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Dimensionless amplitude of the internal acoustic field in flue instruments

A. Hirschberg, M.P. Verge, B. Fabre, A.P.J. Wijnands

ISMA 95, Dourdan, 1995

Abstract:

Dimensionless representation of the pressure signal measured inside a flue organ pipe shows that the dimensionless amplitude is a function of the Strouhal number only. This behavior indicates that amplitude saturation is due to a non-linear interaction of the acoustic flow with the jet flow. Correlation of these results with flow visualizations stresses the importance of vortex shedding at the edge of the labium.

Introduction

The aim of the present paper is to demonstrate the power of dimensionless representation of experimental data as a tool to track down basic physical mechanisms in the sound production of wind instruments. Using the example of the amplitude of the fundamental oscillation mode we will, by correlation with flow visualizations, obtain a caricature which may explain some features of the sound production in flue instruments.

Amplitude of the fundamental

We present in Figure 2 the amplitude \hat{p}_1 of the fundamental as a function of the driving pressure p_f . The acoustic signal was measured, under steady blowing conditions, by means of a microphone placed within a small flue organ pipe in the wall opposite to the labium such as shown in Figure 1. Details of the instrument and of the measurement techniques are given by Verge [,] and Fabre [,]. We see in Figure 2 that by increasing the driving pressure p_f , the pipe can be overblown and oscillation modes corresponding to the successive longitudinal resonances of the pipe are obtained. In this particular case a geometry characterized by a ratio W/h between the distance W from the flue exit to the labium and the height h of the flue exit equal to 4 has been used. A ratio $W/h \simeq 4$ is typical of recorders. With this particular geometry, the travel time of hydrodynamic perturbations from the flue exit to the edge of the labium is always less than an oscillation period of the fundamental and the jet can only oscillate on its first hydrodynamic mode such as observed in Figure 4.

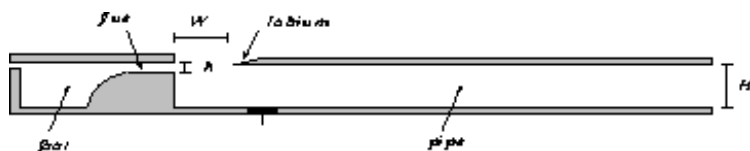


Figure 1: Experimental flue organ pipe.

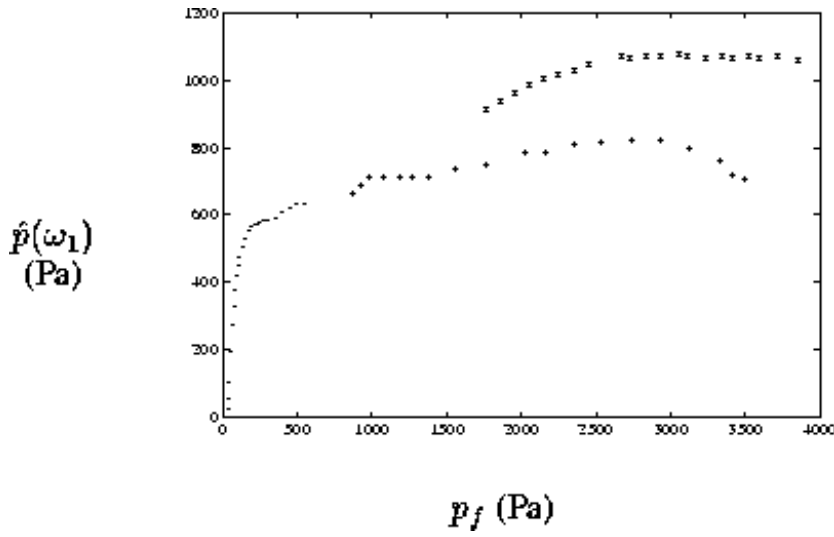


Figure 2: Amplitude $\hat{p}(\omega_1)$ of the fundamental as a function of the driving pressure p_f . The signal was measured inside the pipe of a small recorder-like flue organ pipe just in front of the labium; $W/h = 4.02$ mm.

The data of Figure 2 are obscured by the variations in the position of the microphone relative to the acoustical standing waves in the pipe when it is overblown. We therefore prefer to use the amplitude α_1 of the mode corresponding to the fundamental of the acoustic oscillation in the pipe. We estimate α_1 by means of the formula:

$$\alpha_1 = \frac{\hat{p}(\omega_1)}{\sin\left(\frac{\omega_1(x_m + \delta_p)}{c_0}\right)}, \quad (1)$$

where ω_1 is the angular frequency of the acoustic oscillations, x_m is the microphone position relative to the open pipe end, δ_p is the end correction of the pipe end and c_0 is the speed of the sound in air. For the square cross section $H \times H$ of our experimental pipe, the end correction $\delta_p \simeq 0.8h/\sqrt{\pi}$ because its walls are rather thick. We now present, in Figure 3, the data of Figure 2 as the ratio:

$$(u_\alpha/U_j) = \left(\frac{\alpha_1}{\rho_0 c_0 U_j}\right) \left(\frac{H}{W}\right), \quad (2)$$

of the average acoustical velocity through the window: $u_\alpha \simeq (\alpha_1/\rho_0 c_0)(H/W)$ and of the estimated jet velocity:

$$U_j = \sqrt{\frac{2p_f}{\rho_0}}, \quad (3)$$

where ρ_0 is the air density. The data (u_α/U_j) are presented as a function of the Strouhal number St_W defined as:

$$St_W = \frac{\omega_1 W}{2\pi U_j}, \quad (4)$$

which is a measure of the ratio between the travel time of perturbations along the jet W/U_j and of the oscillation period $2\pi/\omega_1$.

In this dimensionless representation, the data corresponding to the first three acoustical mode of the pipe collapse into a single curve. This implies that (u_α/U_j) is a function of St_W alone and no-other

dimensionless parameter. This result is quite striking because it shows that the data do not depend on the viscosity of the fluid (Reynolds number) nor on the ratio between the pipe width H and the wave length (Helmholtz number: $H\omega/c_0$). Clearly the amplitude of the acoustic oscillations can not be determined by a balance between acoustical energy production by a jet drive and energy losses due to friction or radiation as assumed in most models [1].

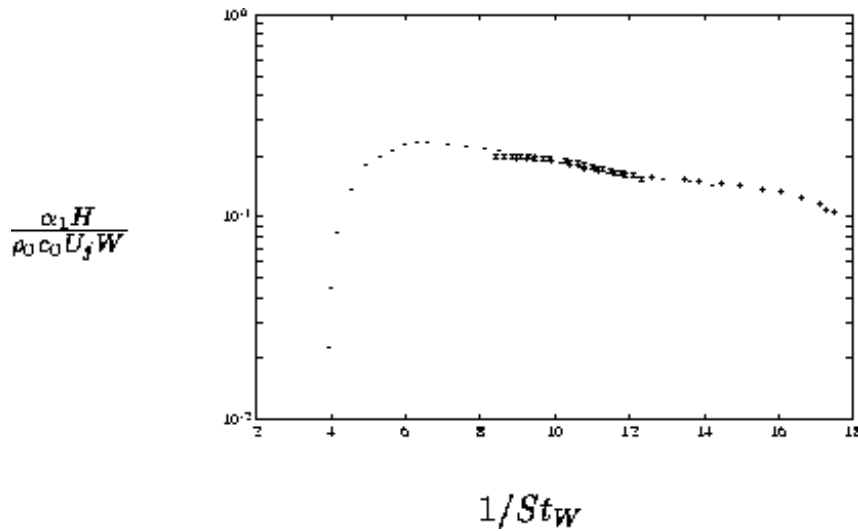


Figure 3: Dimensionless amplitude of the fundamental in a flue organ pipe; $W/h = 4.02$.

Vortex shedding at the labium

The key of this surprising result is that at typical saturation amplitudes, most of the energy losses are due to vortex shedding at the labium. This effect has been already pointed out by Coltman [2] who found that the impedance of the mouth of a flute behaves non-linearly at amplitudes corresponding to playing conditions. The effects of vortex shedding can be taken into account by means of a quasi-stationary free jet model such as proposed by Ingard and Ising [3] which assimilates the effects of vortices to a fluctuating pressure Δp across the mouth given by

$$\Delta p_{\text{vortex}} = \frac{1}{2} \rho_0 \left(\frac{u_a}{K} \right)^2, \quad (5)$$

where K is the vena-contracta factor of the jet which depending on the geometry can vary in the range $0.6 \leq K \leq 1$. This pressure drop opposes the acoustical flow u_a and corresponds to the turbulent dissipation in a free jet, formed by separation of the acoustical flow at the edge of the labium, without pressure recovery. Fabre [4] shows that this simple model provides results comparable to the model of Howe [5] assuming a discrete vortex shedding at the labium.

As can be observed by flow visualizations, two vortices are shed when the jet passes the labium

- one during the jet-labium interaction
- one after the jet has passed the labium.

The second vortex can be observed in Figure 4 and appears to be crucial for the generation of higher harmonics in the sound. As discussed by Fabre [4], when the second vortex disappears due to the laminar to turbulent transition in the jet flow we observe a drastic reduction of the higher harmonics. The first one is observed in Figure 5 where flow separation of the jet flow occurs at the edge of the labium.

The original jet drive model of Fletcher [6] has been modified by Verge [7] and seems to predict reasonably

well the linear behavior of a recorder during a smooth attack transient. The quasi-stationary "acoustically driven" vortex shedding model discussed in this section explains some of the non-linearity which is responsible for a saturation of the amplitude of the acoustical oscillation []. However, a quasi-stationary model of the vortex shedding induced by the jet, and which can be observed in Figure 5, would also be necessary but is not available at the present time. This interaction between the jet and the labium seems to be important in order to understand the difference between a laminar and turbulent jet behavior but also as demonstrated experimentally [] we expect that this vortex shedding is crucial for the attack transient.

Figure 4: Vortex shedding at the labium due to flow separation of the transverse acoustic flow in the mouth of an experimental flue organ pipe; $W/h = 4.02$ mm and $p_f = 270$ Pa.

Figure 5: Flow separation of jet flow at the edge of the labium of of an experimental flue organ pipe; $W/h = 4.02$ mm and $p_f = 270$ Pa.

Effects of the mouth geometry

In recorders, the ratio W/h is adjusted to a value close to four. In other instruments, such as large flue organ pipe, this ratio can be up to three times as high. In flutes, it is adjustable by the musician. Changing this ratio modifies the operating characteristics of the instrument. Figure 6 shows the amplitude \hat{p}_{ω_1} of the fundamental as a function of the driving pressure p_f for a ratio $W/h = 8.0$. Comparison with Figure 2 shows that transitions between the different acoustic mode of the pipe appear at higher blowing pressures. This can be understood by the fact that the perturbations on the jet have a longer distance to travel before they reach the labium; a higher jet velocity is therefore required in order to fulfill the oscillation conditions of the feedback loop of the system. At very low driving pressures, the operation of the instrument displays jumps between different modes of oscillations. This is due to jet oscillations on a higher hydrodynamic mode such as can be observed in Figure 7. In these conditions, the travel time of perturbations on the jet is longer than one period of the acoustical oscillations of the pipe. In this range of driving pressures, the playing frequency changes very rapidly and a chaotic response of the instrument is observed at the transition between hydrodynamic modes of the jet. Increasing the driving pressure enables the instrument to reach the first hydrodynamic mode of the jet such as observed in Figure 8.

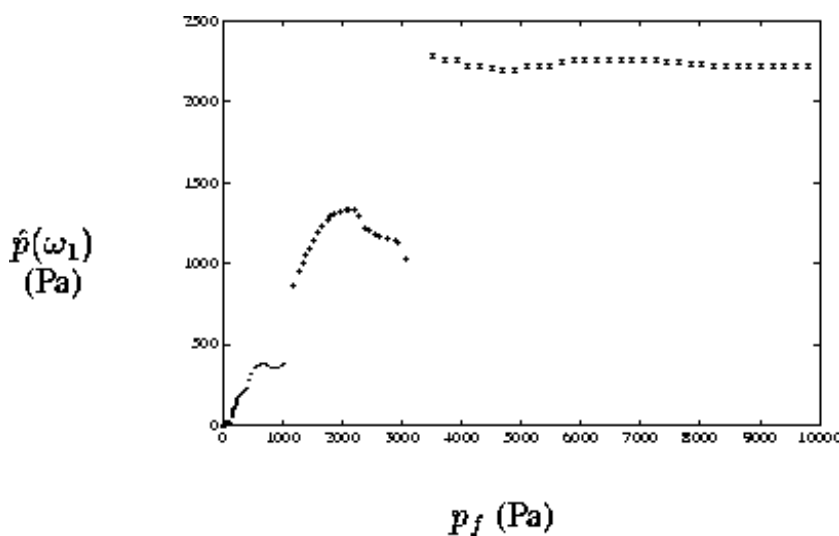


Figure 6: Amplitude $\hat{p}(\omega_1)$ of the fundamental as a function of the driving pressure p_f ($W/h = 8.0$).

Figure 7: Jet oscillation on its second hydrodynamic mode ($W/h = 8$, $p_f = 40$ Pa).

Figure 8: Jet oscillation on its first hydrodynamic mode ($W/h = 8$, $p_f = 270 Pa$).

In Figure 9, the same information is displayed in a dimensionless representation. At low jet velocities, the operation of the instrument on higher hydrodynamic modes of the jet is clearly observed. On this mode, the dimensionless amplitude is weak compared to that of the first hydrodynamic mode of the jet. This could be due to the fact that, as can be observed in Figure 7, the jet oscillation is saturated by a break down of the jet into discrete vortices. At higher blowing pressures, the curves corresponding to operation on the different acoustic modes of the pipe again collapse on a single curve. The curve has roughly the same shape and amplitude as that of Figure 3. It is quite fascinating to note that the measured maximum ratio u_a/U_j is again close to 1/5 even though the mouth geometry has changed. This indicates that this dimensionless representation grasp a fundamental characteristic of the functioning of flue instruments. The mechanism involved are however not yet quantitatively understood.

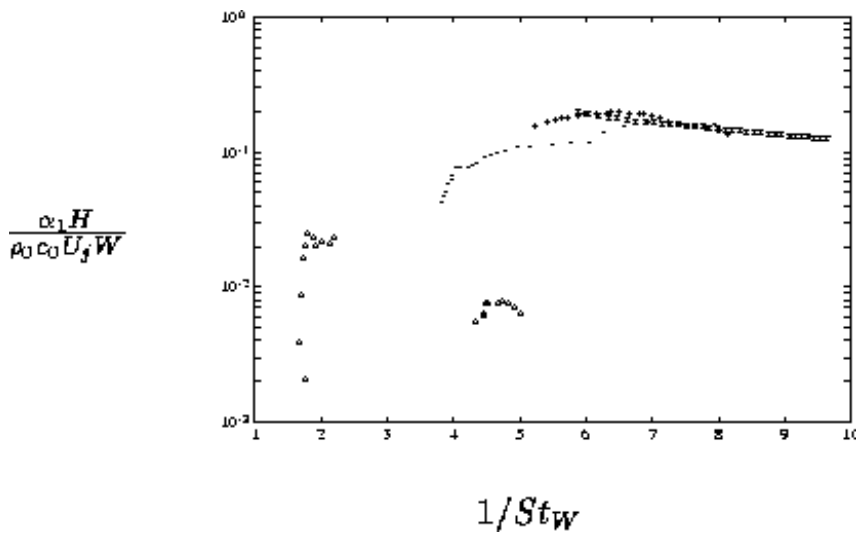


Figure 9: Dimensionless amplitude of the fundamental in a flue organ pipe; $W/h = 8.0$.

Although the dimensionless amplitude of the instrument does not seem to depend on the geometry of the mouth, the ratio W/h strongly affects the timbre of the instrument. The maximum efficiency of flue instruments is obtained, for the fundamental, for values of the Strouhal number lying in the range $0.14 < St_W = f_1 W/U_j < 0.2$. The instrument is however usually played at a Strouhal number $St_W \simeq 0.1$ in order to obtain a strong second harmonic. The corresponding jet velocities necessary to obtain these Strouhal numbers are determined by the ratio W/h . For small ratios such as in recorder-like instruments, the jet is laminar for this range of Strouhal numbers while it is turbulent for larger distances such as in large flue organ pipes. The higher jet velocities found in flue organ pipes enable to obtain a much more powerful sound than in recorders but at the expense of a turbulence noise. Background noise is typically at least 40 dB higher for a ratio $W/h \simeq 8$ than for a ratio $W/h \simeq 4$ for similar driving pressures. The large distance between the flue exit and the labium further enhances this effect because the the jet has more time to develop into turbulence before it interacts with the labium. This is clearly observed in Figure 8. In Figure 4 and 5, obtained with similar driving pressures and a ratio $W/h \simeq 4$, the jet is only turbulent downstream of the labium.

Recorders require a minimum of airflow in order to obtain a rich timbre which is a reasonable requirement for an instrument driven by human power. The shorter ratio W/h also implies that transitions between operation on the different acoustic modes of the pipe are reached at lower blowing pressures which is convenient in order to be able to play the instrument over a large register. Another advantage of a small W/h ratio for recorders is the fact that they always operate on the same (the first) hydrodynamic mode of the jet which means that there is no chaotic transition region between different jet modes. This probably results in a better control of attacks by the musicians. This flexibility is probably not as important in flue

organs where a pipe is adjusted by the organ builder to play a single note.

Conclusion

Dimensionless representation of data measured on different flue instruments shows that the dimensionless amplitude of the fundamental of the acoustic response of the instrument is, for the first hydrodynamic mode of the jet, a function of the Strouhal number only regardless of the acoustic mode excited and the pipe and mouth geometry of the instrument. The maximum ratio between the acoustic flow velocity in the mouth and the jet velocity appears to be approximately equal to 1/5. This universal behavior indicates that amplitude saturation is due to a non-linear interaction of the acoustic flow with the jet flow. The amplitude of the fundamental can not be simply determined by a balance between acoustical energy production by a jet drive and energy losses due to friction and radiation. The optimal efficiency of the instrument is obtained at a Strouhal number $St_W = fW/U_j \simeq 0.2$. Playing the instrument at a Strouhal number $St_W \simeq 0.1$ enables to obtain a strong second harmonics, sometimes as important as the fundamental, and the presence of high frequency components in the spectrum. These observations are correlated with visualizations of the flow in the mouth of the instrument which suggest that vortex shedding at the edge of the labium plays an important role. Although the dimensionless amplitude of the acoustic response of flue instruments appears to be determined by a physical mechanism common to different instruments, the choice of a particular mouth geometry has important consequences on their timbre. In large flue organ pipes, the jet velocities involved are such that the jet is turbulent which yields a noisy sound while in recorders the jet remains laminar, in typical playing conditions, before it reaches the labium. Recorders seem to have been optimized by craftsmen to yield an optimal harmonic content to noise ratio and clear attacks rather than a powerful sound such as in flue organ pipes.

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