The sound produced by flutes depends not only on the physical characteristics of the instrument but also on the control exerted by the musician. The latter is very important in some instruments of the flute family, especially in those where the air jet is shaped with the lip of the player. Some of the most relevant parameters controlled by the flautist, such as the distance from the lips to the sharp edge, the shape of the lips hole and the speed of the jet, are experimentally measured in this paper. Data produced by an experienced and a novice flautist are collected, analyzed and compared. Subjects are studied under normal musical playing conditions, playing phrases made out of simple musical intervals with subjective dynamics. Images of performer’s lips are taken together with measurements of the blowing pressure and the sound inside and outside the instrument. Data analysis shows remarkable differences between the two subjects. The optimized coordination of several parameters in order to obtain a desired musical response, coupling between performer’s mouth and the instrument, as well as the efficient use of the available resources are some of the differences observed.

1 Introduction

A complete sound synthesis model for flute-like instruments should include two parts: a good model of the instrument and a realistic set of control parameters. The latter is particularly complex in the case of lip blown flutes where a strong correlation between the geometry at the mouth of the instrument and the blowing pressure is required to produce a desired musical pitch and dynamics.

The work presented in this paper is based on measurements from two modern flute player: an advanced and a novice flautist. The subjects were chosen in order to emphasize the differences in the control exerted. The data is analyzed in the scope of the current knowledge on the sound production in flute-like instruments.

The paper is structured in the following parts: Section 2 presents the experimental setup used during the experiment. Section 3 briefly explains the basic operation of flutes and the expected parameters for normal sound production. Section 4 shows the comparison between the two subjects and Section 5 summarizes the observed results.

2 Control parameters and experimental setup

Among the big number of parameters controlled by the flautist a limited group have been selected for the measurements. The parameters chosen are those presumed more relevant to the sound production. There are also some parameters that were left outside for technical reasons, this is the case of jet angle of incidence and the labium offset with respect to the jet axis, which would require a more complex setup to be measured.

The experiment was done in a small room without anechoic treatment. The dimensions of the room are 2.76 x 6.45 x 3.15 m (56 m³) which provides an environment similar to that found in a normal practice room. The experiment has been set as close as possible to the normal playing conditions except that the flute was fixed with the help of a camera tripod and therefore the flautist needs to accommodate its body to the position of the flute, and cannot turn it in or out. This was a necessary compromise to assure the accuracy of the measurements. The perceived sound quality obtained by both subjects was very close to what they would get in normal conditions. The musical excerpts chosen include scales and intervals such as fifth and octaves.

Fig.1 shows a picture of the setup. The flute used for the experiment is a Yamaha 281 S, a very popular beginner flute, silver plated and with C-foot extension. The mouthpiece is the standard mouthpiece of the flute, but equipped with the necessary sensors and conditioning electronics. The original cork has been replaced by one with a hole in the center, that remains sealed after inserting a microphone probe inside the flute through it. Pressure inside the resonator is measured through this microphone 20 cm downstream from the cork. To measure the pressure inside the mouth cavity, the end of a calibrated differential pressure sensor is placed inside the mouth of the player through a soft tube (23.5 cm. long and 1 mm. internal diameter). Another microphone is placed 1.5 m
away from the embouchure to register the radiated sound.

Figure 1: Picture of the experimental setup, showing the player and the flute, with its mouthpiece equipped with sensors and the mirror.

A digital camera is placed 2 meters away from the embouchure. It is almost aligned with the direction of the air jet, intending to catch a frontal view of the lips hole. Images are taken at a rate of 17 images per second, which provides a sufficiently large sampling rate to capture the dynamics of the control. A mirror is placed near the embouchure forming an angle of approximately 45 degrees with the flute and thus providing a lateral view of the lips when observed from the front. Fig.2 shows the type of images captured by the camera.

Figure 2: Image captured by the camera with detection of lips hole and flue-labium distance, showing on the right of the picture the 45° mirror that allows to measure simultaneously lip opening and lip-edge distance.

Image processing allows to extract geometrical data from the pictures: the jet length $W$ corresponding to the distance between lip exit and labium, the height $h$ of the lip opening and the total area $S_m$ of the lip opening.

### 3 Sound production

Flute operation can be globally described as a coupling between the hydrodynamic modes of a jet with the acoustic modes of a resonator. The jet transverse oscillation induced by a harmonic acoustic perturbation is expressed as a the propagation of a wave of growing amplitude. For soft blowing conditions, the jet is laminar. The instability of a laminar jet was first described by Rayleigh [6] and followed by Mattingly & Criminale, Fletcher [4], Nolle [5], Ségoufin [7]. The convection velocity as well as the spatial amplification factor of the wave are functions of the dimensionless frequency, the Strouhal number $Str_h = fh/U_j$ where $f$ is the frequency, $h$ is the height of the flute from where the jet flows and $U_j$ is the velocity of the jet centerline. Following Nolle [5] and de la Cuadra [1], the jet instability appears to be maximum around:

$$0.02 < Str_h = fh/U_j < 0.05$$

depending on the jet velocity profile. For a jet issuing from a very short channel such as the player’s lips, the velocity profile is expected to be sharp ([7],[5]) and the maximum amplification of the instability is expected for $Str_h \approx 0.03$.

The structure of the jet is related to the Reynolds number ($Re = U_j h/\nu$, where $\nu$ is the cinematic viscosity of the air, $\nu = 1.5 \times 10^{-5} m^2/s$). Although difficult to predict ([8], [2]), the transition from laminar to turbulent jet seems to occur in the range $Re = 2500 – 3000$. $Re$ up to 10000 has been measured in the higher register of the flute.

Since the convection velocity of perturbations on the jet is about half the jet centerline velocity [6], the optimal condition corresponding to half a period delay on the jet may be expressed as:

$$Str_w = f W/U_j = 0.25$$

where $W$ is the flue-exit to labium distance. Combining equations 1 and 2, the optimal range of the thickness ratio $W/h$ of the jet is:

$$5 < W/h = \frac{Str_w}{Str_h} < 12$$

In the case of a short channel like the lips, the maximum jet instability occurring at $Str_h \approx 0.03$ indicates an optimal value of $W/h \approx 8$.

### 4 Comparison between players

Measurements come from two subjects, and experienced flautist ($F_A$) who has completed a formal musical education and has been playing for more than 20 years and a self-trained flautist ($F_B$) who at the time the experiment had been playing the flute for only four months.

Fig.3 top, compares the jet velocities measured from $F_A$ and $F_B$ playing intervals of octaves. $F_B$ shows lower
jet velocity on low notes and higher jet velocity on high notes than \( F_A \), resulting in an average increment of 60% per octave for \( F_B \) and only 10% per octave for \( F_A \).

Although \( W \) decreases with frequency for both players (fig.3 center), \( F_B \) requires a longer \( W \) to compensate the high \( U_j \). Yet, the resulting Strouhal number (\( Str_W = W f/U_j \)) remains in the range [0.08-0.3] (fig.3 bottom) which seems to be a necessary condition to produce a flute sound.

Because of the high \( U_j \) and the lack of control over the shape of the lips hole, \( F_B \) uses a much bigger lips surface and amount of air to produce his sound, which results in higher values of the total jet flow (fig.4). For example on E3, the total jet flow used by \( F_A \) is approximately 0.6 liters/s and for \( F_B \) is 0.2 liters/s. If we consider a respiratory capacity of 4.8 liters (average value for a 70 kg. males [3]), \( F_B \) can hold that note for 8 seconds while \( F_A \) can do it for 24 seconds.

The increase in total jet flow affects the Reynolds number, which for \( F_B \) has an average value of 3000 and maximum up to 7000. \( F_A \) keeps the values of \( Re \) in a small and well defined region below the transition limit to turbulent and below \( F_B \), who spreads data over a much wider region. Which means that \( F_B \) is putting more energy in producing his sound and his jet could easily become turbulent producing a noisy sound. When turbulences are triggered before the jet reaches the labium, the jet velocity slows down rapidly, asking for even more blowing pressure from the player to keeping \( Str_W \) around 0.2 in order to maintain the oscillations.

Coupling between the instrument and the performer's mouth cavity has been observed. Fig 5 shows the ratio \( \rho_m'/\rho_m \) displayed as function of frequency for \( F_A \) and \( F_B \) playing intervals of octaves. This ratio is much bigger in \( F_A \) than \( F_B \) and decreases with frequency. \( \rho_m' \) can induce varicose modes in the jet that could have been utilized by \( F_A \) to influence his tone. Acoustic pressure fluctuations in the mouth \( \rho_m' \) can be emphasized by tuning the mouth resonances.

Fig.6 shows the same ratio for \( F_A \) playing a chromatic scale. It is observed that the ratio increases around the octave shift, which could be interpreted as an effort from the performer to compensate the unevenness of the resonator around that frequency range, to produce an homogeneous timbre. The real influence of the observed coupling on the resulting sound remains to be studied with more details.

### 5 Discussion

Measurements carried on an advanced player as well as on a beginner indicate that a Strouhal number \( Str_W = W f/U_j \) around 0.2 (in the range 0.1-0.3) seems to be a
necessary condition to produce a flute sound. This balance between jet velocity and jet length to produce the desired pitch is obtained through a low jet velocity combined with a short jet length by the advanced player, while the same balance is obtained using a faster jet velocity and a longer jet length by the beginner. Together with a wider lip opening, this takes about three times more air to produce the same note for the beginner. Furthermore, the jet produced by the beginner is expected to become rapidly turbulent after the lip exit due to the high Reynolds number. This results in a more noisy sound quality, typical for beginners on the modern flute.

Pressure fluctuations in the mouth of the player have been observed, induced by the coupling between the acoustic waves in the flute body and the mouth of the player. The amplitude of these pressure fluctuations are much lower for the beginner. This may be due to a poor tuning of the mouth cavities, but also to a weaker acoustic coupling between the pipe resonance and the mouth cavities for higher jet velocities, as discussed by Verge [9].

References


Figure 6: Acoustic pressure inside the mouth


