EVOLUTION OF SOUND SPECTRA OF FLUE INSTRUMENTS WITH THE CONTROL PARAMETERS AND THE ROLE OF AEROACOUSTICAL SOURCES.

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May 25, 2007

Abstract

In flue instruments, the generation of acoustic energy is concentrated at the interaction between the jet and the sharp edge located in the undisturbed jet path. The periodic excitation of the air column is ensured by the alternating arrival of vortical structures to the inner and outer surfaces of the edge, producing an oscillating force that feeds the standing wave in the resonator.

In this communication we will introduce measurements of the pressure difference accross the edge of the instrument, and the modal pressure amplitudes in the resonator of an experimental flute. A progressive enrichment of the sound spectra is observed as the jet velocity is increased. This can be interpreted in terms of the aeroacoustical sources around the edge. This kind of analysis also allows a discussion of the influence of the jet turbulence on the noise content of the sound.

INTRODUCTION

In flue instruments, sound is generated by the interaction between a standing wave inside the resonator and a jet oscillating between both sides of a sharp edge situated physically in one of the extremities of the resonator [Cremer and Ising, 1968].

This interaction involves a feedback between different mechanisms that influence each other, for instance, the acoustic wave perturbates the jet position, but the movement of the jet alters the standing wave in the resonator.

In the complete instrument, the amplitude of the standing wave and the amplitude of oscillation of the jet are related through this feedback loop. It is the saturation mechanism that imposes a limit to the growth of the auto-oscillation, but it is also responsible for the alteration of the harmonic content in the auto-oscillation.

In fact, the saturation mechanism of the oscillating flow is not the only mechanism capable of generating higher harmonics in the instrument. As referred by Verge [Verge, 1995], for high acoustic flows in the resonator, the sharp edge in the mouthpiece of the instrument can induce the detachment of the flow.

The aim of this article is to investigate the main non-linear mechanisms in a flue instrument that are responsible for the enrichment of the timbre as the dynamics is increased.

SPECTRAL ENRICHMENT AS A FUNCTION OF BLOWING PRESSURE

The increase of the harmonic content in the sound generated by the instrument is easily observable by a measurement of the internal pressure inside the resonator.

The internal pressure measurement is done at a point close to (but not exactly at) the input of the resonator, at an effective distance l_{eff} that takes into account the length correction due to sound radiation at the edge of the instrument. In order to be able to compare the different harmonics, the amplitude of each measured harmonic should be corrected to obtain the amplitude of the corresponding standing (nth) mode:

$$p_{\text{mode}} = \frac{p_{\text{meas}}}{sin(n\pi l_{\text{eff}}/L)} \tag{1}$$

where L is the effective length of the resonator. Using this correction, the amplitude of each of the modes is plotted in figure 1 as a function of the adimensionned velocity $St_W^{-1} = \frac{U_j}{fW}$, where W is the window length (distance between the jet exit and the edge), U_j the central velocity of the jet and f the frequency of the oscillation. Since this number is proportional to the jet velocity, it increases as the square root of the blowing pressure $p_m^{1/2}$.

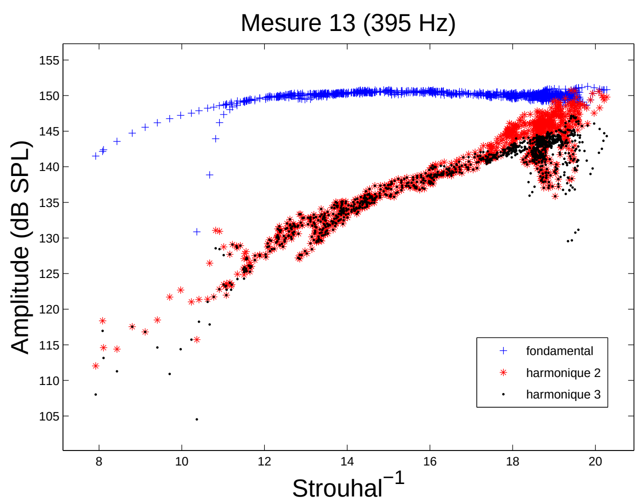

Figure 1: Amplitude of different harmonics p_i of the acoustic pressure as a function of the blowing pressure

In several experiments similar to the one that generated the results in figure 1, but involving different fingerings and different flutes [Blanc, 2006] [Gäbriels, 2006] [Verge et al., 1997], the fundamental is seen to remain nearly constant for most of the blowing pressure range. In fact, it reaches a maximum value for a Strouhal number of about $Str_W = 14$

The growth of higher harmonics seems to start at the blowing pressure corresponding to the maximum value of the fundamental.

HARMONIC GENERATION MECHANISMS

In the following paragraphs we characterise two of the non-linear mechanisms acting on the flute auto-oscillation. A comparison is made between the power injected into harmonics by each of two non-linear mechanisms when excited by a sinusoidal input. In the auto-oscillating instrument harmonics become important as soon as their filtering by the linear terms of the instrument are of same magnitude as the new harmonics generated by non-linearities. In terms of perceived sound, however, harmonics can become important at lower dynamics, because the radiated sound can be seen as the result of applying a filter to the internal acoustic wave, roughly a high-pass filter.

Saturation in the jet-drive mechanism

The interaction between the jet and the acoustic wave is the main mechanism that can feed the auto-oscillations of a flue instrument. One of the models available to describe this mechanism is the *jet-drive* model [Verge et al., 1994] which can be a considered as a first-order aproximation to the complex aero-acoustic interaction at the edge . It also provides an intuitive way of taking into account the jet oscillation in a one-dimensional instrument model.

The displacement of the jet η is approximately proportional to the acoustic perturbation (the sound wave in the resonator) [de la Cuadra, 2005]:

$$\eta(x,\omega) = \eta_0 \exp\left(-\imath\left(\frac{\omega}{c_j} - k\right)x\right) \tag{2}$$

where η_0 depends on both the amplitude u_{ac} and the frequency ω of the acoustic wave in the resonator [Verge, 1995]:

$$\eta_0 = \frac{u_{ac}}{U_j} h \tag{3}$$

A bigger displacement amplitude of the jet causes the flow input Q_1 and output $Q_2 = \int_{-\infty}^{+\infty} U_j(y)dy - Q_1$ on both sides of the edge to increase:

$$Q_1 = H \int_{\eta - y_0}^{+\infty} U_j(y)dy \tag{4}$$

with H the transverse dimension of the flue window and y_0 the transverse position of the edge relative to the centre of the flue. This *jet-drive* model [Verge et al., 1994] implies that the injected flow is approximately linear only as long as the jet does not move beyond the edge, otherwise the induced flow cannot grow beyond the total volume flow in the jet $\int_{-\infty}^{+\infty} U_j(y)dy$.

The local oscillating pressure difference $(\Delta p)_{jd}$ is calculated from the unstationary flow dipole (Q_1, Q_2):

$$(\Delta p)_{jd} = \frac{\rho_0 \delta_d}{S_m}\frac{dQ_1}{dt} = \frac{\rho_0 \delta_d}{S_m}\imath\omega Q_1 \tag{5}$$

Two extreme cases of jet profiles (figure 2) can be compared corresponding to very short (top-hat) and very long (Bickley) flue channels. The interest is to investigate the influence of the steepness of the profiles on the harmonic generation.

For a given sinusoidal oscillation of the acoustic velocity $u_{ac}(t)$, both the time variations of $Q_1(t)$ and $(\Delta p)_{jd}(t)$ are calculated, and the amplitude of the harmonics in each signal analysed as a function of the amplitude of u_{ac}.

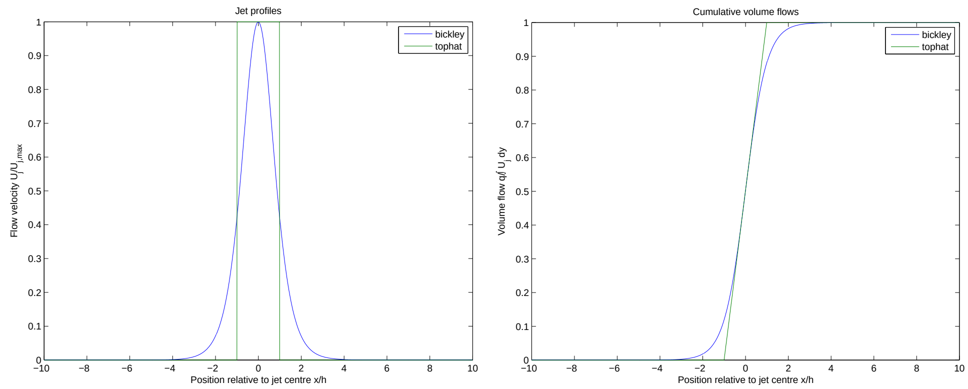

Figure 2: Jet profile and cumulative flow for two extreme cases of the jet profile

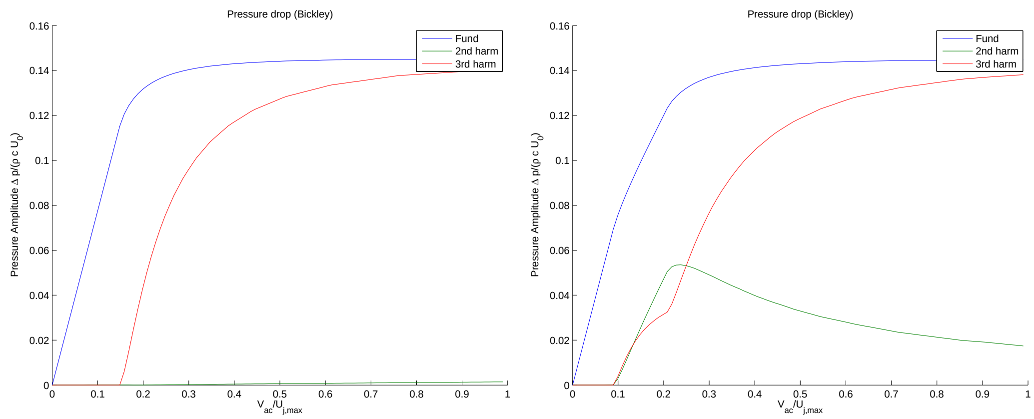

Figure 3: Amplitude of the "jet-drive" pressure source $(\Delta p)_{jd}$ as a function of the acoustic wave u_{ac} for a centred (at left) and uncentred top-hat jet

The oscillation of the steepest possible profile (top-hat) is simple to analyse. For narrow oscillations the amplitude of Q_1 varies linearly with the amplitude of the acoustic wave, because the integration limits in equation (4) also vary linearly. No harmonics are added to the signal. As soon as the jet boundaries cross the edge, the saturation occurs either completely or partially depending on whether the jet is centred or not on the edge (figure 3). Displacing the edge from the centre-line of the jet has the effect of adding content in even harmonics which are otherwise absent [Fletcher and Douglas, 1980].

A similar plot can be done for the Bickley jet, showing a smoother buildup of the higher harmonics due to a gentler velocity profile.

Flow separation in the window

As the blowing pressure is increased, the flow amplitude can become sufficiently strong that the flow detaches from the sharp walls of the edge. Due to the coupling with the resonator, the injection of a higher harmonic is amplified by the feedback-loop.

Some proposed models [Fabre et al., 1996] based on vortex production can predict a distribution of harmonics biased towards high frequencies due to generation of short-lived vortexes. In this text we will suppose a pressure drop induced by

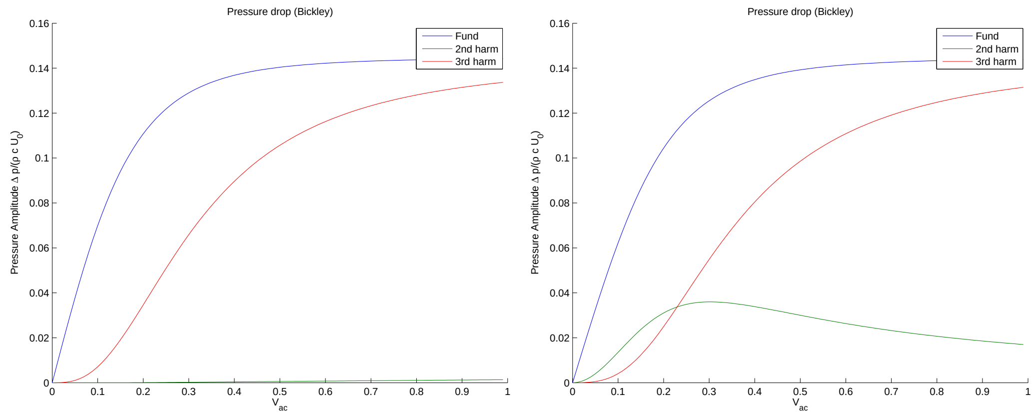

Figure 4: Amplitude of the "jet-drive" pressure source $(\Delta p)_{jd}$ as a function of the acoustic wave u_{ac} for a centred (at left) and uncentred Bickley jet

flow separation maximised by a complete energy loss of the jet after the window [Ingard and Ising, 1967]. If, however we suppose the flow separation to occur only for outgoing flows, the pressure drop due to flow separation should disappear when u_{ac} is positive:

$$(\Delta p)_{fs} = \mathrm{sign}(u_{ac})\frac{1}{2}\rho u_{ac}^2 \tag{6}$$

This "flow separation" term introduces higher harmonics whose amplitude can be calculated by an inverse Fourier transform of the $(\Delta p)_{fs}(t)$ for a sinusoidal input $u_{ac}(t) = u_0 \sin(\omega t)$. Equation (6) is used as an upper bound of the harmonic power induced by this effect.

Experimental measurement of harmonic generation in the window

The previous analysis is based on a simplified model of the flow separation in a window. The generation of harmonics can be verified experimentally by forcing the resonator with a sinusoidal wave by an external source such as a loudspeaker.

This configuration is different from the normal functioning of the flute in the sense that the usual excitation mechanism and non-linear feedback of the flute (the jet-drive) is not driving the oscillation in the resonator. The acoustic wave is also supposed to be independent from the excitation, that is, no feedback from the acoustic wave is supposed to influence the loudspeaker.

If the device (figure 5) is driven at its resonance frequency (which can be searched by scanning of the amplitude of the acoustic wave for different frequencies around the natural resonance frequency of the flute), the acoustic flow u_{ac} will have an anti-node at the window. This ensures that an eventual flow-separation is maximised an the acoustic configuration of the resonator is maintained from the normal use of the flute.

Simultaneously, a measurement of the force on the edge due to the pressure difference between both sides of the edge is recorded for comparison with data from a jet-blown flute.

The device must be driven at very intense sound fields so that the acoustic power in the resonator is of similar magnitude as when the flute is blown. As a consequence,

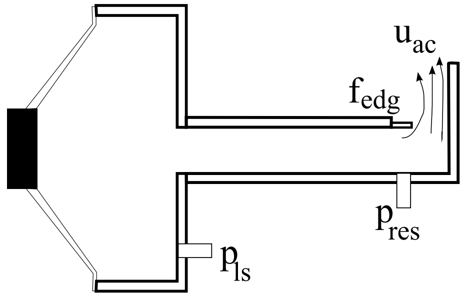

Figure 5: Experimental device used for the measurement of harmonic generation by flow separation in the window: a sinusoidal acoustic wave is generated by the loudspeaker (on the left) and the pressure near the window p_{res} is measured

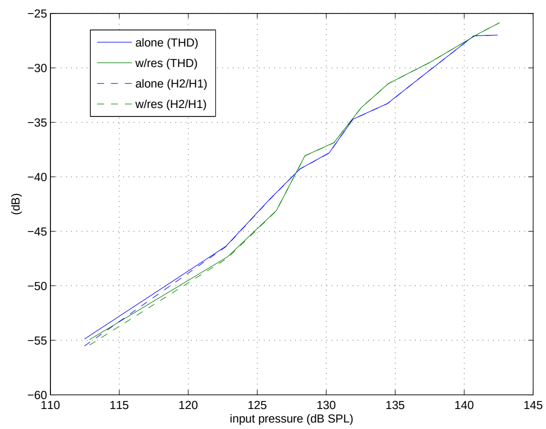

Figure 6: Total harmonic distortion (THD, solid line) and second to first harmonic amplitude ratio (dashed line) in the loudspeaker chamber with and without the flute coupled to it (against loudspeaker pressure amplitude).

slight distortions are expected in the acoustic wave generated by the loudspeaker. These are measured by removing the flute resonator from the loudspeaker chamber.

Harmonic distortion with the flute coupled to the loudspeaker chamber is compared to the intrinsic harmonic distortion of the loudspeaker (figure 6). The difference between both cases is lower than 2 dB. And the two curves oscillate above and below each other. This leads to the conclusion that the intrinsic harmonic distortion in the loudspeaker completely masks the distortion due to flow separation. The curves represented in figure 6 are thus a maximization of the real distortion due to flow separation.

Comparison of non-linear effects

Measurements of the harmonic generation by the jet-drive mechanism of equation (4) as an isolated component are difficult to achieve in a complete flute, because they are responsible for the generation of the auto-oscillations in the flute. A first evaluation of the relative magnitudes of both studied mechanisms (jet-drive and flow separation at the window) can be done by comparing the calculations of the jet-drive harmonic generation (figure 3 and 4) and the measurements presented in figure 6 for the flow separation (figure 7). This shows the higher harmonics in the

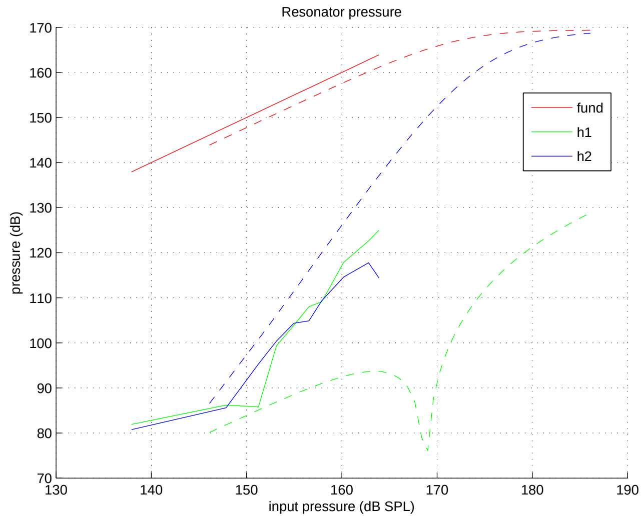

Figure 7: Comparison of the harmonic power generated by the two mechanisms, against pressure amplitude in the resonator: jet-drive (calculated, fixed $U_j = 10m/s$) and flow separation in window (measured, upper bound).

flow separation to be below the ones calculated for the jet drive.

Another comparison can be made between the calculations for the jet-drive and the overall spectral content in the instrument auto-oscillation (figure 8). This includes not only the harmonics generated by both non-linearities acting upon a sinusoidal excitation but also the amplification of higher harmonics already present in the acoustic wave by the linear term in equations (4) and (5).

For small amplitudes, however, the contribution of the latter to the signal resulting of the application of the non-linearity can be neglected, as shown for example in figure 1. It is seen that the relative harmonic content in the auto-oscillation, in particular for the second harmonic, is much higher in the auto-oscillation.

CONCLUSION

In this article we presented a preliminary comparison of the different non-linear generation mechanisms in a recorder. Although there are some difficulties with these measurements, a curve that maximises the harmonic content due to flow separation on the window was found, and is shown to produce significantly lower harmonic content than the jet-drive mechanism.

Further investigation will include the measurement of the non-linearity by replacing the waveguide resonator by a sinusoidal acoustic excitation. This will allow a clearer comparison with the theoretical harmonic generation plots of figures 3 and 4.

This work was funded by the CONSONNES project.

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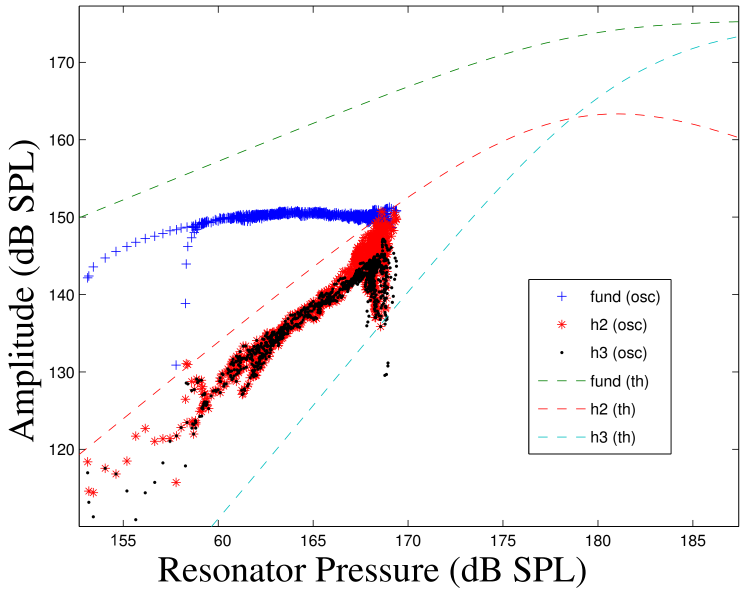

Figure 8: Total harmonic distortion (THD, solid line) and first to second harmonic ratio (dashed line) in the resonator with and without the flute coupled to it.

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