WOODWIND ACOUSTICS

ACOUSTICAL LOSSES IN FLUTE PADS

by John W. Coltman

In a 1993 article[1] I discussed the various loss mechanisms that occur in the flute. These losses determine the blowing energy required to achieve a particular loudness. The losses that were discussed included losses at the wall due to viscous and thermal effects, turbulence and vortex formation at apertures, radiation of sound energy, and leaks when the pads fail to seal completely. Since then, experimental work by Jim Schmidt[2], using a tester he devised, gave evidence that appreciable acoustic losses may occur in the pads themselves, even though they produce an adequate seal. The work reported here is intended to investigate this matter further. Jim's cooperation and help are gratefully acknowledged.

Theory and Procedure

To measure the pad losses, a long section of flute tubing, 19mm ID, was supplied with a tone hole of 14.0 mm diameter, with a conventional chimney for the pad to seat on. The tube was plugged a few mm beyond the hole with an acoustically rigid piezo-ceramic microphone. Up the tube a distance of 33.3 cm a small hole was made to couple to another small microphone. A sound source derived from a loud speaker and a damped exponential cone was used to launch waves down the tube. Waves reflected back to the source were largely absorbed by the damping in the cone.

At the location of the small microphone, a pressure is observed that is the algebraic sum of the down-going wave plus the upcoming wave reflected from the far end. When the frequency is such that the distance from the mike to the end is one quarter of a wavelength, this pressure is the difference between the amplitudes of the down-going wave and the reflected wave. If there were no losses the wave amplitudes would be equal and the pressure would be zero. Because wall losses attenuate the waves, the minimum pressure measured at the microphone is finite, and is a measure of the wall losses. If, in addition, the pad at the far end has losses, this minimum pressure is slightly larger. This difference, between the pressure minimum with the pad in place, and that with a perfect rigid seal at the tone hole, is the measure of the pad losses. Because this is a small change in an already small number, the precision is limited for the kinds of losses that were encountered. The frequency at which the minimum occurred was close to 252 Hz, approximately B_3, the lowest note on the flute. Some measurements were made also at 3/4 of a wavelength, 765 Hz.

A measure of the pad loss is its acoustical conductance, that is the acoustical current or volume velocity, produced by the acoustical pressure. In cgs units the conductance unit is the mho. The micromho, 1 millionth of a mho, abbreviated here as umho, is a more practical measure for the conductances encountered here. The same unit is appropriate for leakage under constant pressure. To provide a feel for the size of the umho, a leak that allows one cc/sec of air to flow under a pressure of one inch of water has a conductance of 402 umho.

The formula for pad loss conductance measured in this fashion is Ga = G(Pa/P-1). Here Pa and P are the small mike pressures measured with the pad and with a perfect seal, respectively, the pressure at the terminating microphone being held constant. G is the conductance due to wall losses. It is measured separately by determining the Q of the tube, and calculated as G = n/4QZ, where n is the number of quarter-wavelengths in the tube, and Z its characteristic impedance.

The procedure then is first to derive a value G for the sealed pipe by measuring Q. This need be done only once, as the wall losses are fixed and stable. Measure the minimum P when the tone hole is sealed, and note the stopper mike value. Substitute a pad, return the stopper mike reading to the same value by adjusting the amplitude of the driving wave, and measure Pa, the new small mike reading. One may need to adjust the frequency slightly to stay on the minimum, as the pad may introduce small reactances also. Because pad losses are small compared to wall losses, Pa is often very close to P. Thus several readings may be required, with substitution of the perfect seal to check P. As an example, the Q of the tube was 42.1 at 251 Hz, giving a value for G of 1265 umho. Typical values of P and Pa with seal and pad respectively might be 6.70 and 6.75, giving Ga = 9 umho.

The value of Ga determined in this fashion includes any losses due to leaking, that is, the failure of the pad to seat properly, or leakage under the retaining washer or retaining screw, all of which are quite common occurrences. Accordingly, a separate means was employed to determine leakage under static air pressure. The tube described above was separable at a point 7.3 cm above the center of the tone hole. This small section, containing the keyhole and stopper assembly, could be mounted on a fixed stand for leak measurements. A small plunger made from polyethylene plastic was fitted with an O-ring at its end so that it could slide easily into the tube but maintain a good seal. A hole in the plunger permitted connection to a tee of small tubing, connected in turn with rubber and plastic tubing to a pressure meter and to an air source. With the pad in place, air is introduced into the source tube using a squeeze bulb or the mouth. The pressure meter had a full scale reading of two inches of water, and enough air was introduced to produce a nearly full scale reading. The source tube was clamped shut, and the decay in pressure timed as the needle passed particular points on the scale. The decay was exponential, and the time constant (number of seconds for decay to 1/e) was calculated from the readings. Timing was accomplished with a short timer program written in BASIC that permitted a computer to display the times at which the space bar was depressed. Calculation of the time constant and flow was done quickly with a spread sheet program (Excel) that produced a trend line from the readings.

The unit must be calibrated to determine what air loss corresponded to a change in pressure readings, since most of the uptake was not due to compression, but rather to the expanding bellows in the pressure meter. The calibration was done by closing the source tube, and moving the plunger in the tube to obtain a given pressure change reading. The dimensions of the plunger and its distance moved sufficed for the calibration. Leak rates were usually small enough to give time constants in the hundreds of seconds, so in contrast to the acoustic loss measurement, leak rates could be determined to high precision.

Significance of Losses

Pad losses are small compared to wall losses. There is then a need to supply some measure of what pad loss might be significant in determining the satisfactory performance of an instrument, that is, in striving to reduce such losses, what values are "good enough"? Accordingly, disks containing known calibrated leaks were substituted for pads on a flute or a test pipe.

A known leak having a conductance of 280 umho was placed close to the acoustic center of a straight flute tube provided with a flute embouchure, giving a note at about low B (247 Hz.). The leak could be opened and closed with the finger at its exit hole. When this flute was blown, no difference in loudness or tone quality could be heard when the leak was opened and closed. The flute was also provided with a microphone at the stopper. When blown with an artificial lip to give a tone much steadier than was possible with actual blowing, the microphone output showed a change of about 8% in amplitude with the leak open or closed. Careful listening under these conditions could barely perceive a slight change in loudness. A .wav file recording was made of the microphone output when played by a flutist, the leak being open and closed at about three times a second. Displaying the waveform on the computer exhibited an unsteadiness in amplitude that masked any effects of opening and closing the leak. However, the flutist's heartbeat could be seen, an effect not usually commented on when discussing the tone of the flute! It is concluded that adding a conductance of 280 umho at the maximum pressure point, when sounding low B, gives an additional loss that is imperceptible either to the player or the listener.

Most of the measurements were made at low B. It is here that all the pads on the flute come into play, and at the same time, the wall losses are greatest and the flute output weakest. There are 14 large pads on the flute that are closed when playing low B. Each of them is subject to a different pressure, which is maximum at the hole just below the thumb key, and falls off sinusoidally to zero at a point a little beyond the open end of the foot. Thus in calculating the effect of several pads, one must take into consideration the fact that each pad operates at a different pressure, and makes a smaller contribution to the losses than if it were located at the maximum pressure point in the instrument. For low B, if each of the 14 pads had the same conductance, their total effect would be equal to the conductance of 9.5 such pads located at the maximum pressure point, where the test leak of 280 umho had been placed. Dividing 280 by 9.5 gives about 30 umho, which may now be taken as a conservative upper limit for a satisfactory conductance of a single pad.

All measurements reported here were made using a tone hole diameter of 14 mm, characteristic of the right hand holes on the flute. Left hand holes are a little smaller, and it is safe to assume that pads there would produce smaller losses. The larger foot joint pads might have somewhat larger losses; however they always operate at quite low pressures. At low B, the four foot joint pads together would contribute only 10% of the total pad losses if all the pads were alike. It was therefore thought unnecessary to test other pad sizes.

Tests made at 765 Hz showed individual pad losses similar to those at 252 Hz. But at this frequency (F# in the middle register), the pressure distribution gives an equivalent loss for all pads in operation equivalent to that for only 5 pads at the pressure maximum. A similar situation holds for D in the middle register, where 12 pads are in use, but their total effect is like that of 4 pads. Thus testing at 252 Hz and setting an upper limit of 30 umho for a single pad appears to give a conservative criterion for satisfactory performance over the entire range of flute operation.

Pad Mounting

The chimney on which the pads were seated was honed flat with a diamond hone, finishing off with 600 grit polishing paper. This paper was used to break the very sharp edges left, but the seat was essentially flat rather than having a semicircular profile as is often used in the flute.

Pads were contained in flute key cups that had only a short stem; any axle tubing was cut away. The cup and pad were placed directly on the seat, not pivoted on an axle. There was no need then to shim the pad for tilt; it was necessary only to assure the pad was flat. Two adjustable vertical posts were mounted on the flute tube just to the rear of the tone hole chimney. They were positioned so that when the cup was in contact with them, it was centered on the tone hole. A third post was positioned to contact the stem, to fix the rotation. These vertical posts did not hamper vertical movement due to compression of the pad, but otherwise assured that the pad could be replaced precisely in the same position if removed.

Some key cups were used in the conventional fashion, with paper washers (or for the Straubinger pad, its stabilizer) to adjust the height in the cup. In other cases a thin brass washer was used under the pad for support. One key cup was partially filled with silver-tin solder and then turned on the lathe to produce an accurately flat bottom in the cup. Most pads were mounted with the usual washer and retaining screw. Small sealing washers under the screw (supplied by Jim Schmidt) prevented leakage at this point. Conventional skin pads were moistened, ironed to remove wrinkles, moistened again and set on the seat under a strong clip for several hours.

A "perfect seal" for comparison was provide by a flat disk of rubber, 0.05 inches thick, cemented to the bottom of a thick rigid disk of polyethylene, and closed when on the seat with a strong clip. This added no additional loss, as tested by comparing it with a thick brass disk sealed with a thin film of oil.

Force

Both the leakage and the acoustic loss vary with the force applied to the key. Using a small transducer mounted between the finger and the key of a flute, measurements were made of the finger force used by a few professional and skilled amateurs flutists. The force varied substantially with the flutist, the finger used, and the note played. Measured forces varied over the range of 100 to 350 gm weight, with a grand average of 185 gm. A detailed description and analysis of these results is left until more flutists have been tested.

In many cases, more than one key is being held down by a single finger. In the case of B-flat, the first finger in the right hand is closing three keys, and the finger force must be shared among them. Most often two keys are so depressed. If we take this as typical, the grand average force per key is about 90 gm. Now the key is also lifted up by its spring. This force varies somewhat with the instrument and the key, but was typically 20 gm on the professional flute measured, and 25 on a student flute. Thus the force between pad and seat is more like 70 gm. There will be substantial variations about this average.

Forces applied in the measurements ranged from 20 to 100 gm weight. Measured force was applied to the center of the key cup in two different ways. One was to use a lever, its short arm hooked under a wire pivot, its fulcrum resting on the key cup, and its long arm holding a sliding weight that allowed various forces to be applied. Under some conditions it was found that this assembly would resonate at the frequency of the sound applied to the pad, giving wildly varying readings at certain positions of the slide weight. The same was true for a single balance weight of a particular value resting directly on the key. The lever was therefore abandoned for acoustic tests, but was used in the static leak tests. A second method, used in most of the tests, was to apply the force with a long light vertical spring, one end attached to a hook bearing on the center of the cup, and the other end attached to a slider below the tube, the extension being calibrated to show the force applied. This assembly also showed some small resonance effects at 766 Hz, but was with one exception free from that phenomenon at 250 Hz. The forces quoted here are those applied to the cup, not including the weight of the cup and pad, about 6.5 gm.

Results

Table I summarizes the results for tests of the various pads at 252 Hz. The numbers given for conductance are averages of several readings, in some cases taken at different times and after reinstallation in the cup. The lines marked "Total" show the acoustically measured losses, and include any leak losses such as given on the line below. The difference in these two numbers represents those acoustic losses that take place in the pad itself. There is a variation about these averages that may be as much as 3 umho, however the ensemble provides a fairly consistent picture of the pad behavior. Table 2 lists results for some pads at 765 Hz. It will be noted that contrary to most results at 252 Hz, some of the pads exhibit higher values of conductance at stronger closing force than at weak. In all of these cases, resonance of the spring loading was apparent - at certain spring loadings the reading changed when the spring was lightly touched. Resonance effects were even larger with mass loading, and were not entirely absent when loaded with the finger, that is, as the finger force was gradually increased, a point was reached where the conductance peaked and then diminished again. Resonance then may not be simply a peculiarity of the measurement setup, but may well be present in playing the flute. Note that the Straubinger and JS pads are free of this phenomenon, but that synthetic pad 940, a quite "springy" pad, showed strong resonance effects, even at 252 Hz, as indicated by the 120 umho reading at 80 gm force.

Table I

Pad Loss - Loss Conductance in Micromhos, 252 Hz.

Specimen	Force, gm wt.	20	40	60	80	100
Skin*, 915 Thick Firm	Total	52	11	12	8	5
	Leak		2.2		2.0	
Skin, 924 Medium thick	Total	91	30	3		
	Leak		27	8		
Skin, 904 Thin firm	Total	25	8	5	3	3
	Leak		2	1	1	1
Skin, 944 Very thin Firm	Total	85	38	27	22	22
	Leak		25	15	13	10
Synthetic, 940	Total		25	21	120	
	Leak		7	4		
Straubinger synthetic	Total	20	13	9	5	4
	Leak		3	2		
JS (Jim Schmidt) synthetic	Total	25	7	4	3	2
	Leak		3			
Valentino synthetic	Total	32	27	19	21	20
	Leak		2.5	1.8	1.5	1.3

** Pads marked "skin" are double bladder on felt, supplied by Ed Myers Co. Synthetic 904, a rubberlike foam with synthetic skin was also supplied by them. The numbers are their identification numbers. The Straubinger pad is bladder skin over ultrasuede , JS is a synthetic skin over ultrasuede.*

Table II

Pad Loss - Loss Conductance in Micromhos, 765 Hz.

Specimen	Force, gm wt.	20	40	60	80	100
Skin*, 915 Thick Firm	Total	34	15	25	42	20
	Leak		2.2		2.0	
Skin, 904, Thin firm	Total	15	22	22	48	48
	Leak		2	1	1	1
Skin, 944 Very thin firm	Total	59	52	27	27	27
	Leak		25	15	13	10
Straubinger synthetic	Total	19	13	9	9	6
	Leak		3	2		
JS (Jim Schmidt) synthetic	Total	33	9	6	5	5
	Leak		3			

Discussion

The measurements made here do show that flute pads may introduce acoustic losses other than those due to leakage. Those measurements are not precise, partly because of limitations in the method, but also because the conductance loss is affected by how the pad is seated in the cup and how it is treated during installation. Minimum losses and best repeatability were obtained when the pad was supported uniformly over its rear surface, either by the flat bottomed cup prepared for that purpose, or by the special structures in the JS and Straubinger pads.

The loss conductances at the higher frequency, 765 Hz (about F# in the mid range of the flute) were generally higher, and exhibited resonance effects in some cases. However, the tolerance of the flute to such additional losses at the higher frequency is considerably greater since pad losses represent a smaller fraction of the total loss, and fewer pads are involved. Behavior at the low frequency is much more critical.

As a general conclusion, most types of pads now in use have, when properly installed, acoustical losses that will not contribute detectable changes in the power or tone quality of the instrument. There are of course other considerations in the choice of a pad, such as the "feel" of the pad when depressed by the finger, noise on closing, durability, sticking and the like. These matters were not addressed in the present research..

1. Acoustical Losses in the Boehm Flute, John W. Coltman, The Flutist Quarterly, Fall, 1993 37-41

2. High Tech Flute Pads, Jim Schmidt, The Flutist Quarterly, Spring, 2002

"You heard me, Simmons!...You get that cursed bugle fixed!"

The audience at a piano recital were appalled when a telephone rang just off stage. Without missing a beat, the soloist glanced in the direction of the stage manager and said, "If that's my agent, tell him I'm working."