $D = 2$ cm and a tone-hole diameter $d_p = 1$ cm this corresponds to acoustic flow velocities through the tone-hole of up to $|u'_p| = 40$ m s^{-1}. The Strouhal number $\omega_0 d/|u'_p|$ is the ratio of the tone-hole diameter and the amplitude $|u'_p|/\omega_0$ of the acoustic particle displacement. For $f_0 = 220Hz$ we have $Sr \geq 0.3$ so that the fluid particle displacement can reach three time the tone-hole diameter. For typical tone-holes in a clarinet the tone-hole diameter is comparable to the wall thickness t_p. As shown by flow visualisation of Ingard and Labate [2] the pulsating flow separates from the wall to form free jets, one directed out of the pipe and one directed into the pipe. Under these circumstances the amplitude fluctuating pressure difference $|\Delta p'|$ is proportional to $\rho_0|u'_p|$. The experiments of Ingard and Ising [3] for a tapered orifice with sharp edge show that the transfer impedance $Z_{orifice} = \Delta p'/u'_p$ has a nonlinear (amplitude dependent) real part given by $\rho_0|u'_p|$. It is interesting to note that in the derivation of this relationship Ingard and Ising [3] neglect the effect of the vena contract effects [4]. This compensates almost exactly an error of a factor 2 in the equation of Bernoulli they use. The nonlinear losses due to vortex shedding provide at least a qualitative explanation for an experiment designed by Benade and carried out by Keffe [5]. Two cylindrical pipes with a row of open tone-holes are build which have the same linear impedance. While the first one has thick wall comparable to that of a clarinet, the second one has very thin walls. To compensate the reduction of the tone-hole inertia when using a thin wall one has to reduce the tone-hole diameter. This increases for a given amplitude A_0 the flow velocity u'_p through the tone-hole and increases the nonlinear losses. While both pipes can make sound by blowing using a bass clarinet mouthpiece (private communicate C.J. Nederveen 1993) when using a regular clarinet mouthpiece only the thick walled pipe can make sound ([5], private communication H. Dane 1993). Recently Guilloteau et al. [6] studied such effects on a pipe terminated by an orifice.

Related studies have been carried out on the nonlinear acoustic response of open pipe terminations by Disselhorst and Van Wijngaarden [7], Atig et al. [8] and Buick et al. [9]. One can distinguish two regimes from these studies and the work of Ingard and Labate [2] : For low Strouhal numbers ($Sr < 0.5$) a quasi-steady free jet formation is observed while for lower amplitudes ($Sr > 1$) one observes local vortex shedding. These vortices remain in the vicinity of the edges of the orifice or open pipe termination. For sharp edges Disselhorst and Van Wijngaarden [7] obtained an analytical expression for the sound power dissipated by local vortex shedding. They predict an increase of $\Re\{Z_{pipe}\}/(\rho_0|u'_p|) \propto Sr^{1/3}$ with increasing Strouhal number. Simplified models with a single line vortex are discussed by Peters and Hirschberg [10]. Peters [11] discusses the influence of the edge angle on the local vortex shedding from which one can predict the sound absorption by localised vortex shedding. The nonlinear real part of the impedance appears to be very strongly dependent on the exact shape of the edges ([7],[8]). Rounding of the edges does drastically reduces these losses.

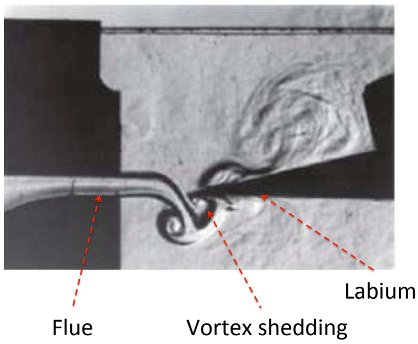

Figure 1 – Flow visualisation of vortex shedding at the sharp edge of the labium of a flue organ-pipe. This vortex shedding is an important amplitude limiting phenomenon. Foto A.P.J. Wijnands.

Vortex shedding at the labium in the mouth of a flue instrument (see Fig. 1) appears to be an essential amplitude limiting sound absorption mechanism [12].

There are major differences between tone-holes and orifices. The orifices such as studied by Ingard and Labate [2] have sharp square edges. However instrument makers do undercut tone-holes in the process of tuning the instrument. He actually makes chamfer on the inside of the tone-hole by cutting off the inner edges. As shown by Mcdonald [13] the acoustic flow from the pipe into the tone-hole is furthermore quite asymmetric. This is due to the fact that the potential flow associated with a bend (turning from the pipe into the side hole) will have a larger flow velocity at the inner part of the bend than at the outer part. This results into a stronger flow separation at this inner part than at the outer part of the bend. Of course this asymmetry will increase with increasing ratio d_p/D of tone hole to pipe diameters.

In a previous paper we discussed the nonlinear response of square edged orifices [14]. We present here some complementry acoustic impedance measurements allowing to asses the effect of chamfers on the nonlinear impedance of an orifice. The influence of chamfers on the linear response of orifices was discussed in another paper [15]. The present study is quite limited : We limit our study to the case of a wall thickness t_p comparable to the tone-hole diameter d_p. For very thick walls as used in some instruments $t_d/d_p >> 1$ the flow separation at the inlet of the tone-hole will be followed by re-attachment to the wall within the tone-hole, even at very low Strouhal numbers.

We neglect the asymmetry due to the bending of the acoustic flow from the main pipe into the tone-hole. We ignore furthermore the possible effect of a steady flows through the pipe. One expects the steady flow velocity to be an order of magnitude smaller than the oscillating flow amplitude, however one cannot exclude an effect on the tone-hole response.

2 Experimental set-up

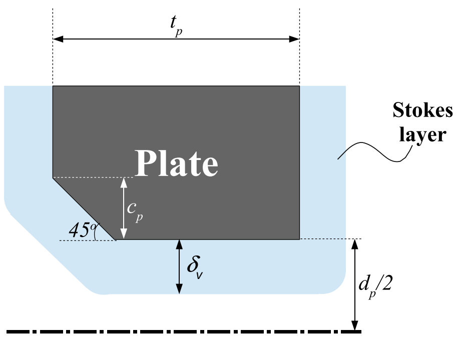

FIGURE 2 – Geometry of perforation and chamfers : diameter d_p, wall thickness t_p and chamfer length c_p. Chamfer angle is $\pi/4$.

A circular orifice of $d_p = 4.2$ mm is drilled in a plate with thickness $t_p = 4$ mm. We consider three orifice geometries. The geometry B_1 has sharp square edges (chamfer length $c_p = 0$ mm). The geometry B_2 has a chamfer under $\pi/4$ of length $c_p = 0.35$ mm on one side of the orifice. The geometry B_4 has a chamfer under $\pi/4$ of length $c_p = 1$ mm on one side of the orifice. This plate is placed at the open end of an impedance tube of inner diameter $D = 50$ mm and 10mm wall thickness, driven by a loudspeaker. Hence the plate has a porosity $\sigma = (d_p/D)^2 = 7.06 \times 10^{-3}$. There is no imposed steady flow. The acoustic reflection coefficient ζ just upstream from the orifice is measured using a 6 microphone-method described in some detail in our earlier papers ([14],[15]). The amplitude of the velocity u'_p through the orifice is deduced from this reflection coefficient and the pressure amplitude p' at a calibrated microphone. The transmission impedance is given by : $Z_t = \rho_0 c_0 (1 + \zeta)/(1 - \zeta) - Z_R$, where Z_R is the radiation impedance of the open impedance tube. Note that $Z_t = Z_{orifice}/\sigma$ where σ is the porosity. The measurements are carried out in a semi-anechoic room to avoid the effect of resonances outside the impedance tube. Acoustic absorbing wedges are placed on the flow under the open pipe termination to reduce the effect of reflections on the floor. Typical accuracy in the reflection coefficient ζ measured at a closed end wall is better than 0.5 %. This was estimated by carrying measurements on a closed end-wall (plate without orifice).

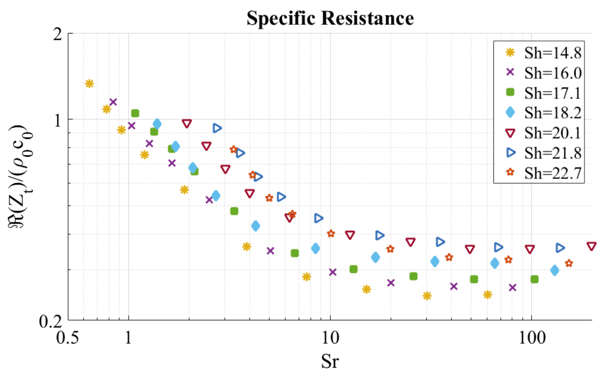

FIGURE 3 – Dimensionless resistance of the orifice with sharp square edge (B1). We observe that for high Sr the asymptotic behaviour corresponding to the linear behaviour.

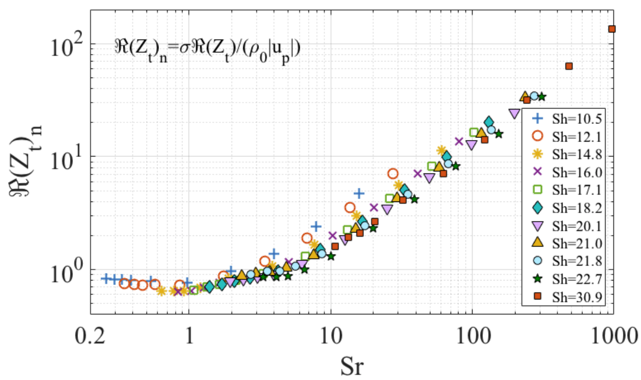

FIGURE 4 – Dimensionless resistance $\Re[Z_t]_n = \sigma\Re[Z_t]/(\rho_0|u'|)$ of the sharp square edge orifice (B1). We observe that for high Sr the the asymptotic behaviour corresponding to the linear behaviour $\sigma\Re[Z_t]/(\rho_0|u'|)$ increasing proportionally to Sr. For low Strouhal numbers one approaches the quasi-steady limit $\sigma\Re[Z_t]/(\rho_0|u'|) = 1$.

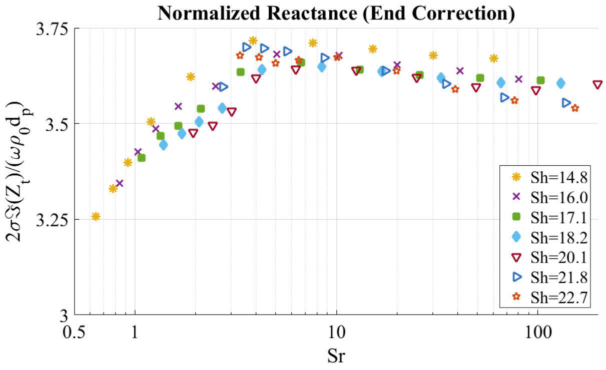

FIGURE 5 – Dimensionless reactance of the sharp square edge orifice (B1). In the quasi-steady limit $Sr < 1$ we observe a decreasing reactance. For $Sr > 1$ in the linear limit the reactance approaches an asymptotic value corresponding to a linear behaviour. Using the theory of Nomura et al. [16] we find in the linear limit $2\Im[Z_t]/(\rho_0\omega d_p) = 3.54$, which agrees well with the measurements. For intermediate values we observe an overshoot, which we associate to the local vortex shedding described in figure 6.

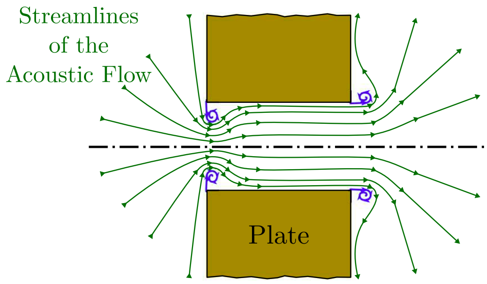

FIGURE 6 – Acoustic streamlines for local vortex shedding at high Strouhal and Shear numbers. The contraction of the flow due to vortex shedding at the inlet results into a local increase of kinetic energy. The vortex shedding at the downstream side increases the effective plate thickness. Both effects result into a positive end-correction.

3 Results

The influence of the edge chamfering on Z_t was studied for the linear regime in an earlier paper [15]. The measured linear impedance $Z_{t,L}$ is predicted by a function of the Shear number $Sh = d/\delta_\nu$ where the Stokes layer thickness is given by $\delta_\nu = \sqrt{\nu/\omega}$ with ν=1.5E-5 m^2 s^{-1}. The results of the nonlinear impedance is given in dimensionless resistance $\Re[Z_t]/(\rho_0 c_0)$ and end-correction $2\Im[Z_t]/(\rho_0\omega d)$.

In Fig. 3 to 5 we shown the data obtained as function of Sr for $Sh > 14$ for the sharp square edged orifice B_1. Typically for musical instruments one has $Sh = O(10^2)$. The behaviour at low Sh is discussed in an earlier paper [14]. The data for higher Sh show a high Sr asymptotic behaviour. The dimensionless resistance $\Re[Z_t]/(\rho_0 c_0)$ approaches an horizontal asymptote with increasing Sr. Disselhorst and van Wijngaarden [7] observed in the high Sr limit decrease of the non-linear contribution to the resistance following $Sr^{-2/3}$ as predicted by theory for very small edge angles (an open tube termination with very thin walls). This would be the result of local vortex shedding. This would be more obvious when considering the dimensionless resistance $\sigma\Re[Z_t]/(\rho_0|u'|)$, obtained by using the quasi-steady limit of Ingard and Ising [3] $\rho_0|u'|$ as a reference. Here σ is the porosity of the perforated plate and $|u'|$ is the amplitude of the acoustic velocity just in front of the plate. Hence $|u'|/\sigma = |u'_p|$ is the surface averaged flow velocity in the perforation. In limit of low Sr one approaches the quasi-steady behaviour $\Re[Z_t]_n = \sigma\Re[Z_t]/(\rho_0|u'|) = 1$ as observed by Ingard and Ising [3] involving the formation of free jets. (see Fig. 4). In the high Strouhal limit $Sr > 10$ we see an increase of $\sigma\Re[Z_t]/(\rho_0|u'|)$ proportional to Sr, which does not correspond to the behaviour observed by Disselhorst and van Wijngaarden [7]. As shown by Atig et al. [8], there is indeed at $Sr < 1$ a drastically different behaviour of the non-linear behaviour of an open pipe termination with square edges compared to sharper edges (angle 30 degree) considered by Disselhorst and van Wijngaarden [7].

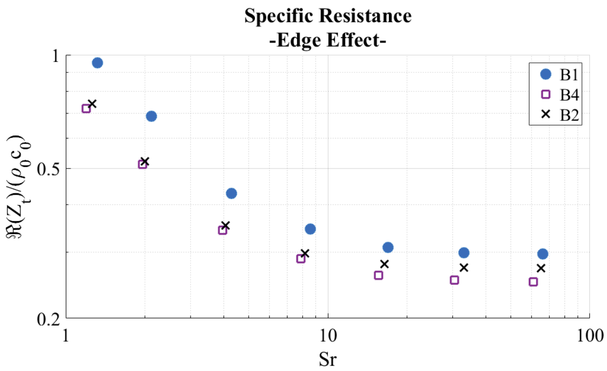

FIGURE 7 – For $Sh = 18$ the presence of a chamfer reduces drastically the resistance. This effect is not dependent on the magnitude of the chamfer. Results are identical for $c_p = 0.35$ mm (B2) and 1.0 mm (B4).

Dimensionless reactance of the sharp square edge orifice (B1). In the quasi-steady limit $Sr < 1$ we observe a decreasing reactance, with decreasing Sr. For high Sr in the linear limit the reactance approaches an asymptotic value corresponding to a linear behaviour. For a flanged pipe with sharp square edges the linear end correction predicted by Nomura et al. [16] is $0.41 d_p$. This corresponds for our orifice with $2\Im[Z_t]/(\rho_0\omega d_p) = 3.54$. This value agrees quite accurately with our results for $Sr >> 1$ (see Fig. 5). The quasi-steady limit for $Sr < 1$ is lower than this linear limit. For intermediate values we observe an overshoot, which we associate to the local vortex shedding described in Fig. 6.The overshoot in end correction above the linear asymptote, due to local vortex shedding at Strouhal numbers around $Sr \simeq 4$, has been explained qualitatively by Temiz et al. [14].

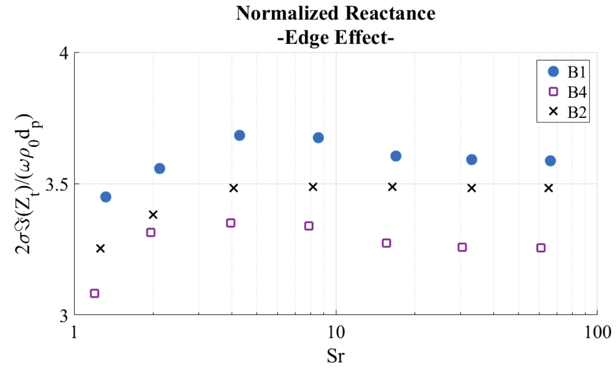

Figure 8 – For $Sh = 18$ we observe a significant effect of chamfers on the reactance. At low Strouhal numbers this effect is not strongly dependent of the magnitude of the chamfers $c_p = 0.35$ mm (B2) and 1.0 mm (B4). While we do observe a significant overshoot in the reactance around $Sr \simeq 4$ for geometries (square edges B1) and (large chamfer B4) we do not observe this overshoot for the small chamfer (B2).

The effect of chamfers on the dimensionless resistance is shown in Fig. 7. We observe a significant decrease in resistance in the presence of chamfers. It is interesting to note that there are only minor differences between the results for the smaller $c_p = 0.35$ mm (B2) and larger chamfer $c_p = 1$ mm (B4). Hence while the chamfer does influence the nonlinear behaviour the size of the chamfer seems less critical. Even a very small chamfer can already have a strong influence on the nonlinear response of tone-holes. It is also interesting to compare these results to the influence of rounding of edges on the non-linear resistance of an open pipe termination as measured by Atig et al. [8]. Atig et al. [8] observed a drastic decrease in non-linear resistance when the edges of an open pipe termination with square edges where rounded off. Similar effects are reported by Guilloteau et al. [6].

The effect of chamfers on the dimensionless nonlinear reactance is shown in Fig. 8. Again for $Sr < 1$ there is not a strong influence of the size of the chamfers. Furthermore the nonlinear contribution to the end-correction is negative at low Strouhal numbers. For intermediate Strouhal numbers $Sr \simeq 4$ we see a positive contribution to the end-correction and for $Sr > 10$ the linear asymptote. The overshoot, which is supposed to be due to local vortex shedding disappears for the small chamfer (B2) but is present for the large chamfer (B4).

4 Conclusion

As observed by flow visualisation by Ingard and Labate [2] for high Shear numbers $Sh \geq 14$ we can distinguish two non-linear behaviours in the transfer impedance of an orifice : the quasi-steady flow separation at low Strouhal numbers $Sr < 1$, the local vortex shedding for $Sr \simeq 4$ and the linear behaviour at high Strouhal numbers $Sr > 10$.

At high Shear numbers ($Sh > 18$) chamfering the edges of the tone-hole influences drastically the nonlinear effects associated with flow separation even for small chamfer length $c_p/d_p < 0.1$.

The present study is quite limited but demonstrates the complexity of the flow in tone-hole. Further studies involving the bending of the flow from the pipe into the tone-hole [13] and the steady flow in the main pipe should be considered. One should also consider the behaviour of longer tone-holes, as found in some musical instruments.

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