Measuring leakages in flute pads

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The fine adjustment of pads in modern flutes is crucial to the player. Craftsmen need several years of experience to reach a point where they can do a fine and rapid adjustment of all the flute pads. Pad adjustments can have a compensating role for small geometrical defects of the flute chimney or keys. They are also expected to be efficient under severe mechanical and moisture conditions, and during several years. Many pad types are developed by instruments and pads makers to match those requirements, resulting in different inner structures, skins or fastening means. We present a simple experimental setup to measure the leakages associated with different types of flute pads. The quasi-static measurements allow us to compare the different types of pads. The different values of the acoustic resistance associated with these leakages are then used to feed an acoustic model, in order to discuss the significance of the results in terms of the acoustic response of an instrument. This acoustic response can then be compared to actual measurements of input admittances of instruments equipped with different pads.

1 Introduction

During the 19th century, the development of modern woodwind instruments like the so-called Boehm flute had a major impact on the instruments tone holes [1,2]. Firstly, the number of holes roughly increased from six or seven (diatonic scale) to more than twelve (chromatic scale), avoiding an extensive use of cross-fingerings. Secondly, the hole diameter increased in such a way that it became impossible to close them directly using the player's fingers. The holes are therefore all closed using pads, through a complex key mechanism that allows controlling the 17 holes opening/closing, by using only 9 fingers on a modern B-foot flute.

The good adjustment of the pads is essential to the instrument sound quality, and therefore constitutes an everyday challenge for flute makers and repairers. Indeed, the player is expecting a stable, long lasting, and reliable adjustment while the pads operate under severe and rapidly changing conditions of temperature, humidity and mechanical constraint.

While traditional pads made of bladder skin and wool felt are still widely used, other technological solutions have appeared, changing the material as well as the pads structure; but their influence on the sound quality is not clear. The aim of the present paper is to investigate experimentally the influence of different pad types on the acoustical response of flute-like instruments. Section 2 presents some different pad structures, mounting and adjustment existing. Section 3 describes the experimental setup used, and section 4 discusses the results of the measurements done.

2 Pads structure, mounting and adjustment

Traditional pads are often made of three main layers: the skin, the body, and the back. The skin used is generally made of cow's intestine named *bladder skin*, or even *fish skin*. The body is made of wool felt while the back is made of cardboard.

Standard size pads are fixed inside the key cup using a screw and a washer, placed in the centre of the pad. The modern flute includes three small size holes, two of them corresponding to the trill keys. The pads used for those small holes are directly glued in the key cups. Open hole keys are also used in flute making, and are equipped with ring pads held by bushings.

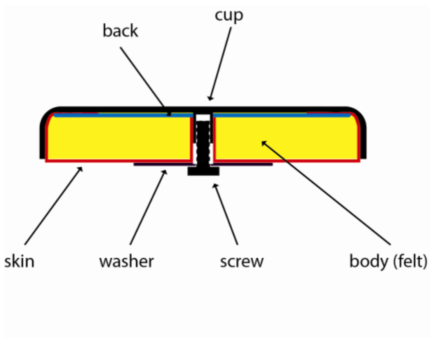

Figure 1: the pads are held in the key cup using a screw and a washer.

The basic pad adjustment is made by inserting fine cardboard washers between the pad and the key cup, so that the pad skin all over covers the hole chimney without leaking. Partial washers are often used to find the right adjustment, compensating for flatness defects of the chimney or specific geometry of the key. After some use, the pad skin shows marks of contact with the tone-hole rim. These marks probably lead to reduce the air leakages between the chimneys and the pads.

Many flute makers have developed new pads, changing the back material from cardboard to plastic, changing the wool felt to synthetic felt, changing the animal skin to synthetic skin like Teflon for instance, or any combination of these different changes. Different pad structures have also been tested, like foam or silicone solid body pads without any layered structure. Those different pad types sometimes call for specific mounting and adjustment techniques.

3 Experimental setup

In order to investigate the pads influence on the instruments acoustic behaviour, a specific device has been built by a flute maker. A German silver tube 25cm long, 19mm diameter and 0.35mm wall thickness is equipped with four 13.5mm diameter chimneys. The material used and the fabrication method are standard in flute making.

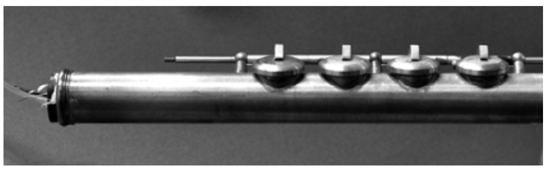

Figure 2: measurement device, equipped with four pads.

Four simplified keys have been added to the tube, allowing fast and easy pads change and adjustment. The keys are closed thanks to standard flute needle springs. The force exerted by the springs was checked to be about 0.5 N. Different pad types were tested:

- *a-* double skin and wool felt pads with cardboard back, which is the traditional pad type used in flute making,
- *b-* double skin pads with plastic back,
- *c-* double skin pads with plastic back and rubber coating on the skin,
- *d-* teflon skin pads,
- *e-* solid body foam pads,
- *f-* leather pads.

Pads *a* and *b* are standard commercial pads, pads *d* and *f* are used in flute making and repair, while pads *c* and *e* correspond to experimental types.

Two complementary types of measurements are performed using the device: low level linear acoustic impedance measurements and leakage measurements.

Input impedance is measured using a sensor developed by Laum and CTTM (Le Mans, France), made up of a piezo-electric buzzer and two microphones, one on each side of the buzzer. The admittance on the unknown side is deduced from the two pressure signals, while the closed cavity admittance on the other side of the buzzer is known [4].
Measurements of pads leakage properties are inspired from makers' way to test pads. The measurements are carried under quasi-static conditions, closing both ends of the test pipe. A positive or negative air flow, ranging from 1 to 5ml, is injected in the closed pipe while the inside pressure is recorded using an 8507 Endevco sensor.

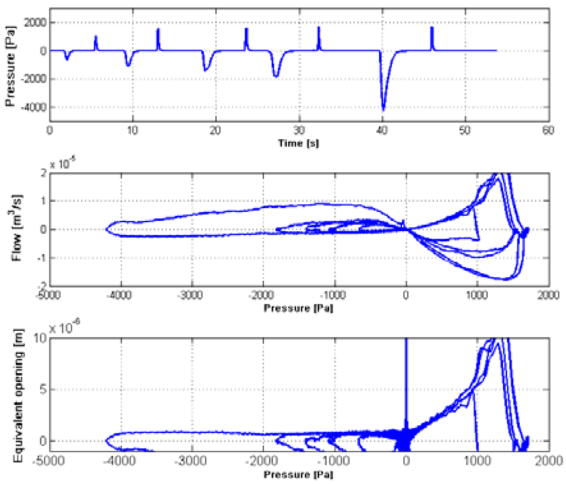

Figure 3: testing leakage using traditional pads. Air injection from -1, +1 to -5, +5 ml. The upper plot shows the pressure evolution inside the pipe, the middle plot shows the volume flow as a function of pressure, and the lower plot shows the equivalent opening height as a function of pressure (see text).

After an air injection, the pressure falls down again to the atmospheric pressure, at a rate depending on the tube leakages. Mass conservation under adiabatic assumption allows relating the outward leaking flow *Q* to the time derivative of the inner pressure *p* using:

$$Q = -\frac{V_0}{\rho_0 c_0^2}\frac{dp}{dt} \quad (1)$$

where V_0 is the volume of the test pipe, ρ_0 is the air density and c_0 is the speed of sound.
Leakage can as well be plotted as an equivalent opening height *h* of pads, assuming a Bernoulli relation between pressure and velocity U_B :

$$Q = U_b\, 2\pi\, rh = 2\pi\, rh\sqrt{\frac{2p}{\rho_0}} \quad (2)$$

where *r* is the chimney radius.
The data presented in figure 3 shows that the leakage increases slowly for positive pressure under 1500 Pa. Above this pressure value, the leakage increases rapidly: it corresponds to the key opening due to the force exerted on the pad by the inner pressure. Indeed, positive pressure values never reach 2000 Pa while it can get as low as -4000 Pa when pressure sucks the pad skin in. The order of magnitude for the key opening pressure can be checked to be coherent with the value expected from the ratio of the spring force f_s to the chimney cross section πr^2, which is about 3500 Pa. The leakage characteristics will be deduced from the time where the pressure returns to the atmospheric pressure, after an air injection or depression. The regions of interest are therefore given by $pQ>0$ (positive pressure and outwards flow, or negative pressure and inward flow). The other regions ($pQ<0$) correspond to the flow (positive or negative) injection in the closed volume.

4 Results and discussion

4.1 Admittance measurements

Three pad types were mounted on the tube: traditional pads (bladder skin and wool felt with cardboard back), reference pads made in Teflon (see 4.2) and foam pads. The input admittances measured for each configuration are shown in figure 4. The input admittance of the tube is then calculated using a transmission line model, with zero admittance at the pads. This admittance is compared to the measurements.

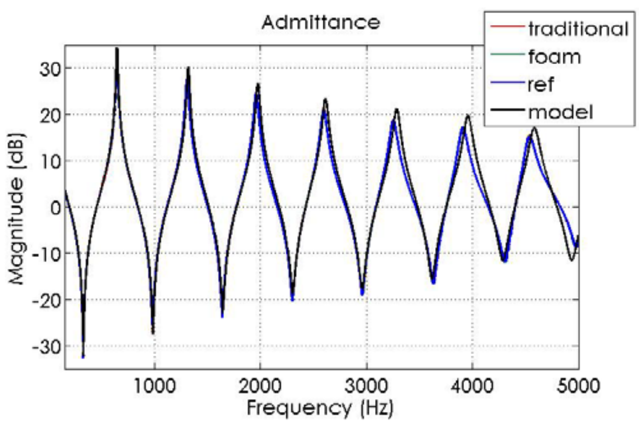

Figure 4: input admittance of the pipe. Three different pad types are tested. Measurements are compared with the input admittance calculated using a transmission line model.

Six measurements were carried for each pad set, in order to check the influence of the pad changing process and the temperature fluctuations associated with the operator manipulations. As a result, the differences observed on the admittance curve quality factor are in the order of 20% for the first maximum and 2% for the 2^{nd} to 7^{th} maxima. Differences in frequency are in the order of 1 cent and 0.5 cent respectively. Anyway, the differences between the pad sets appear to be in the same order of magnitude than the standard deviation for the 6 measurements inside one set. In view of these results, other pad characteristics are investigated through the leaking pad behavior.

4.2 Leakage measurements

The residual air leakage of the device was tested using some reference pads made of a flat metal plate with a thick Teflon skin glued on it. The residual air leakage was checked to be at least one order of magnitude smaller than all the other leakages measured.

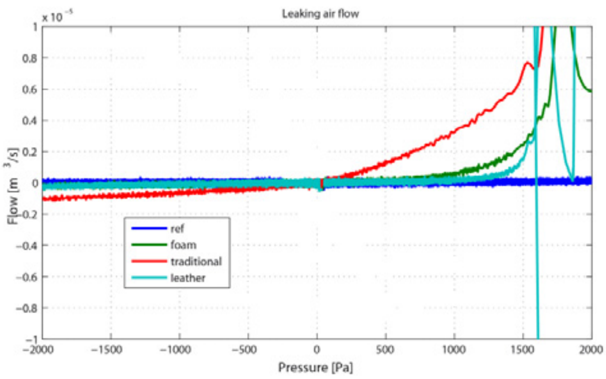

Figure 5: flow leaking as a function of inner pipe pressure for different sets of pads. The *ref* curve indicates the residual air leakage measured with the reference pads sealed on chimneys.

The same data can be plotted as equivalent opening heights, as shown in figure 6. Please note that the estimation of the opening height for low pressure values is highly sensitive to the noise in the experimental setup, due to the $p^{-1/2}$ dependence of the estimated opening height (see eq. 2).

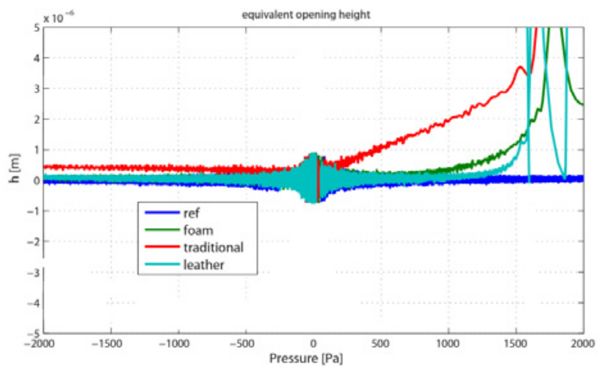

Figure 6: equivalent opening height as a function of inner pipe pressure for different sets of pads. The *ref* curve indicates the residual air leakage measured with the reference pads sealed on chimneys.

For negative pressures, all the pads show a Bernoulli type of leakage, with a constant equivalent opening height. However, this equivalent opening height is the smallest for the leather pads and the biggest for the traditional pads. For positive pressures, the sets of pads show different behaviors: while the traditional pads present a progressive opening, the leather and the foam pads present a quasi-constant opening followed by an abrupt opening close to the key opening pressure.

Under normal playing conditions, acoustic pressure reaches values in the same order of magnitude as blowing pressure [5], between 500 and 1000 Pa for standard playing conditions and reaching 1500 Pa for *forte* dynamics in the highest octave of the compass [6]. Therefore, acoustic pressure in the flute is expected to keep lower than the key opening pressure.

4.3 Using leakage measurements to feed an acoustic model

Admittance measurements done in section 4.1 shows differences between all the configurations tested: in particular, 20% for the quality factor of the first admittance maximum and 2% for the 2^{nd} to 7^{th} maxima. Moreover, the standard deviation for many measurements of one configuration is in the same order of magnitude than the differences between configurations.

Those changes in pads properties can be deduced from the leakage measurements done in section 4.2. The pads admittance is calculated by doing a linearization of quasi-static flow leaking curve as function of inner pipe pressure shown in figure 5. As seen in the previous section, the acoustic pressure range is in the same order of magnitude than the blowing pressure under normal playing conditions, that is, between 500 and 1000 Pa [5]. However, the quasi-static flow/pressure leaking curve shows a non-linear behavior. Pads impedance will be estimated by linearization of the quasi-static flow/pressure curve in range 500 to1000 Pa, but also in ranges -1000 to -500 Pa and -100 to 100 Pa.

Simulations are done using the pad admittances calculated to feed a classical transmission line model [3]. The input admittances calculated for the three different pads types with pads admittance estimation between -1000 and -500 Pa, are shown in figure 7. A comparison of the impedance maxima characteristics for all the configurations is shown in table 1.

		diff. in frequency		diff. in quality factor	
Diff. between configurations	Measurement or Interp. range	1^{rst}	2^{nd} to 7^{th}	1^{rst}	2^{nd} to 6^{th}
Foam/ Ref	Measurement	0.06 cents	<0.5 cents	-20 %	< 2%
	500 to 1000 Pa	-0.4 cents	<0.2 cents	-67 %	-37 to -19%
	-1000 to -500 Pa	-0.02 cents	<0.02 cents	-23 %	-7 to -2.9 %
	-100 to 100 Pa	-0.04 cents	<0.01cents	-25%	-10 to -4%
Foam/ traditional	Measurement	- 0.7 cents	<-0.5 cents	21.5 %	< 1.5 %
	500 to 1000 Pa	-6.5 cents	<2.5 cents	-73 %	-61 to -42 %
	-1000 to -500 Pa	-0.2 cents	<0.1 cents	-53 %	-26 to -12%
	-100 to 100 Pa	-0.35cents	<0.2 cents	-53%	-30 to -15%

Table 1: differences in frequency and quality factor for the 1^{rst} to 7^{th} admittance maxima, between two calculated or measured configurations. The admittance calculations are done using pads impedances deduced from the linearization of figure 5, for three different ranges of pressure: -1000 to -500 Pa, -100 to 100 Pa and 500 to 1000 Pa. Differences in frequency between two calculated or measured admittances are expressed in cent, while differences in quality factor are expressed in percent.

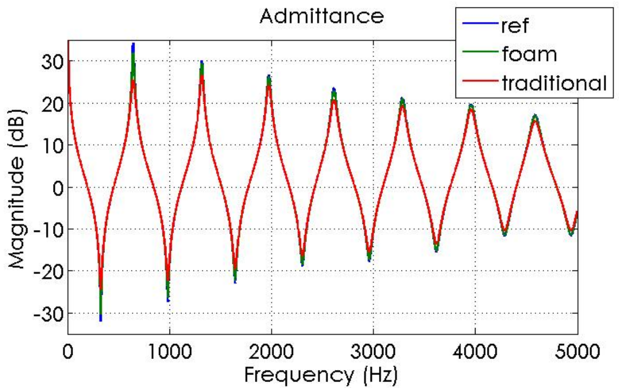

Figure 7: input admittance calculated, using pad impedances deduced from quasi-static leakage measurements between -1000 and -500 Pa, with three different pad sets.

For the three pressure ranges of flow/pressure linearization, the nearest differences between two calculated or measured configurations are shown for the estimation range from -1000 to -500 Pa and -100 to 100 Pa. For the foam to reference pads comparison, the difference calculated from the measurements is -20% for the quality factor of the first admittance maxima, and <2% for the 2^{nd} to 7^{th} maxima. For the calculated configurations using -1000 to -500 Pa and -100 to 100 Pa linearization ranges, those differences are respectively 23 % and <7%, and 25% and <10.

For the three kind of pad tested, the smallest differences are shown for the foam and reference pads comparison. Differences are greater for the foam and traditional pads comparison, especially if the pad admittance estimation is done by linearization between 500 and 1000 Pa. The difference is -73% for the first calculated quality factor, versus 21.5% for the measurements.

The three pad types tested by leakage measurement method show differences in their leakage characteristics. The estimated values of the pad admittances deduced from those measurements induce significant differences in the input admittances calculated. Those differences are larger than the differences shown by the measurements done in section 4.1, especially for the estimation range of 500 to 1000 Pa, where pads show greater differences in their leakage characteristics.

The behavior of the pads shown by leakages measurement doesn't allow finding an accurate estimation of the pads admittance for all the pads tested. Dynamic measurements or acoustic measurements for high amplitudes should be done to investigate the issue.

5 Conclusions

Different types of pads were compared when mounted on a specific testing device. All pad sets were expected to be in good condition, and the testing device was designed to facilitate a good adjustment of the pads. While the input admittance measured at low acoustic amplitude did not allow differentiating the sets of pads, the leakage characteristic of the sets of pads proved to be quite different.

The technique developed allows easy and fast measurements of the leakage characteristics, making easy to test different configurations. For example, the effect of piercing two small holes with a needle in the pad skin, on both sides of the chimney wall, proved to be easily monitored. However, the measurements are carried under quasi-static conditions. The relation between this quasi-static characteristic and the behaviour of the pads under acoustic pressure may not be straightforward. Acoustic measurements for high acoustic amplitudes may be an issue related to this aspect.

Flute players are used to compensate for small leakage problems by applying extra force on the keys. Future work should investigate the influence of this force (spring or finger) on the leakage characteristics. Flute players report quite different feelings concerning the flute mechanics when changing the pads. This may be related to the pads behaviour during transitions (key closing and opening, see [7]) as well as to the leaking characteristics. Different feelings also seem to be correlated to the felt structure: indeed, when the key is closed, the pad skin is compressed between the felt and the chimney. The feeling under the players' fingers may be associated to the felt compression behaviour rather than to the skin leakage characteristic. While harder pads may be associated to a less progressive leakage characteristic and higher acoustic impedance, they require a more accurate adjustment and are less tolerant regarding the instrument condition. Therefore, the question of the best type of characteristics for real playing conditions remains open.

Acknowledgments

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References

[1] S. Maclagan, "A dictionary for the modern flutist", *Scarecrow Press Inc.,* (2009)

[2] A. Baines, "The oxford companion to musical instruments", *Oxford University Press* (1992)

[3] A. Chaigne, J. Kergomard, "Acoustique des instruments de musique", Belin (2008)

[4] J.P. Dalmont "Acoustic impedance measurement, Part II : a new calibration method." Journal of Sound and Vibration (2001) 243(3),

[5] M.P. Verge, B. Fabre, A. Hirschberg, A.P.J. Wijnands "Sound production in recorder-like instruments. I. Dimensionless amplitude of the internal acoustic field" J. Acoust. Soc. Am. 101 (5), 1997

[6] I. Cossette, B. Fabre, V. Fréour, N. Montgermont, P. Monaco "From Breath to Sound: Linking Respiratory Mechanics to Aeroacoustic Sound Production in Flutes", Acta Acustica united with Acustica,Vol. 96 (2010)

[7] A. Almeida, R. Chow, J. Smith, and J. Wolfe "The kinetics and acoustics of fingering and note transitions on the flute" J. Acoust. Soc. Am. 126, 2009