Contributions of Bram Wijnands to Experimental Aeroacoustics, part II: woodwind musical instruments

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A.P.J. (Bram) Wijnands (1934-2017) was a skilled musician and music instrument builder. He was mostly involved with renaissance music with the group *Au Joly Bois*. Around 1984 Bram initiated a study on the geometry of the recorder mouthpiece, based on flow visualization. Inspired by the work of Philippe Bolton, he was seeking for the optimization of the flue-labium combination. Collaboration was initiated in 1988, thanks to René Caussé, with Ircam and with the Laboratoire d'Acoustique Musicale (LAM, UPMC), where physical models were developed for sound synthesis. The flow visualization of Bram was primordial ; in particular it allowed a study of the complex flow during the attack transient, which had been ignored in the literature. This is an ongoing research. The physical models have been incorporated in sound synthesis by Applied Acoustics Systems (AAS, Montréal). In parallel, work was carried out in collaboration with the Laboratoire d'Acoustique de l'Université du Maine (LAUM) on the clarinet and trombone. Bram's experiments provided quantitative relationship between flow and pressure difference in the mouthpiece of reed instruments. They also demonstrated the relationship between brassy sounds of copper instruments and the formation of shock waves. One can state that Bram has revolutionised various aspects of our understanding of the fluid mechanics of wind-instruments. Research on those subjects is still ongoing in France and is described in the paper.

1 Introduction

The first part of the work presented in this article originated in the early nineties and is the fruit of a collaboration between researchers from LAM, IRCAM, and TUE. The goal was to develop an understanding of the functioning mechanisms of flute-like instrument and eventually to obtain a simple model suitable for musical applications of sound synthesis. The sound production mechanisms of flue instruments, such as recorders, pipe organs, and flutes, is based on complex hydrodynamic phenomena in the mouth of the instrument. Flow visualizations have been a crucial element in the identification and understanding of the phenomena involved and of prime importance in the development of a time-domain simulation model. These flow visualizations were carried out on a clever experimental set-up put in place by Aberham, Petrus, Joseph (Bram) Wijnands and based on an organ pipe with a geometry similar to that of dutch street organs and renaissance recorders. Around 1984 Bram initiated, at the Technische Universiteit Eindhoven (TU/e), a study on the geometry of the recorder mouthpiece based on flow visualization. Inspired by the work of the musical instrument maker Philippe Bolton [1], he was seeking for the optimization of the flue-labium combination for renaissance recorders. This experimental set-up, described in details by Fabre [2] and Verge et al. [3], allowed for simultaneous flow visualization in the mouth of the instrument and acoustic measurements in the foot and resonator of the instrument, see Fig. 1. It is a perfect example of the unique contribution of Bram, resulting from the combination of his know-how as an engineer, musician, and instrument maker.

While Bram had initiated the research on flue instruments at TU/e around 1984, Hirschberg and Bram decided in 1985 to focus on the physics of reed instruments. In 1988 this work was continued in close collaboration with the LAUM. The focus at TU/e was to obtain high quality measurements of the quasi-static pressure-flow relationship through a slit shaped channel representing a reed [4]. The work at the LAUM was more on the dynamics of the instrument and included acoustic coupling between the reed and the pipe. Later the collaboration was extended to the non-linear behaviour of brass-instruments. The brassy sound of such instruments appeared to be due to shock-wave formation [5]. These contributions of Bram are the subject of the second part of the present paper.

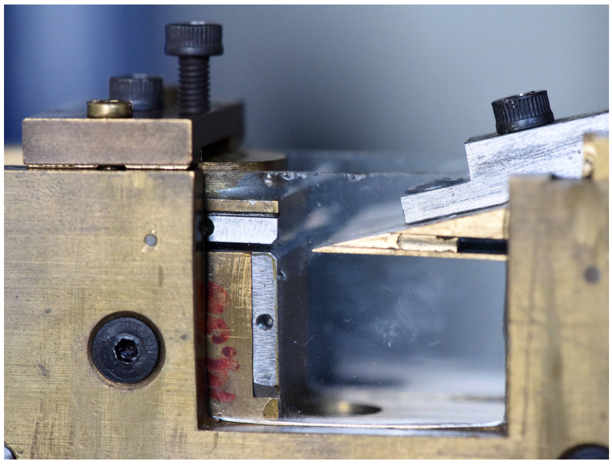

FIGURE 1 – Experimental adjustable organ pipe built by Bram Wijnands, allowing simultaneous flow visualization and acoustic measurements.

2 Flow Visualization and Modelling of Flute-like Instruments

2.1 A Simple One-Dimensional Model for Sound Synthesis

The functioning of flue instruments, such as recorders, pipe organs, and flutes, can be viewed as a feedback loop between an air jet oscillating around a sharp edge, the labium, and an acoustic field in the pipe of the instrument. This system had earlier been studied by Powell [6], Cremer and Ising [7], Coltman [8], Fletcher and Twaithes [9] and Yoshikawa and Saneyoshi [10]. Verge et al. [3] proposed a simple model for real-time simulation, shown in Fig. 2, based on a one-dimensional representation of these instruments. The tube of length L_p represents the resonator of the instrument where acoustic wave propagation phenomena occur. The small tube of length $\delta_m = \delta_{in} + \delta_{out}$ represents the mouth of the instrument where the flow is assumed to be locally incompressible. The flue exit, from which the jet flow Q_j emerges, is located at a distance $-\delta_{in}$ from the entrance of the pipe. A detailled analysis of the influence of the pipe's geometry on the small tube length has recently been proposed by Ernoult [11]. In the model described Fig.2, all the sound producing mechanisms have been lumped into a pressure jump Δp across the mouth of the instrument. These mechanisms include the jet-drive mechanism, vortex shedding at the labium, and turbulence noise. We will discuss how flow visualization has contributed to the modelling of each of these components.

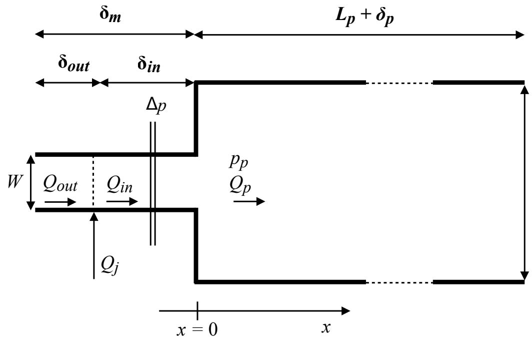

FIGURE 2 – Simple one-dimensional model used for sound synthesis of flute-like instruments.

2.1.1 Jet Formation and the Attack Transient

The steps of the jet formation during the attack transients are shown in Fig. 3 for a slow and fast attack respectively. Transients are very important perceptively and they vary a lot in flute-like instruments depending on the type of pressure rise used. It is therefore crucial for a synthesis model to be able to reproduce them.

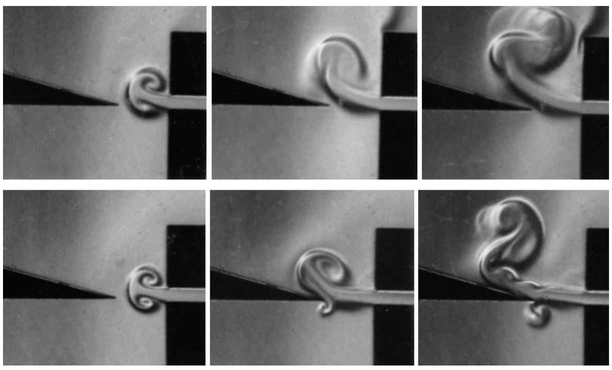

FIGURE 3 – Three successive steps of the jet formation during the attack transient in a small organ pipe. **Upper line** : slow attack. The different pictures were taken at a) 4.0 ms, b) 5.5 ms, and c) 7.0 ms after the onset of the driving pressure in the foot of the instrument. **Lower line** : fast attack. The different pictures were taken at a) 1.98 ms, b) 3.03 ms, and c) 2.49 ms after the onset of the driving pressure in the foot of the instrument.

The first signal measured at the entrance of the resonator following a driving pressure rise is a pressure pulse due to the onset of the volume injection into the mouth of the instrument as the jet is formed at the flue exit. This triggering signal is reflected back at the end of the pipe and starts interacting with the unstable jet. The amplitude of this signal, which triggers the oscillation of the system, is determined by the time derivative of the jet velocity which implies that it is higher in the case of a fast attack. The peak of this pulse in the case of a fast attack also coincide with the shedding of a vortex when the jet reaches the labium, as seen in the visualization. This last event generates an additional acoustic wave at the entrance of the pipe which triggers the transient and excites high frequencies. The contact of the jet with the labium therefore appears to be an important element in the triggering of the acoustical oscillation. It is very interesting to observe on the flow visualization of the slow attack that the jet initially misses the labium, because it is bent toward the exterior of the pipe. Consequently, the initial interaction with the labium is delayed by several oscillation periods. This curved trajectory of the jet can be explained in terms of the impedances experienced by the jet on both sides of the labium. This results into a very slow attack transient. The model of Fig. 2 can simulate the main differences between a slow and fast attack. The model is controlled by the driving pressure signal from which the jet flow Q_j is calculated using the unsteady Bernoulli equation. The model is therefore triggered naturally by the driving pressure rise and needs no arbitrary impulse to start oscillating. It can keep track of the vertical and horizontal position of the jet when one starts blowing allowing the generation of an impulse associated with the initial vortex shedding at the labium, with an amplitude proportional to the jet velocity.

2.1.2 Steady-state Oscillations

The motion of the jet during steady-state oscillation on the first mode of the pipe is shown in Fig.4. In the simulation model of Fig. 2 , this jet-drive mechanism is estimated from the amplitude of flow sources resulting from the oscillation of the jet between both sides of the labium. The amplitude of these sources is calculated using a semi-empirical jet displacement model inspired by the work of Fletcher and Twaithes [9] and driven by the value of the acoustic velocity in the mouth of the instrument. In order to test and validate this model, acoustic measurements in the pipe were used to estimate the phase and amplitude of the acoustic velocity in the mouth, which were then used in the jet model to estimate the jet position at the labium during one period of oscillation. The predicted jet displacement was then compared to flow visualization carried out for the same driving pressure.

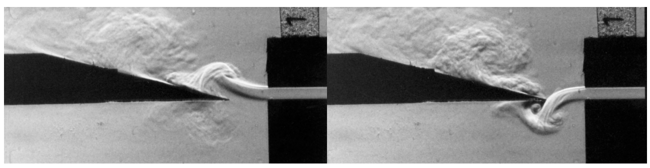

FIGURE 4 – Two complementary phases during the steady-state oscillation of the jet for a driving pressure of 250 Pa.

The visualization shown in Fig. 4 clearly shows the formation of vortices at the edge of the labium. The importance of vortex shedding at the labium, which are usually considered as a secondary effect, was first pointed out by [12]. Vortices produce acoustic work as a result of the reaction of the wall to the unsteady hydrodynamic force associated to the vortex. The formalism of Howe allows deduction of this from the dynamics of the vorticity $\omega = \nabla \times \mathbf{v}$. Models for the evolution of the vorticity are based on flow visualization. Fabre et al. [2, 13] confirmed the crucial importance of vortex shedding from the edge of the labium. It was shown that the work performed by the vortex on the fundamental is negative and therefore that it represents a loss mechanism for the fundamental. Calculations furthermore showed that this loss mechanism is the main dissipation mechanism in flute-like instruments, much more than the radiation losses. The most simple model for this is to assume a quasi-steady jet flow transversal to the jet blown by the player. This jet induces a total pressure loss incorporated in the pressure source discussed above. This appeared to be a crucial element of our simulation model in determining the correct playing amplitude. Using the original model by Fletcher [9], which neglects this phenomenon, unrealistically high oscillation amplitudes are predicted. The last source of sound in our model is due to turbulence. This aeroacoustic source produces a broadband noise which is very typical of the timbre of flute-like instruments. The amplitude of this source can be estimated by combining the analogy of Lighthill with empirical data. It is shown to scale with the square of the jet velocity data [14]. Visualizations indicate that puffs of turbulence appear intermittently on each side of the labium as the jet oscillates. Furthermore, turbulence takes time to develop and is more important on one side of the labium when the jet is on the other side. This suggests that the amplitude of the noise source in the synthesis model can be modulated by the jet oscillation and that a phase lag should be introduced. Simulations have shown these effects to be clearly perceptible.

2.2 Including instrument making parameters

The model described in the previous section allowed since the middle of the 1990's to produce realistic sound synthesis. However, instrument makers describe some geometrical "details", that are not included in the previous models, to be of the outmost importance for the sound quality.
The length and detailed inner curvature of the windway channel in the recorder is one of these important "details". The pipe designed and built by Bram (see Fig. 2), was used by Segoufin [15] to analyse the effect of the channel geometry in terms of its influence on the jet velocity profile and subsequent stability properties, on the bifurcation behavior under steady-state oscillation as well as on the attack transient. Chamfers at the exit of the windway channel are also described by recorder makers to have a strong influence on the sound quality, affecting the attack transient and the stability of the oscillation. This was studied by Blanc [16], using flow visualizations together with numerical flow simulations, to show that the effect of chamfers could be described as a combination of a *protection* of the jet at the flue exit, reducing the perturbation of the jet by the transverse acoustic flow, and a change in the *orientation* of this perturbation.
In the case of the transverse flute, the jet thickness and its position relative to the labium is constantly moving under the control of the player's lips, as studied by De La Cuadra [17]. Furthermore, the labium geometry is quite different from that of the recorder, with an angle between the two sides of the labium of about 50 degrees as compared to the 15 to 20 degrees found in the recorder. Both effects where studied by Dequand [18], who showed that this has a strong effect on the sound source.

2.3 Player's Control

Recent work on the recorder focused on the influence of the vocal tract tuning on the sound production [19]. Recorder players claim to change their mouth volume and/or open nasal cavity in order to modify the quality of the sound during the stationary part of a musical tone. Measurements carried out on players and then replicated under controlled laboratory conditions, showed that the energy balance between odd and even harmonics of the sound could be modified, according to the tuning and coupling between the pipe resonance and the mouth resonance. The effect on the sound spectrum is quantified by the parity spectrum index. A model of the jet oscillation, including both anti-symmetrical (sinuous) mode and symmetrical (varicose) mode, see fig.5, was then combined with the so-called jet drive source description to analyse in details how the players mouth modifications could affect the sound spectrum.

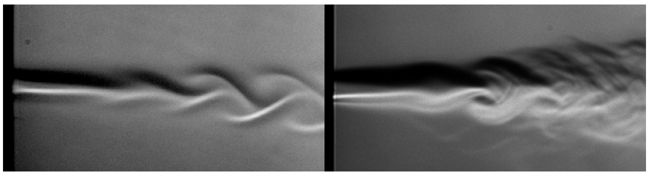

Figure 5 – Comparison between sinuous and varicose oscillation of the jet. The jet, issuing from a 1mm height slit is excited using loudspeakers.

Another important aspect of the player's control was studied recently by Ernoult [20], analyzing in details the influence of the instrument maker and that of the player on the attack transient in recorders. The comparison between a novice and two experienced players suggested splitting the transient in two complementary phases : the birth of the oscillation and its growth and saturation. While the birth of the oscillation is controlled by the player (with a factor ten between mouth pressure rise time of novice and experienced players) the growth and saturation of the acoustic oscillation are determined by the instrument's geometry, as given by the maker. The analysis further showed that a fast mouth pressure rise, faster than the acoustic growth at the resulting sounding frequency, is associated with the appearance of higher frequency components during the transients. Depending on aesthetical considerations, the player may want to enhance or avoid these higher frequency components during attack transients.

2.4 Panpipes

Models of the oscillation in flute-like instruments, as presented in the previous sections, were developed for open-ended pipes. While a simple modification of the acoustic resonance frequencies can be used to turn these models to stopped pipes modellisation, this procedure misses one important aspect of the hydrodynamical behavior in closed-pipes : the mean flow entering the pipe cannot anymore exit the pipe from the passive end and creates a mean cross flow at the blowing end of the pipe. Panpipes used in Andean music are played in open spaces, requiring loud sound generated using high jet fluxes, resulting in turbulence. Stopped-pipe blown by turbulent jets have been shown by Auvray [21] to offer the player wider range of control parameters than open-ended pipes, in relation with a feedback loop in which the crossflow controls the direction of the jet flow. This mechanism makes stopped pipes easier to play than open pipes, allowing a fast change from pipe to pipe, as panpipe players do.

3 Visualisation and measurements for reed and brass instruments modelisations

3.1 Flow through the reed channel

Sound production in reed instruments, such as clarinets, involves non-linearities of the flow entering in the instrument. The most obvious non-linear fluid dynamical phenomenon in a clarinet is the modulation of the volume flow through the reed channel by the oscillation of the reed. In basic models, the modulated volume flow at the entrance of the pipe acts as an oscillating piston which generates the acoustic waves in the pipe : it is the sound source. At low frequencies of the fundamental and reasonable mouth blowing over-pressure Pm (mouth pressure), the flow in the reed channel can be considered to be frictionless, incompressible and quasi-stationary [22]. The action of friction however is essential to explain the flow control mechanism. Friction is responsible for the separation of the flow from the walls in the reed channel which results into the formation of a free jet with a section S_j closely related to the reed channel area. The intrinsic instability of the free jet results into a chaotic vortical motion called turbulence. Typical for a turbulent flow is that even at high Reynolds numbers the kinetic energy of the jet is very efficiently dissipated by energy transfer to small vortical structures and eventually dissipated by viscosity. As the ratio of typical jet height reed channel h_j to acoustic pipe diameter D is very small $(h_j/D) = O(10^{-1})$, we can neglect the recovery of total pressure in the mouthpiece. As a consequence in first approximation the pressure p_{mp} in the mouthpiece is uniform. This yields a volume flux through the reed channel given by (Figure 6) :

$$U = Wh_j\sqrt{\frac{2\Delta P}{\rho}}, \qquad (1)$$

where $\Delta P = P_m - p_{mp}$, ρ is the density of air, W the (effective) width of the reed channel and h_j a height (closely related to the reed channel height h). Even if equation (1) above has been called to mind for example by [23], [24], [25], the latter suggested an alternative to Eq. (1) which has never been confirmed after.

A considerable research effort has been carried out in parallel at the LAUM and at the TUE to obtain a reliable model for the relationship between the jet height h_j and the reed channel height h. Using many simplified experimental set-up with $2D$ geometries, designed by Wijnands [4], it was demonstrated that in steady flow conditions two types of reed channel flow could exist. A fully separated jet flow occurs for short reed channels with $(L/h < 4)$, where L is the channel length and h its height. This jet is narrower by a factor $\alpha < 1$ than the channel height. Hence the jet height is $h_j = \alpha h$, where α is called the vena contracta factor. The jet formation is due to viscous flow separation at the sharp inlet edges of the channel inlet. As expected from potential flow theory, van

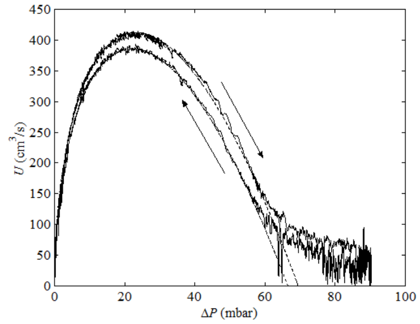

FIGURE 6 – Relationship of the volume flow U as a function of the pressure difference ΔP. Typical experimental result qualitatively compatible with the theory. Due to the complex reed closing (the reed twists and rolls up against the mouthpiece), the curve is smoother than the theoretical one around P_M. Adapted from [31].

Zon [4] found : $\alpha = 0.5$ (see the visualisation of the vena contracta in the Figure 7 below).

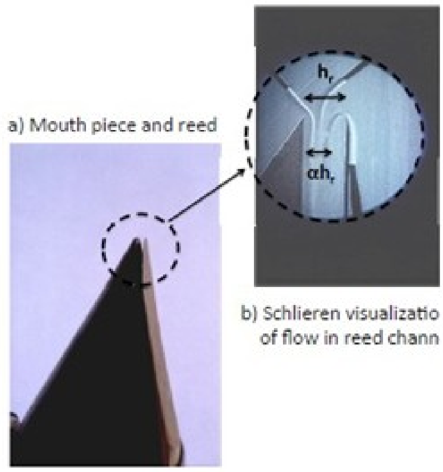

FIGURE 7 – Flow through reed channel of height h : a) Tip of mouthpiece and reed b) Schlieren flow visualization (adapted from [26]), stream lines are made visible in an upscaled (ten times) static model by injection of Carbon Dioxide through three needles. We observe that the jet just downstream of the inlet of the reed channel is narrower than the reed channel height, $h_j = \alpha h$ with $\alpha < 1$ (vena contracta).

Alternatively, for long reed channels $(L/h > 4)$ the viscous entrainment by the jet in the reed channel induces a reattachment of the flow to the walls. At high Reynolds numbers this implies $\alpha = 1$. At lower Reynolds numbers, an analytical model proposed by [4] describes the transition towards a Poiseuille flow and predicts within 5% the experimental data available. Data obtained at LAUM by [27] confirmed these results and provide additional information on the influence of the rounding off of the edges of the reed channel entrance and the confinement of the mouthpiece in the player's mouth. These preliminary results obtained in a highly simplified model of the player's mouth show a drastic increase of α from an initial value of 0.61 up to a value of 0.85. Measurements of stationary flow in actual saxophone mouthpieces by [27] and clarinet mouthpieces by [28] seem to agree with the measurements in simplified geometries. They do not provide a significant improvement of our understanding because of the uncertainty in the geometry of the reed channel. In particular the effective reed channel width W is difficult to estimate (there is a large uncertainty in the contribution of the lateral slits). We suspect that unsteadiness of the flow is an essential feature, so that stationary measurements have a limited value. [29], using the set-up designed by [30], was not able in dynamical measurements of the flux to observe a transition between the fully separated jet flow regime and the reattached flow regime. The data of [29] indicate that the best we can do in a simplified theory is to assume a constant vena contracta factor α. Unfortunately the dynamic data are unreliable for $L/h > 10$. We may conclude that unless better dynamical data are available one should not use a complex model. This would justify the type of reed flow equations using equation (1) taken into account a sensible coefficient α. This conclusion has been confirmed after by the measurements carried out at the LAUM by [31] (see Fig. 6 above).

3.2 From shock waves to brassy sounds

The specificity of sound production in brass instruments is the non-linear wave deformation in the pipe [5] which has been clearly linked with the brassy sounds played at high sound level (fortissimo musical nuance) [32]. In Fig. 8 below (adapted from [5]), the pressure signals are recorded at three nuances (piano, mezzo forte, fortissimo). The distortion of the signal as a consequence of the nonlinear propagation effect is clearly visible on the pipe pressure. If the volume flow exists, its influence is not important [33]. The ability to get brassy sounds from brass instruments depends a lot on their bore geometry. It is possible to define a brassiness parameter, easy to calculate, to define this ability [32].

As a first approximation, the radiated pressure can be seen as proportional to the derivative of the horn exit acoustical volume flow. Then for a distortion of the internal pipe acoustical pressure (extreme case being locally a Heavyside shape), the radiated pressure exhibits very sharp peaks (extreme case being locally a Dirac-pulse shape). For each acoustic period, there is a sudden variation of pressure, which implies a sudden variation of optical index. This variation becomes visible by visualization.

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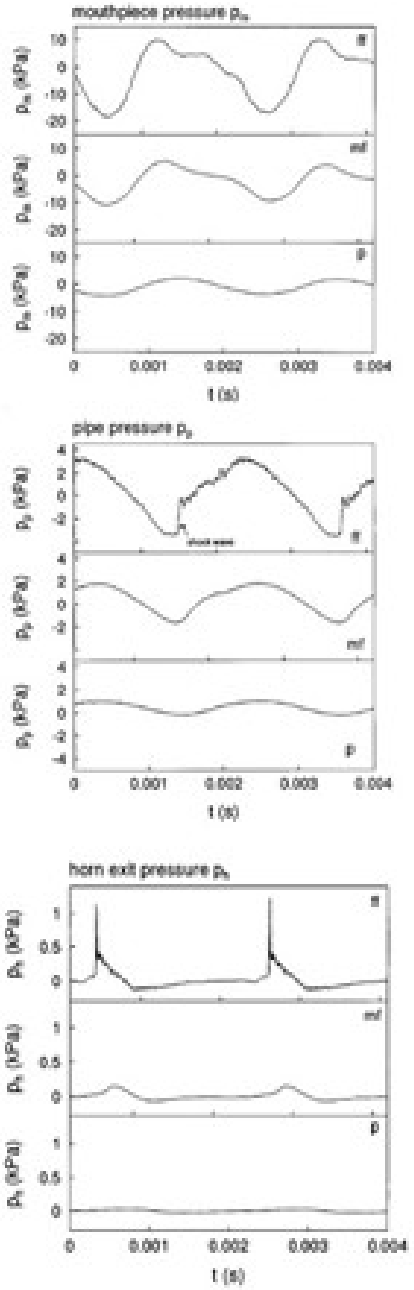

Figure 8 – Measured pressure waveforms for a low frequency. Pressure measured in the first position of a trombone at various playing levels : piano, mezzo-forte, fortissimo. We clearly observe the increased nonharmonicity of mouthpiece pressure pm and nonlinear wave steepening in the pipe pressure p_p with increasing playing level. Comparison of p_m and p_p with the pressure p_h measured at the horn exit clearly demonstrates that the radiated sound is dominated by the high frequencies (adapted from [5]).