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Analysis of Flute Control Parameters: A Comparison Between a Novice and an Experienced Flautist

Patricio de la Cuadra*

CITA, Centro de Investigación en Tecnologías de Audio, Pontificia Universidad Católica de Chile,
Santiago, Chile

Benoît Fabre, Nicolas Montgermont

LAM-IJLRA, Laboratoire d'Acoustique Musicale, Université Pierre et Marie Curie, Paris 6, 75252 Paris
Cedex 05, France

Christopher Chafe

CCRMA, Center for Computer Research in Music and Acoustics, Stanford University, Stanford,
CA 94305, USA

Summary

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 radiated by 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.

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1. Introduction

The control exerted by the performer on the instrument can be of crucial importance in the quality of sound produced. There are some instruments from the flute family such as organ pipes where the quality of the final sound is left almost entirely to the design of the instrument builder. The other extreme is where the interaction of the performer has an enormous influence on the quality of sound produced, such is the case for the European transverse flute, the South American quenas and the Japanese shakuhachi.

While manipulating the excitation mechanisms has the most effect on the sound quality, some instruments allow for a degree of tone control through changes in the resonator. Cross fingering and half holing techniques used in instruments like the shakuhachi have a clear effect in the

tone of the instrument. In this paper we concentrate on the control exerted through the excitation mechanisms on the European transverse flute.

Producing sound on a modern transverse flute normally requires only a few weeks of training, though it typically takes a couple of years to be able to produce the standard compass (C4(262 Hz) - B6(1319 Hz)). Good control of the sound quality to perform at professional level takes at least 10 years [1, 2].

The musician performs simultaneous and synchronized control over several parameters. The air pressure is modulated in the lungs to produce a desired air jet velocity. The tongue provides an exit valve that is used to produce the different types of attacks and, in combination with the velocity of the outgoing air jet, shape the global intention of musical phrases. The geometry of the lips hole shapes the cross section of the air jet and by pushing the lips forward and backward the flautist controls the distance the jet travels before reaching the sharp edge. This movement also alters the surface of the open extremity and therefore the input admittance of the tube [3]. Through years of prac-

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tice an experienced flautist learns refined controls over the mechanisms described above.

Several books and methods have been published (ex. [1, 2]) describing the embouchure techniques from a pedagogical point of view. In this paper the emphasis is put in the quantitative analysis of data from the excitation mechanisms in the flute and is interpreted in terms of the current knowledge of the physics of flute-like instruments.

Measurements captured from two flautists, one experienced and the other a novice, are analyzed and compared aiming to fulfill two principal objectives: observe the equilibrium between the different parameters that are necessary to produce a flute tone, and contrast the differences in control applied by the two players. Data from the experienced flautist can be generalized to provide a simplified caricature of the flautist's behavior, which could be useful to provide synthesis control inputs for a flute physical model. A study with more subjects remains to be done to generalize some of the observation of this paper.

The article is structured as follows: Section 2 presents a summary of the current knowledge of the physics of flute-like instruments to determine the parameters that need to be measured. Section 3 presents the experimental setup used to do the measurements and Section 4 presents the data and its processing. The analysis of the playing of the experienced flutist is then presented in Section 5 and Section 6 compares the behavior of the experienced and novice player. Finally, the main results are discussed in Section 7.

2. Basic flute model: current state of knowledge of flute-like instrument physics

Flute operation can be globally described as a coupling between the hydrodynamic modes of a jet with the acoustic modes of a resonator. An integral approach of this problem has been proposed by Howe [4], Crighton [5] in the case of the edge-tone, Elder [6] and Bechert [7], for simplified geometrical conditions. The pipe resonances depend, among other things, on the characteristics of the pipe ends. The operation of the jet takes place in one open end, which is also where part of the acoustic radiation of sound takes place. Therefore a lumped study of the pipe resonances, the jet instability and the aero-acoustic sources induced by the jet is questionable, as discussed in [8]. However, the description of the flute operation in such independent elements is more tractable and has become very popular in the literature [9, 10, 11]. The different elements (resonator, jet, sources) are supposed to interact locally and are therefore analyzed separately and then concatenated to produce a simplified caricature of the flute operation, as sketched in Figure 1.

The acoustic resonances of the flute body have been studied in details by Fletcher [12], Wolfe [13], Benade [14], Coltman [15], Castellengo [16], Nederveen [17]. The pipe may then be described by its input acoustic admittance at the embouchure hole.

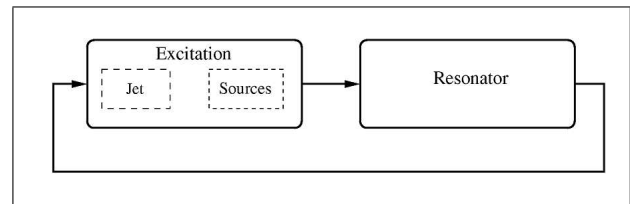


Figure 1. General description of flutes operation.

The jet transverse oscillation induced by a harmonic acoustic perturbation is expressed as 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 [18] and followed by Mattingly & Criminale [19], Fletcher [20], Nolle [21], Ségoufin [22]. The convection velocity as well as the spatial amplification factor of the wave are function of the dimensionless frequency, the Strouhal number ($Str_h = fh/U_j$ where f is the frequency, h is the height of the flue from where the jet flows and U_j is the velocity of the jet center line).

Following Nolle [21] and de la Cuadra [23], the jet instability appears to be maximum around

$$0.02 < Str_h = fh/U_j < 0.05, \quad (1)$$

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 similar to a top-hat [24, 21] 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 ν is the kinematic viscosity of the air, $\nu = 1.5 \cdot 10^{-5} m^2/s$). When blowing harder, the jet becomes turbulent. Although difficult to predict [25, 26], the transition from laminar to turbulent jet seems to occur in the range of $Re = 2000 - 3000$. Re up to 10000 has been measured in the higher register of the flute. Because of the chaotic nature of turbulence and of the fast kinetic energy dissipation induced, the instability of a turbulent jet submitted to a transverse acoustic field is more difficult to describe. The work of Bechert [7] offers a simplified model, while the work of Thwaites [27, 28], shows a way to transpose the results obtained for laminar jet to weakly turbulent jets. Turbulence is known to produce a breathy wide band noise [26, 4]. As discussed by Verge [29], this noise filtered by the passive resonance of the pipe is an important part of the perceived characteristic flute sound. In western classical technique, the player is expected to reduce as much as possible this part of the flute sound, while it is considered as an expressive resource that needs to be enhanced and controlled by the player in other musical practices such as the traditional Japanese shakuhachi technique [30].

Laminar and turbulent jets may be used in normal operation of flutes, and because the transition from laminar to turbulent is dependent on the upstream flow conditions, one might expect an experienced performer to be able to influence that transition.

Changing the blowing pressure allows the flautist to adjust the delay induced by the convection of perturbations on the jet. As shown by Coltman [31], the flute sounds at the frequency of its passive resonance for a delay equal to half of the oscillating period. This corresponds to the optimal phase relation of the sound source at the labium compared to the acoustic field as discussed by Fabre [32]. Coltman also shows that, in order to develop the harmonic content of the sound, players may blow at pressures a little higher than this optimal pressure, resulting in a playing frequency slightly above that of the passive resonance of the pipe. The convection velocity of perturbations on the jet is about 30% to 50% of the jet center line velocity [18], the optimal condition corresponding to half a period delay on the jet may be expressed as

$$Str_W = \frac{fW}{U_j} = 0.15 \dots 0.25, \quad (2)$$

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

$$3 < W/h = \frac{Str_W}{Str_h} < 12, \quad (3)$$

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 $W/h \approx 8$.

At the flue exit, the acoustic pressure oscillation may induce a modulation of the jet velocity at the frequency of the sound. Jet velocity fluctuations are expected to induce varicose modes on the jet. In the case of a short channel like the lips, the jet velocity fluctuations are shown by Verge to induce acoustic losses. The effect of the varicose modes on the harmonic content of flute sound is not fully understood yet. A simple model of the influence of the mouth cavity on the jet velocity fluctuations has also been proposed by Verge [33].

Finally, the production of acoustic energy by the oscillating jet is commonly described as a dipole [34, 35, 36, 37] with a strength proportional to the total jet flow Q_j .

In the present research, the players' control is analyzed in terms of the physics of the sound production. Therefore the main control parameters measured (W, h, U_j) are analyzed in terms of the dimensionless numbers discussed above: Str_W, Str_h, Re .

3. Control parameters and experimental setup

Among the large number of parameters controlled by the flautist, a limited group has been selected for the measurements. The parameters chosen are those presumed more relevant to the sound production. There are also some parameters not incorporated for reasons of technical simplicity, 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.

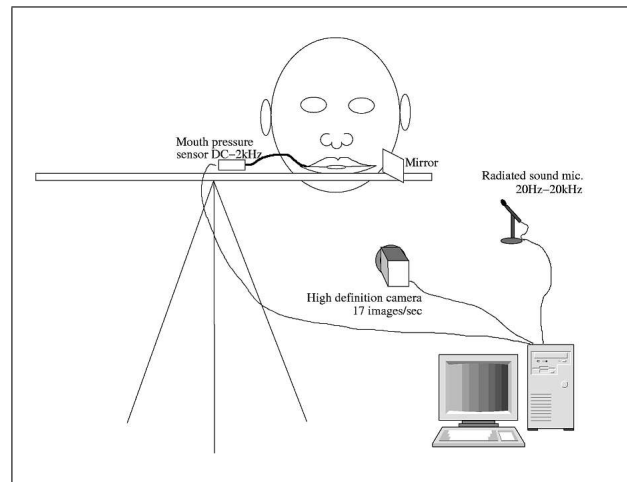


Figure 2. Experimental setup.

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 mts. (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 his body to the position of the flute. This was a necessary compromise to assure the accuracy of the measurements. According to the players themselves, the sound quality produced by both subjects was very close to what they would do in normal conditions.

The musical material chosen included intervals such as fifths, octaves and scales, and some dynamic changes like *crescendo* and *diminuendo*. The "score" explores only the first two octaves of the instrument.

Figure 2 shows a scheme 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. 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).

The radiated sound pressure (p'_{rad}) is measured with a fixed external microphone placed in front of the mouth piece, 1 meter away from it. Although the room is non-anechoic neither the microphone nor the flute have changed position throughout the experiments, which allow for a relative comparison between subjects. Due to interaction between acoustic sources at both open ends of the flute, the radiated acoustic field is rather complex [38]. In order to compare the efficiency in sound production of the two subjects, a simple approximation to estimate an upper bound of the acoustic radiated power is used together with an estimation of the total jet power.

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

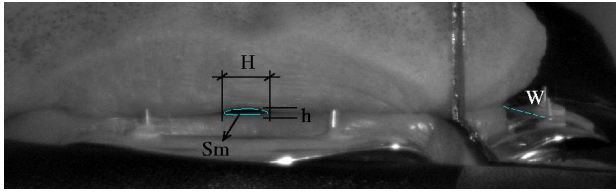


Figure 3. Image captured by the camera with detection of lips hole and flue-labium distance, showing on the right of the picture the 45-degrees mirror that allows to measure simultaneously lip opening and lip-edge distance.

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. Figure 3 shows the type of images captured by the camera.

4. Data processing

The pressure measured inside the mouth p_m contains a slowly moving component P_m added to a fast moving component p'_m that oscillates at the frequency of the note played, $p_m = P_m + p'_m$. The two signals are isolated through filtering with a cutoff frequency of 100 Hz.

Considering the very short length of the flue channel formed between the lips of the player, the thickness of the flow boundary layers is assumed to be negligible, and the mean jet velocity (U_j) is estimated using Bernoulli's equation:

$$U_j = \sqrt{\frac{2P_m}{\rho_0}} \quad (4)$$

where ρ_0 is the air density.

Frontal and lateral images provide the raw data from where geometrical information is extracted: the area of the lips hole (S_m), the height (h) and width (H) of the hole, and the distance from the lips to the sharp edge (W), as shown in Figure 3. The detection of these parameters is based on a morphological analysis of the images, which includes stretching the image contrast, black and white conversion, and edge detection.

The radiated sound (p'_{rad}) captured by the external microphone is used to estimate the frequency of the note played (f) and the energy radiated. The harmonic product spectrum algorithm is used to pitch track the signal as described in [39]. The total jet flow is estimated as $Q_j = U_j S_m$. Finally the values of signals sampled at audio sampling rate (44100 Hz) are decimated to synchronize with the parameters measured at images rate (17 Hz) through low-pass/down-sampling techniques to avoid aliasing.

5. Experienced flautist analysis

In the following section we examine data produced by the experienced flautist (from now on F_A) who has completed a formal musical education and has been playing the flute for more than 20 years.

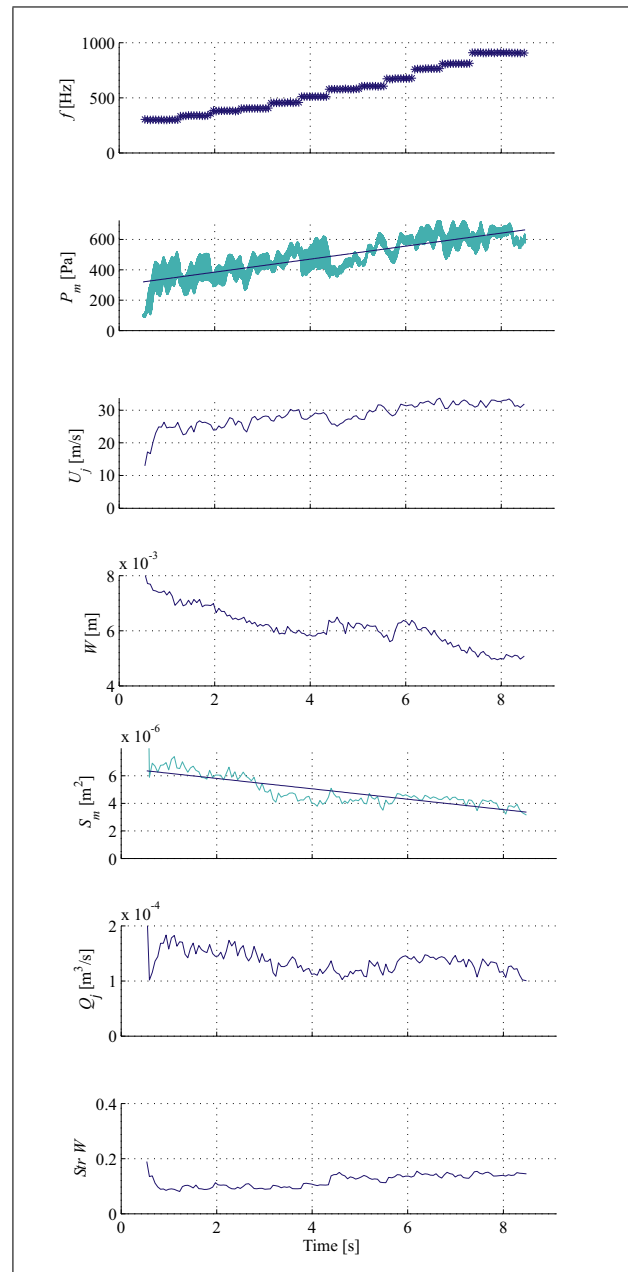


Figure 4. Parameters measured and calculated for the experienced player F_A playing a slurred D major scale from D4 (293 Hz) to A5 (880 Hz).

5.1. Three cases: D major scale, diminuendo and octaves

First F_A is asked to play a D major scale from D4 (293 Hz) to A5 (880 Hz) with a constant dynamic mf . Details of measured and calculated data are shown in Figure 4. It is observed that P_m follows the pitch raise, as it was also observed by Fletcher [40]. A zoom on the data shows that the pressure fluctuations in the player's mouth p'_m are at the same frequency as the played tone. The mean blowing pressure P_m increases of a factor 2 (300 to 600 Pa) over the scale, corresponding to a factor 1.4 in the jet velocity U_j while the frequency increases by a factor 3. The jet length W is decreased by a factor 1.8 (8 mm to 4.5 mm). The

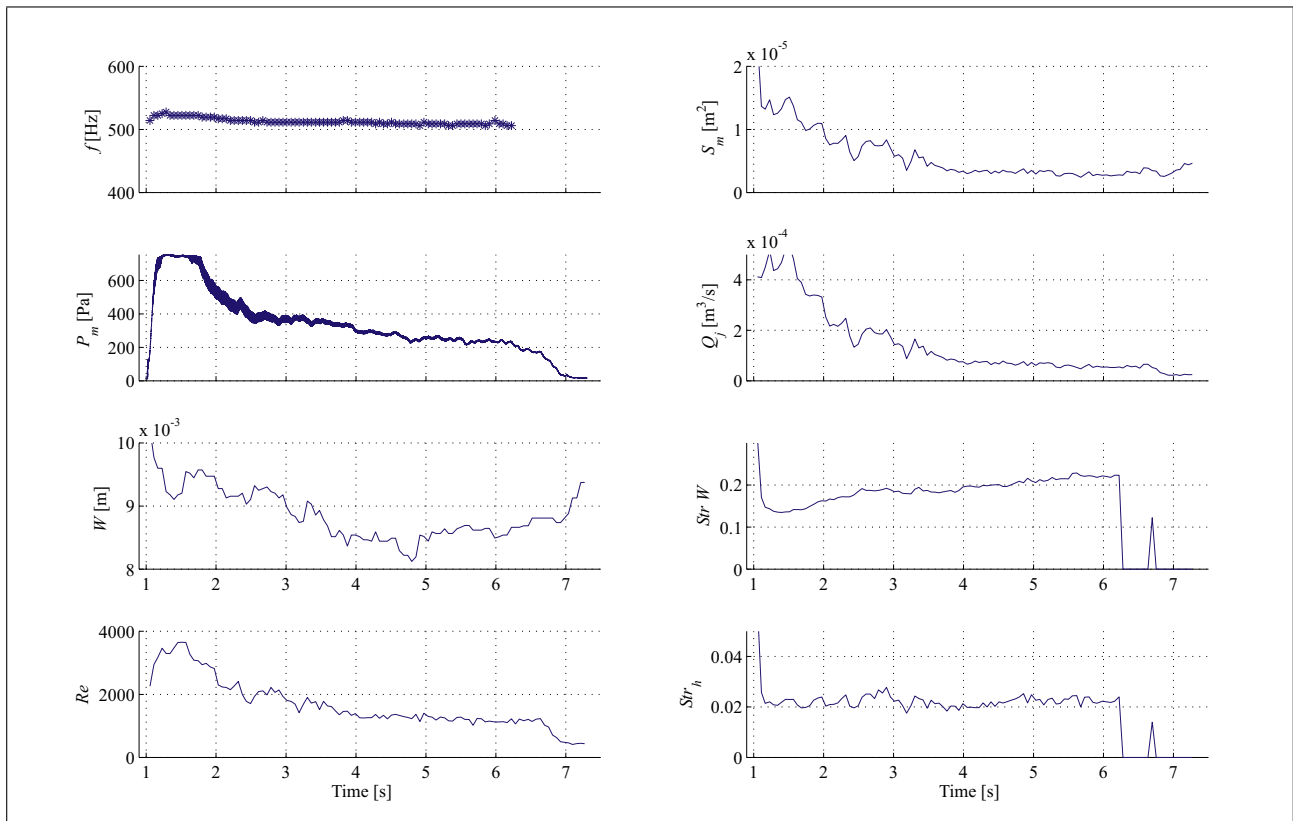


Figure 5. Parameters measured and calculated for the experienced player F_A playing a B4, diminuendo.

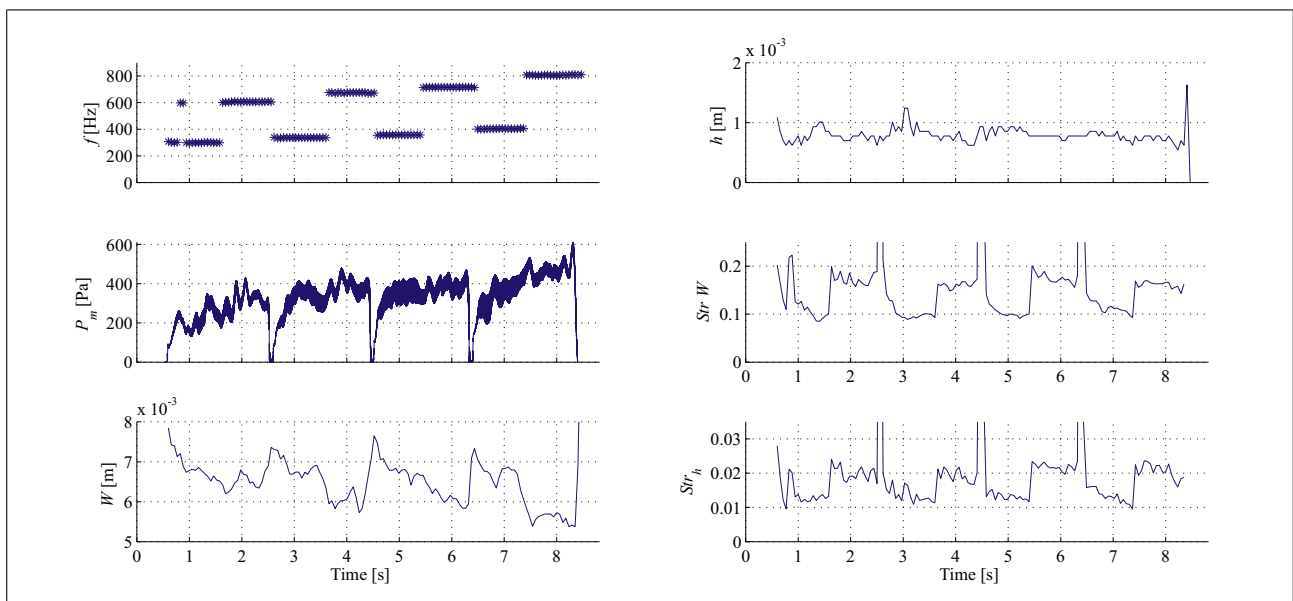


Figure 6. Parameters measured and calculated for the experienced player F_A playing octave intervals: D4-D5 ; E4-E5 ; F4-F5 ; G4-G5 with medium dynamics (mf)

combined adjustment of blowing pressure and jet length allows the Strouhal number Str_W to present a small variation (0.1 to 0.15).

The increment in the jet velocity seems to be compensated by a decrease of lips hole surface S_m , yielding a decreasing total jet flow Q_j , and preventing an extreme incre-

ment of loudness in the higher register. Indeed the player was asked to play the scale at constant dynamics.

The player was also asked to play a note at a constant pitch B4 (494 Hz) decreasing the loudness of the note: the data measured and calculated for a *diminuendo* are shown in Figure 5. Here again, the large variation of blowing

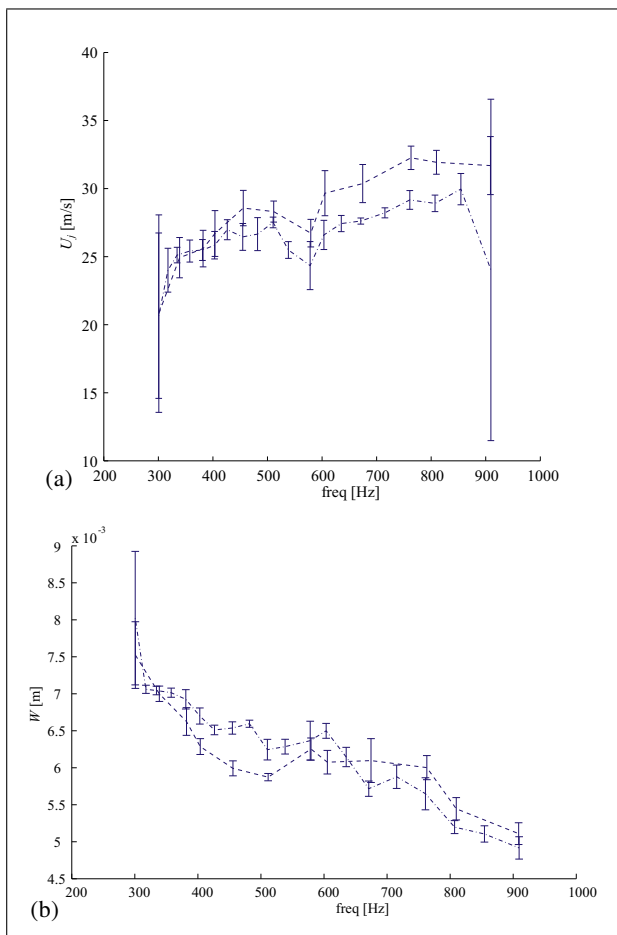


Figure 7. Global dependency between a) Jet velocity U_j and b) Jet length W with the frequency played. Ascending chromatic scale (-) and diatonic scale (-). The measurements are sampled at the image frequency (17 sec) and the figure presents the time average and standard deviation for each note.

pressure is partly compensated by adjusting the jet length W to keep Str_W almost constant. It is furthermore observed that Re , Q_j and W follow the evolution of the note in just the right proportion to maintain stability of f and Str_h . Playing both *crescendo* and *diminuendo* show values of Str_W ranging from 0.14 at the loudest to 0.23 at the softest.

Playing loud is difficult in the flute because of its natural tendency to jump to the higher pipe resonances when blowing harder. This is indeed the case for the octaves from first to second register that make use of the same fingerings to play the two notes one octave apart. For instruments of fixed blowing geometry, like the recorder, the jet length W is fixed and doubling U_j is required to double the frequency (octave) while keeping the same relative position of the frequency played with respect to the passive resonances of the tube, in other words, keep Strouhal number Str_W constant. In the transverse flute W can be adjusted while playing so that, if desired, the combined effect of the two parameters can stabilize Str_W .

It is then interesting to observe the minimum value of Str_W above which the oscillation would jump to the oc-

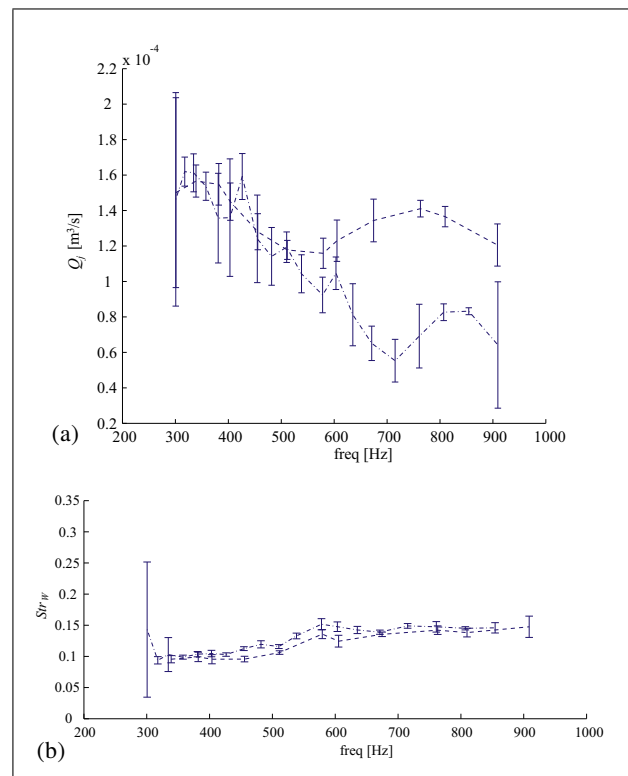


Figure 8. Global dependency between a) Flow Q and b) Str_W with the frequency played. Ascending chromatic scale (-) and diatonic scale (-). The measurements are sampled at the image frequency and the figure presents the time average and standard deviation for each note.

tave for intervals D4 to D5, up to G4 to G5. The data is presented in Figure 6. The octave jumps appear to happen at $Str_W \approx 0.1$ which is slightly lower than the minimum value observed for *crescendo* playing and suggest a lower limit.

Measurements on playing the octaves also show that control parameters P_m , W and h , change very little for octave jump, inducing a jump of almost a factor 2 in Str_W and Str_h . Consequently, it is very difficult to identify the mechanisms utilized to trigger the jump, except for the octave D4-D5 that relies on the opening of the octave key. Obviously, the player is trying to play both notes very closely in terms of the control parameters, which requires a fine control and relies on the hysteresis between registers as discussed by Ségoufin [24]. Further work is required to understand the way in which octave jumps are triggered.

5.2. Global analysis

Aiming to identify common patterns in the control applied by F_A , several musical excerpts are analyzed together.

A global tendency to increase U_j with frequency has been observed. Figure 7a shows the jet velocity U_j as function of frequency for a ascending chromatic and diatonic scale. It is observed that the variation of U_j is small, about 1.35 of increment per octave corresponding almost to a factor 2 for the blowing pressure.

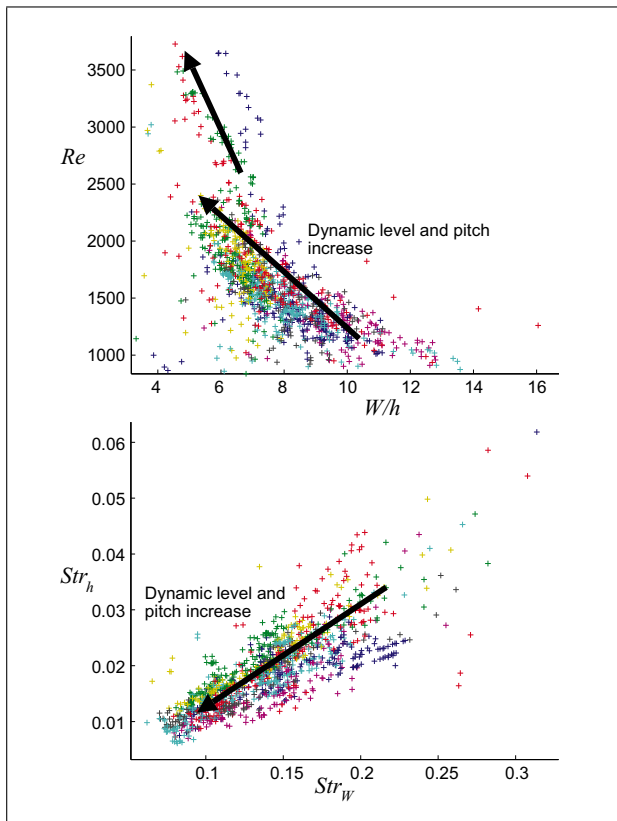


Figure 9. Collapsed data from several musical excerpts that includes scales (chromatic and diatonic), intervals (2nd, minor and major 3rd, 4th, 5th and octaves) and dynamic changes (crescendo and diminuendo). Every point represents the measured parameters between two consecutive images.

At the same time the jet length W decreases as shown in Figure 7b, as observed also by Coltman [3]. The combination of these two parameters produces a variation of the Strouhal number Str_w which remains in the range [0.1 - 0.15] as shown in Figure 8b. It lies at the lower end of the theoretic estimations, close to the octave jump which may be dictated by an attempt to have a rich sound without over blowing. The increment on U_j with increasing frequency is also compensated by changing the lip opening surface, resulting in a decreasing the total jet flow as shown in Figure 8a.

In Figure 9a several musical excerpts have been collapsed in one plot showing the shape of Re as function of W/h . It is observed that range of operation of W/h mainly goes from 4 to 10, which coincides with the values discussed in section 2, while most of the data is below $Re = 2500$. In that region the trajectory of data, as frequency or loudness grows, seems to increase linearly approximately following:

$$3500 = Re + 250W/h \quad (5)$$

$$\text{for } \begin{cases} 1000 \leq Re \leq 2500 \\ 4 \leq W/h \leq 10 \end{cases}$$

As Re increases beyond 2500, the slope of the trajectory changes in such a way that less reduction of W/h is re-

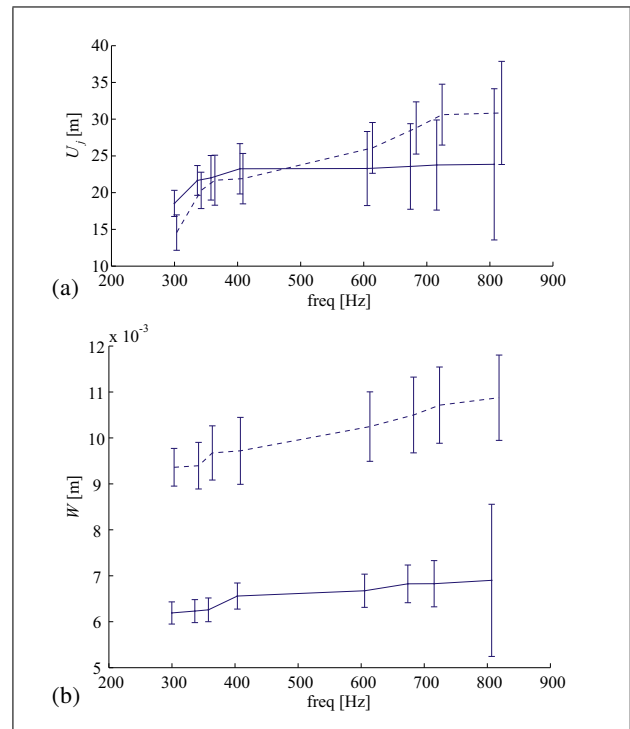


Figure 10. a) Jet velocity U_j and b) Jet length W as functions of frequency. Octave series, experienced flautist (full line), novice (dashed line).

quired to follow the increment on Re , which may suggest that the jet has changed into a turbulent mode.

Figure 9b shows the Strouhal numbers Str_h and Str_w for the same set of musical excerpts. The data is observed to collapse into a small, well-defined region, bounded by $0.07 \leq Str_w \leq 0.3$ and $0.005 \leq Str_h \leq 0.035$. Furthermore, both variables seem to decrease as the pitch raises or the loudness is increased, roughly following the trajectory described by:

$$Str_h = 0.2Str_w - 0.01 \quad (6)$$

$$\text{for } \begin{cases} 0.07 \leq Str_w \leq 0.3 \\ 0.005 \leq Str_h \leq 0.035 \end{cases}$$

6. Comparison between a novice and an experienced flautist

Our second subject is a novice flautist (from now on F_B). He is self-trained and at the time of the experiment had been playing the flute for only four months. He has no classical musical education but shows great interest in music. Due to his very limited flute skills, he was requested to play only simple intervals. He was not asked for a particular sound quality, letting him play with the sound he was able to produce.

6.1. Sound production

Figure 10a compares the jet velocities measured from F_A and F_B playing intervals of octaves. F_B shows lower jet

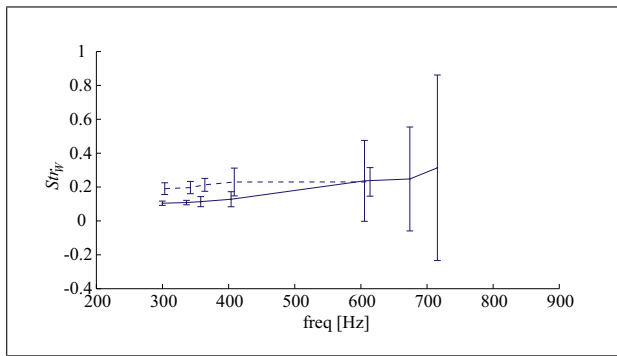


Figure 11. Str_W as function of frequency. Octave series, experienced flautist (full line), novice (dashed line).

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 .

Figure 10b shows that F_B requires a longer W to compensate the high U_j , giving more room for turbulence to develop and adding noise to his sound. Yet, the resulting Str_W remains in the range [0.08-0.3] (Figure 11) which seems to be a necessary condition to produce a flute sound.

6.2. Control of the sound quality

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 hole surface (Figure 12a) and amount of air to produce his sound, which results in higher values of the total jet flow (Figure 12b) and therefore the impossibility to play a long note.

The increase in total jet flow affects the Reynolds number, which for F_B has an average value of 3000 and maximum up to 6000. F_A keeps the values of Re in a small and well defined region presumably 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 into producing his sound and his jet can more easily become turbulent producing a noisy sound. When turbulence is triggered before the jet reaches the labium, the jet velocity slows down rapidly, asking for even more blowing pressure from the player to maintain the oscillations.

The efficiency of the sound production is also compared. An upper bound of the sound power radiated P_{rad} is estimated using a free field monopole approximation:

$$P_{rad} \leq \frac{1}{T} \int_T \frac{|p'_{rad}|^2}{\rho_0 c} 4\pi r^2 dt, \quad (7)$$

where T the period of oscillations, r the distance from the flute embouchure to the microphone and c the speed of sound in the air. We are not aiming to estimate an absolute value of the radiated power (for discussion on this topic, see [43]) but instead, we only want to compare the efficiency of both players: we estimate an upper boundary for the ratio of the sound power generated to the jet flow power.

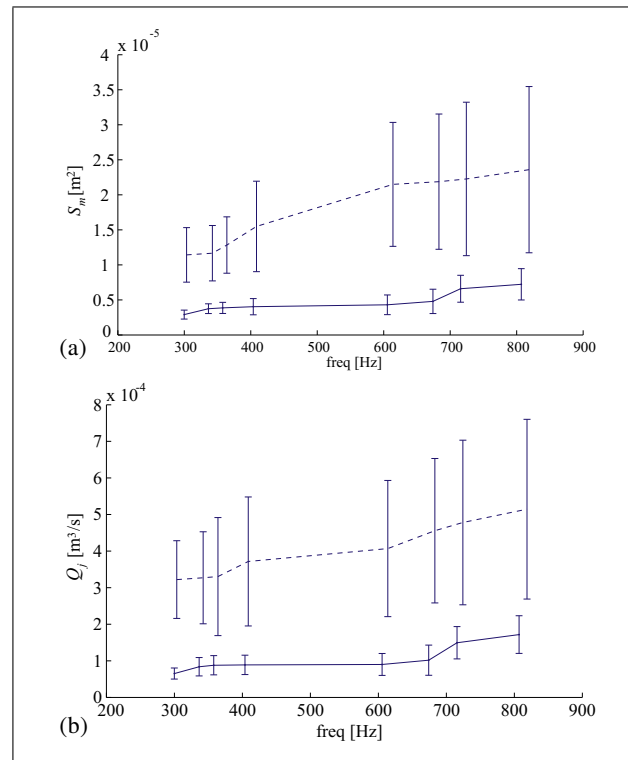


Figure 12. a) Lips surface S_m and b) Flow Q_j as function of frequency. Octave series, experienced flautist (full line), novice (dashed line).

The jet flow power P_p is estimated as

$$P_p = \frac{1}{T} \int_T S_m U_j P_m dt. \quad (8)$$

An upper bound for the efficiency is estimated as $\eta = P_{rad}/P_p$, and is presented in Figure 13b. It is observed that the two groups are this time inverted. Therefore, F_A is achieving a more efficient use of the available resources and F_B 's poorer showing might be attributed to non-optimal transverse dimensions of the jet compared to the dimensions of the sound hole of the flute or the fast dissipation of energy due to turbulence and the increased jet spreading associated with it.

Finally, coupling between the instrument and the performer's mouth cavity has been observed. Figure 14 shows the ratio p'_m/P_m displayed as a function of frequency for F_A and F_B playing intervals of octaves. This ratio is much bigger in F_A than F_B . p'_m can induce varicose modes in the jet that could have been utilized by F_A to influence his tone. At the same time, p'_m excites the cavities in the head of the musician adding another possible source of resonance.

The real influence of the observed coupling on the resulting sound remains to be studied in more detail.

7. Discussion

Simultaneous pressure and geometry measurements allow estimations of the principal parameters suggested by the theory presented above in section 2: Str_W, Str_h, Re .

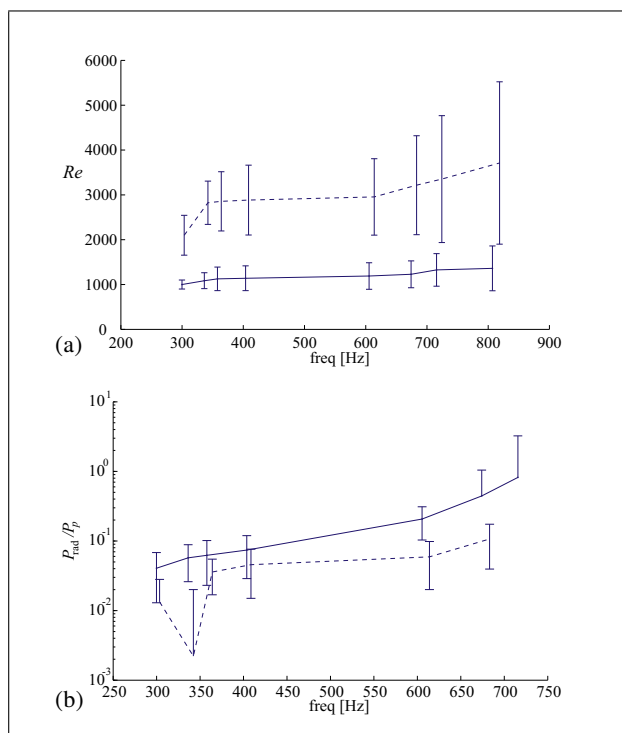


Figure 13. a) Re and b) Upper bound of the sound power radiated over power of the jet flow $\frac{P_{rad}}{P_p}$ as function of frequency. Octave series, experienced flautist (full line), novice (dashed line).

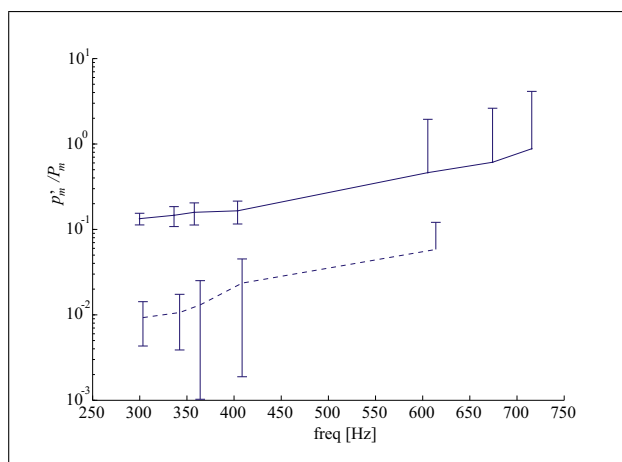


Figure 14. Acoustic pressure inside the mouth. Octave series, experienced flautist (full line), novice (dashed line).

It has been observed that the basic operation of the flute requires Str_W to be close to 0.20 regardless of the quality of the sound produced. A clear and pure sound, which is normally requested for playing traditional repertoire in the flute, is achieved by keeping Re controlled and below its transition threshold for turbulence.

Efficiency and control over the flute timbre requires coordinated control over several parameters, where the coordination among W , U_j and h are particularly important. This coordination is not intuitive and requires assimilation through training.

Table I. Ranges for measured non-dimensional values.

| | min | max |
|---------|-------|-----------|
| Str_W | 0.07 | 0.35 |
| Str_h | 0.005 | 0.035 |
| W/h | 2 | 10 |
| Re | – | 2000–3000 |

Since the maximum amplification of the jet perturbation occurs for $Str_h \approx 0.025$ it is expected that a trained flautist will adjust the control parameters to approach that value and achieve good efficiency. Both Str_W and Str_h are observed to remain stable to keep the timbre homogeneous. Nevertheless, some flexibility is desired in order to obtain timbre variations and a wide dynamic range from the instrument.

In Table I, a range of parameters for laminar operation of the instrument is shown, which together with the trajectories described in section 5.2 can be used as starting values for synthesis with linear physical models.

While the control exerted by the experienced player resembles Fletcher [40] and Cossette's data [41] the control done by the novice player should be interpreted as one of the several possible ways to control the instrument before a more accurate control system is learned.

The shape of the lips holes in our two subjects is very different. Although this could have an influence on the sound, a trained flautist can optimize the behavior of his jet and produce a beautiful sound regardless of the physiology of his or her lips [2]. Good control over the flow helps keep the timbre homogeneous throughout the register of the instrument.

As discussed in section 5.2 and also pointed out by Fletcher [40], changes in frequency are accompanied by comparatively small changes in the jet velocity. This strategy may have a kinesthaetic explanation: an instrument capable of playing fast melodies needs to keep some independence between P_m and the frequency played. Muscles controlling the pressure such as the diaphragm and chest muscles, are comparatively much slower than melodies played by flutes. A way to achieve this economy in the P_m variations is to “overplay” the lower register and “underplay” the higher. That is putting both registers closer.

Although an extensive set of measurements has been studied, a complete description of the mechanisms utilized by the flautist to control their instrument can only come from a study with several subjects.

The data presented indicate that the measured parameters are appropriate to study the players control: they allow to interpret both a necessary condition for sound production (see Str_W in Table I) and contrasted strategies between the two subjects under study to achieve this necessary condition.

We have presented experimental findings based on two subjects in attempt to understand the range of interactions and lay the groundwork for a wider study of these phenomena which are basic to flute performance.

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