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Turbulence Noise in Flue Instruments

A. Hirschberg, M.P. Verge

ISMA 95, Dourdan 1995

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Abstract:

This paper presents a simple turbulence noise model that could be used for time domain simulations of flue instruments. The turbulence noise sources are deduced from spectra measured inside a small recorder-like flue organ pipe and by using a one-dimensional representation of the instrument. The amplitude of these sources display a maximum located at a Strouhal number corresponding, for Reynolds numbers > 3000 , to the maximum instability of a plane jet. The turbulence noise source appears to have a dipolar character and its amplitude scales with the square of the jet velocity.

Introduction

Turbulence noise is an essential component of the tone of flue musical instruments. Although it does not contribute fundamentally to the functioning of the instrument, a noise module is important to include in a simulation model in order to obtain a natural sounding synthesis. Figure 1 shows a power spectra measured in a small recorder-like organ pipe upon steady blowing conditions. The experimental flue pipe is described by Fabre and Verge [1]. The harmonically related frequency components associated with the feedback mechanism of the instrument clearly dominate the spectrum. However the turbulent structure of the jet flow also produces a strong background noise. This broad band sound source is filtered by the pipe resulting in the presence of little bumps at frequencies corresponding to passive resonances of the pipe. The objective of this paper is to describe a simple source that could be used in simulations to reproduce these phenomena. The behavior of this source, in a simple one-dimensional representation of the instrument, is compared to experimental data.

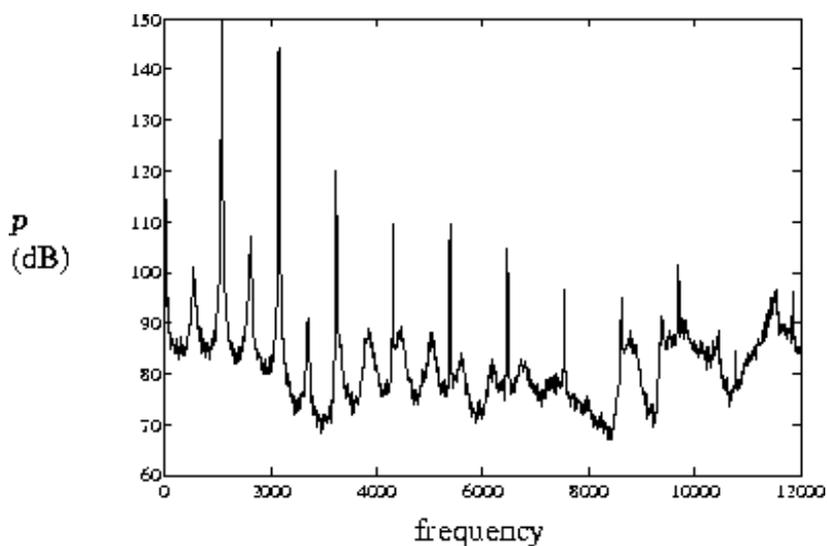


Figure 1: Power spectra of the pressure signal p (in dB rel $20 \mu\text{Pa}$) measured in a small experimental recorder-like organ pipe at the end of the resonator (50.25 mm from the passive end of a 0.283 m long pipe) for a driving pressure p_f of 2500 Pa.

Analytical analysis

The Lighthill analogy [1, 2] enables to describe the sound production from so-called *aero-acoustical* sources induced by unsteady flows. The noise produced by turbulent jets can only be characterized analytically for simple geometries since noise production depends on the jet shape and is strongly affected by the presence of bodies or walls in the flow. This implies that in order to go beyond generalities, we will have to rely on empirical data to describe noise production in complex geometries such as that of flue instruments.

Turbulence in free-field is dominated by weak quadrupoles. Lighthill showed that it is a very inefficient sound production mechanism scaling with the 8-th power of the jet velocity. The efficiency of the noise source is however enhanced by the presence of objects in the flow. In the case of the interaction of a compact edge with a turbulent flow, the sound production is dominated by the force provided by the edge. This was proved by Powell [3] in a beautiful experiment. When placed in a pipe of infinite length, a turbulence noise source interacting with an edge can be shown, following Ffowcs-Williams [4], to radiate like the 4-th power of the Mach number.

Because of the presence of the edge of the labium, the turbulence noise source in flue instruments can be expected to display a dipolar nature and therefore to have an intensity that scales with the square of the jet velocity U_j . Furthermore, because of the confinement of the source in a pipe, the internal far-field radiated intensity should be proportional to the 4-th power of the Mach number. The situation is however further complicated by the finite length of the pipe which induces resonances and the fact that the instrument is usually played at low Reynolds number which might strongly affect the nature of the sound source.

The noise source

Flow visualizations in the recorder-like experimental flue pipe [5] show that the nature of the flow in the mouth of the instrument is strongly dependent on the driving pressure p_f . For driving pressures around 60 Pa the flow is laminar. This driving pressure corresponds to a jet velocity U_j of 10 m/s and a Reynolds number (based on the flue exit height $h = 1.0$ mm) of approximately 700. When the jet velocity is increased, the coherent two-dimensional structure of the jet is destroyed after it has reached the labium and the flow then becomes turbulent. The Reynolds number is therefore high enough for the jet to develop into turbulence but only after a certain delay or having interacted with the edge of the labium. Because of the jet oscillations, puffs of turbulence appear periodically on each side of the labium and the noise is therefore expected to display a pulsating (intermittent) character. When the Reynolds number reaches a value of approximately 3000 ($U_j \simeq 45$ m/s), the jet is already fully turbulent at the flue exit. The turbulence noise is then expected to be less dependent on the acoustically driven jet oscillations.

In real instruments, the importance of the noisy component in the tone is therefore expected to vary greatly depending on the playing conditions. In recorders, the Reynolds number appears to lie within the range $1000 < Re < 2000$ in typical playing conditions. The oscillating jet therefore always remains laminar at least until the labium has been reached. Apparently, this family of instruments has been optimized so that turbulence only plays a secondary role. However in typical playing conditions for flutes and large flue organ pipe, the Reynolds number is well above 3000 and turbulence noise is then very characteristic of the timbre of the instrument.

A noise source was determined by considering a one-dimensional representation of the instrument such as shown in Figure 2 and which is described by Verge [6]. In this representation, a dipolar sound source is equivalent to a pressure jump Δp across the mouth of the instrument. The amplitude of the noise source is obtained by calculating the amplitude Δp that would result in the measured spectra for a given frequency and jet velocity. The noise spectra were obtained by placing the labium above the flue exit in order to avoid auto-oscillations of the instrument. In Figure 3, sources obtained for different jet velocities and obtained by considering a wide range of frequencies are presented. For convenience, we only present the

data corresponding to maxima in the spectra.

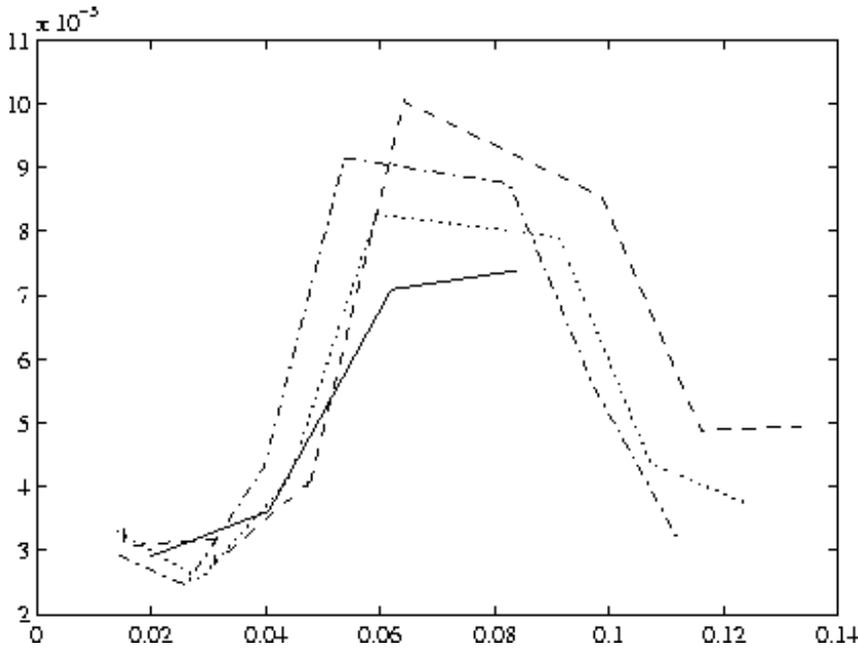


Figure 2: One dimensional representation of a flue instrument.

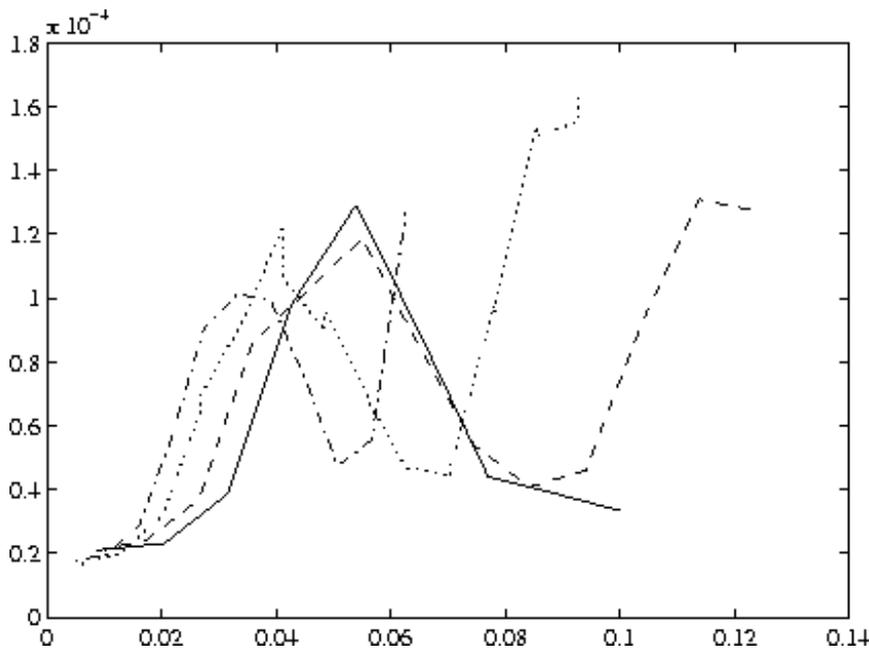


Figure 3: Amplitude of the turbulence noise source Δp calculated from acoustic pressure measurements made at the end of the pipe as a function of the Strouhal number $St = fh/U_j$: a) driving pressure $p_f = 400$ Pa (solid line), 690 Pa (dashed), 800 Pa (dotted) and 980 Pa (dashdot); b) $p_f = 1560$ Pa (solid), 2200 Pa (dashed), 3920 Pa (dotted) and 6080 Pa (dashdot).

The dimensionless amplitude of the different sources appears to be relatively constant over a wide range of driving pressures which indicates that the assumption of a source having a dipolar character and scaling with the square of the jet velocity is reasonable. The calculated noise sources display a maximum amplitude for values of the Strouhal number shifting from approximately 0.08 to 0.03 as the blowing pressure is increased. The fact that noise production is dominant at certain Strouhal numbers suggests that it could be linked to specific movements of the jet. It is a classical idea in turbulence modeling [], that noise production by turbulence, at low frequencies, can be related to instability waves of unbounded

frictionless jets predicted by linear theory. At high driving pressures, the maximum of instability found in Figure 3 coincides with the Strouhal number at maximum sound production found by Bjørnø and Larsen [] in the case of a planar free jet. At lower blowing pressures, the jet could be more sensitive to edgetone oscillations [] of the jet which might explain a shift in Strouhal number. This shift of the maximum could also be linked to a change in the velocity profile from a Poiseuille velocity profile at low velocities to a uniform profile as the jet becomes turbulent at the flue exit. For high jet velocities, the amplitude of the noise sources display a second increase. This can apparently be linked to a transversal acoustic resonance of the pipe.

Similar results can be obtained by considering spectra, such as shown in Figure 4, obtained with a jet blowing on the labium and by damping the longitudinal resonances of the pipe with a muffler. In this spectra the effects of the confinement of the jet in the pipe are clearly observed. Below 8 kHz, the source is "colored" by the passive resonances of the pipe. At 8.1 kHz, a spectacular jump of more than 30 dB is observed. This frequency corresponds to the cut-off frequency of the pipe and this jump is therefore due to a transversal resonance of the pipe. A similar jump is also observed in the spectrum presented in Figure 1. Above this frequency, the pipe responds in a complex manner through transversal oscillations and edgetone feedback loops. These edgetone phenomena were not taken into account in the definition of the turbulence noise source since they should appear naturally in a simulation model as a result of feedback loops.

The source determined by following maxima and minima in spectra similar to that of Figure 4 is shown in Figure 5. The resulting noise source is very similar to that shown in Figure 3. The source obtained by using minima is less dependent on the Strouhal number than that obtained with maxima. The fact that the source obtained by using the maxima has a higher amplitude could be the consequence of the fact that the turbulent jet could respond to an acoustical feedback at the pipe resonances. The source obtained by using minima might therefore be more characteristic of the "pure" turbulence noise source.

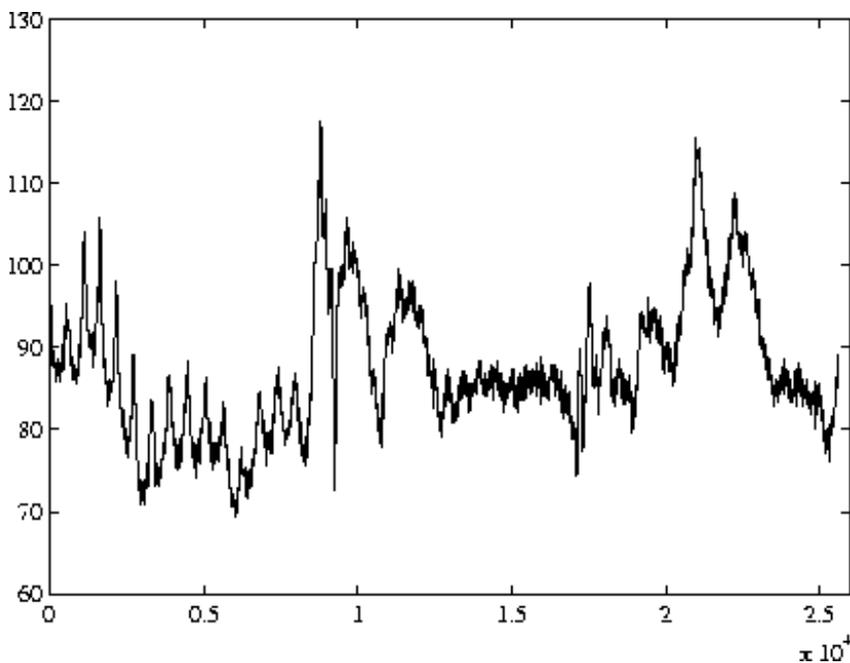


Figure 4: Power spectra of the pressure signal p (in dB rel $20 \mu\text{Pa}$) measured in a small experimental recorder-like organ pipe at the end of the resonator (50.25 mm from the passive end of a 0.283 m long pipe) for a driving pressure p_f of 7250 Pa with a muffler placed at the end of the pipe.

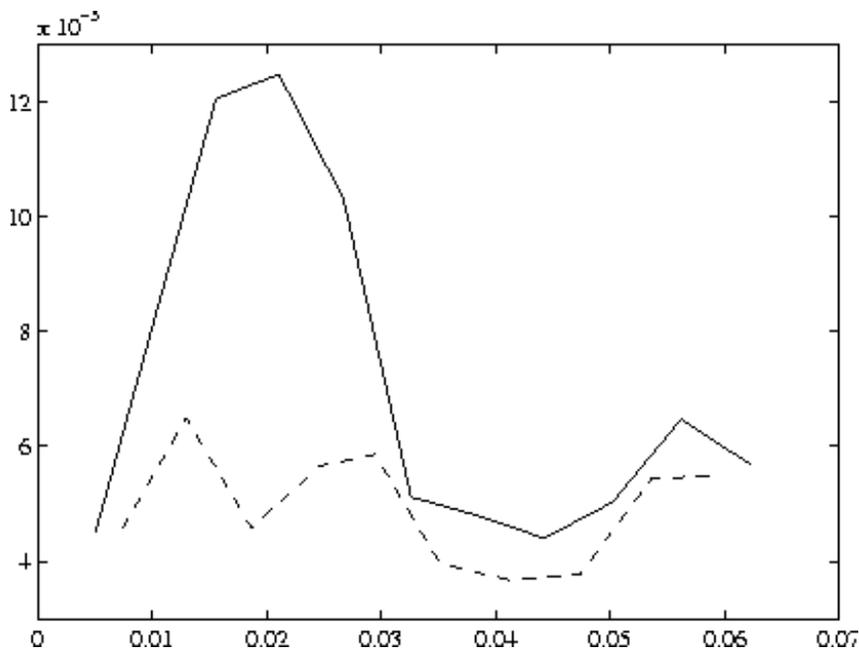
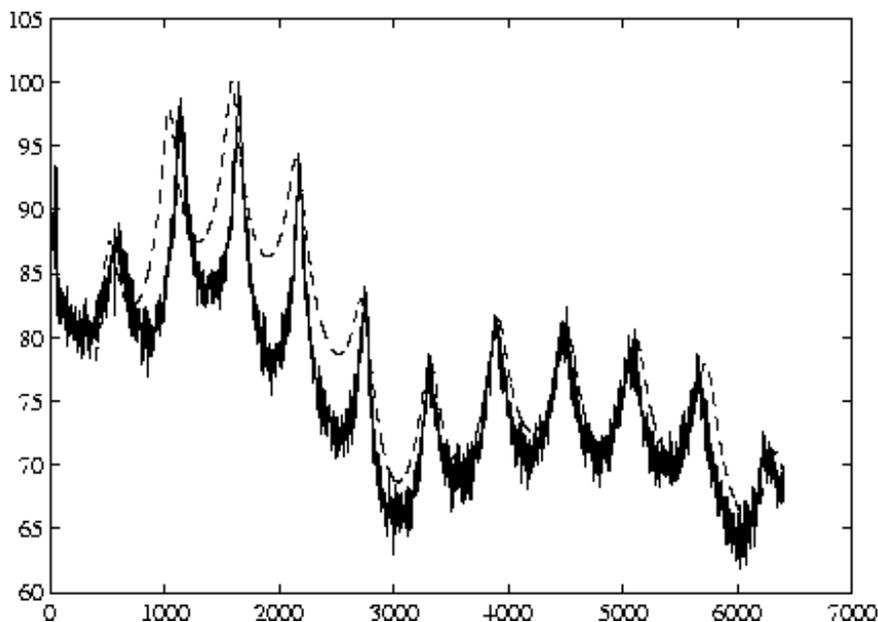


Figure 5: Amplitude of the turbulence noise source Δp calculated from acoustic pressure measurements made at the end of the pipe for a driving pressure p_f of 7250 Pa as a function of the Strouhal number $St_h = fh/U_j$. Source obtained by using the **maxima** on the power spectra: solid line, by using the **minima**: dashed line.

In order to check the validity of the sources deduced from the measurements, one can reintroduce them into the pipe model and compare the resulting responses of the system to the measured signal. In order to calculate the responses at all frequencies, linear interpolation is used to determine the value of the source at points located between maxima (or minima). In this way a complete response of the system is obtained from only about ten measuring points on the noise spectra. Figure 6 shows such responses obtained by using the noise sources shown in Figure 5.



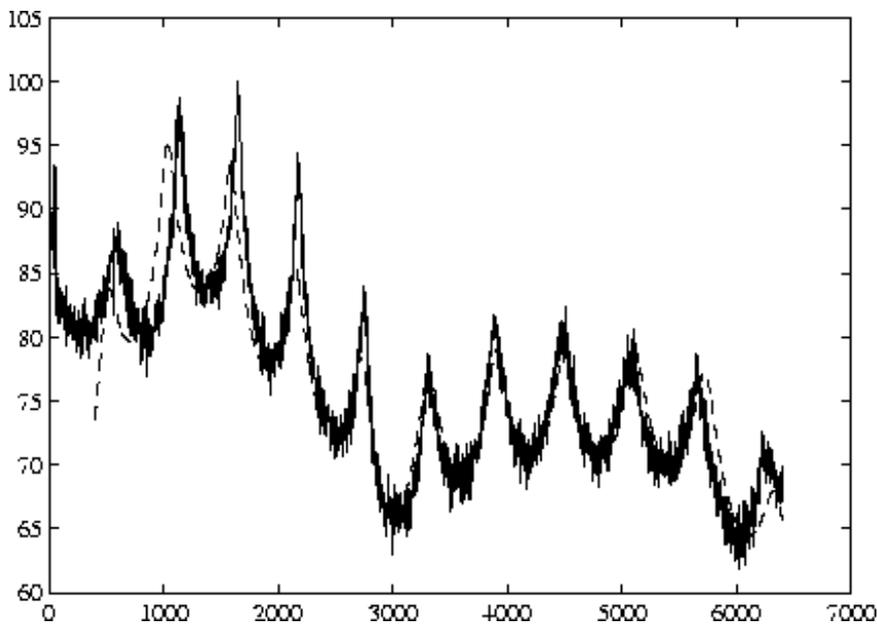
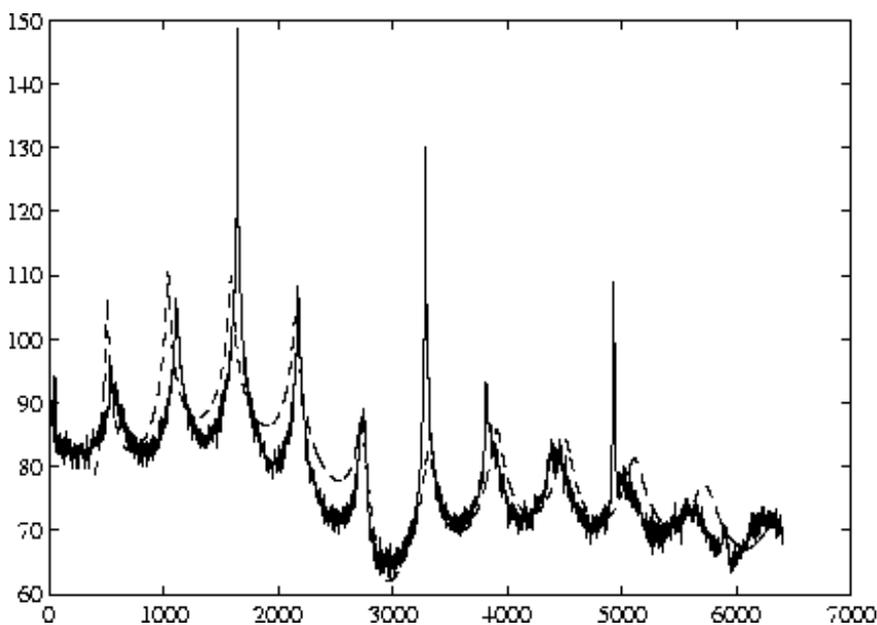


Figure 6: Comparison between internal power spectra of the pressure p (in dB rel $20 \mu\text{Pa}$) measured at the passive end of the resonator with a muffler placed at the end of the pipe (no pipe tone) at a driving pressure of 7250 Pa and the corresponding predicted spectra calculated by using the noise source deduced from a) **maxima** and b) **minima**.

The noise sources have been deduced from measurements performed with a muffler placed at the end of the tube. In order to determine if these sources could be considered as good estimates of the sources that would be obtained with auto-oscillations of the jet and therefore a pipe tone, the calculated noise spectra obtained with the sources of Figure 5 are compared in Figures 7 to the spectra measured without using a muffler. The shape of the responses as well as the level of the noise appear to be very well predicted by these sources implying that globally the movement of the jet does not seem to have a strong influence on the nature of the turbulence noise source. One must however be careful with this conclusion since, in this case, the noise source was obtained for a high driving pressure (7250 Pa) which means that the oscillations of the jet do not have a great amplitude. At lower driving pressures, the movement of the jet should be broader and therefore might have a stronger influence on the noise source.



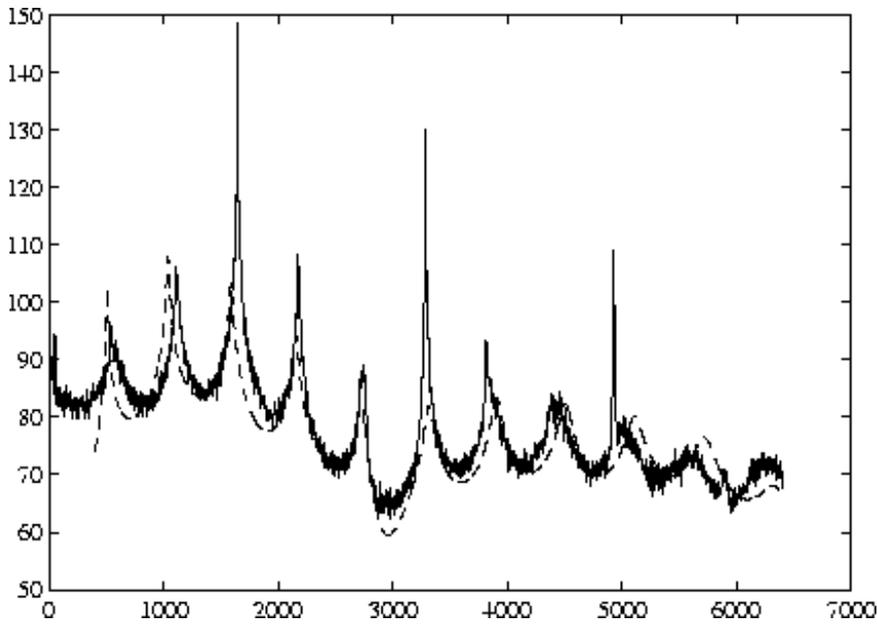
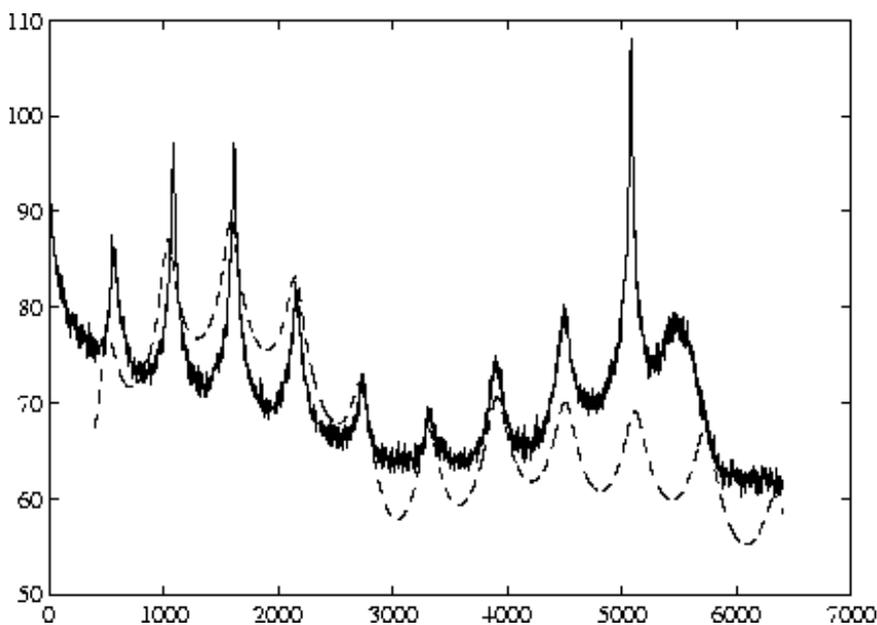


Figure 7: Comparison between internal power spectra of the pressure p (in dB rel $20 \mu\text{ Pa}$) measured at the passive end of the resonator *without a muffler* placed at the end of the pipe (with a pipe tone) at a driving pressure of 7250 Pa and the corresponding predicted spectra calculated by using the noise source deduced from a) **maxima** and b) **minima**.

As a last test of its validity, the noise source found in Figure 5 was used to predict the noise spectra measured at a driving pressure different from that at which it was deduced. Following the assumption that the source has a dipolar nature, the amplitude of the source at any driving pressure can be calculated by assuming that it scales with the square of the jet velocity. Results obtained for a driving pressure of 2090 Pa are compared, in Figure 8, to measurements performed with and without a muffler. For frequencies below 3 kHz, the amplitude is well predicted for all measurement positions. For higher frequencies, the noise level is underestimated. This effect could be corrected by shifting the source maximum towards higher values of the Strouhal number. It is interesting to note that in the case where an anechoic termination is used, the simulations enable to clearly bring out the effects of an edgetone feedback loop which dominates the oscillation around 5 kHz.



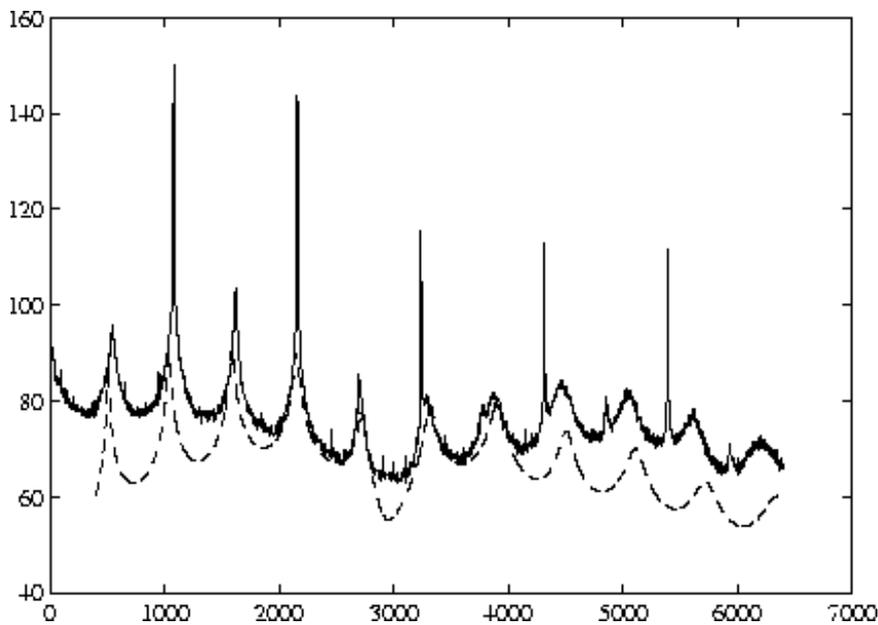


Figure 8: Comparison between power spectra of the pressure p (in dB rel $20 \mu\text{Pa}$) measured in the pipe a) **with a muffler** placed at the end of the pipe (no pipe tone) and b) **without a muffler** (with a pipe tone) at a driving pressure of 2090 Pa (solid line) and the corresponding predicted spectra (dashed line) calculated by scaling with the square of the jet velocity the noise source deduced from **maxima** and shown in Figure 5.

Conclusion

This preliminary study of turbulence noise in recorder-like instruments indicates that the turbulence noise source can, in a first approximation, be represented by a dipole in the mouth of the instrument. In a one-dimensional representation, this can be obtained by placing a fluctuating pressure jump of amplitude Δp , scaling with the square of the jet velocity, across the mouth of the instrument. The shape and level of the measured background noise appears to be well predicted by this model with and without auto-oscillations of the instrument. The steady-state oscillating motion of the jet does not therefore appear to modify substantially the nature of the turbulence noise source. For low Reynolds numbers ($700 < Re < 3000$), the flow only becomes turbulent downstream of the labium, essentially as a result of the jet-labium interaction. For this range of Reynolds number, the scaling of the source amplitude with the jet velocity could not be clearly established because of a lack of experimental data at low driving pressures. Because of the jet oscillations, the turbulence noise is expected to be intermittent. In these conditions, a certain phase lag might occur between the movement of the jet and the development of chaotic three-dimensional motion. Consequently, a thorough study of the behavior of the noise source at low blowing pressures should include an analysis of the dynamics of the noise production phenomena.