Acoustical evaluation of a novel flute head construction

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Introduction

Modern western flutes are designed based on the construction proposed by Theobald Boehm in the middle of the 19$^{\text{th}}$ century [1]. Since the appearance of Boehm's reformed flute several flutists and flute makers suggested minor improvements to compensate certain imperfections of the instrument. Recently, a new flute head construction was proposed and patented by an expert flutist. The novel flute head family introduces a revised geometry of the tuning plug and uses different materials for the tuning and crown plugs.

The top part of Figure 1 displays the longitudinal section of a traditional flute head joint. The flute is played by blowing a thin jet of air over the embouchure hole. The resulting pitch is determined mainly by the effective length of the resonator and the blowing strength. Tuning is achieved by adjusting the position of the tuning plug that consists of a front and a back plate and a cork. The flute head is slightly tapered toward the closed end which is terminated by the crown. Traditionally, the front plate is flat and thus the air column between the embouchure and the tuning plug has the approximate shape of a truncated cone. The bottom part of Figure 1 shows the sketches of two alternative novel tuning plug designs. The left one shows a rounded plug, while the right one is a conical plug with a small cone angle. In both cases, the shape of the plug is significantly different from that of the traditional assembly. Both shapes can be made from different materials, such as wood, bone, or various types of metals and alloys. Furthermore, the new tuning plugs can be accompanied by different crown constructions; however, the latter possibility was not examined here in order to keep the number of variations moderate.

Results of measurements performed on different flute heads are presented in the sequel. During the measurements sound samples played using one traditional flute head and five novel tuning plugs made of different materials were recorded in a semi-anechoic chamber. Steady state and transient properties of the recordings were evaluated and it was found that by means of the novel construction significantly different and enhanced sound characteristics can be produced by the flute. An acoustical model of the flute is also elaborated and the effect of the tuning plug on the harmonicity is discussed.

Measurement and processing tools

Six different head joints were used in the measurement: flutes equipped with a new steel, cocobolo wood, bone, silver or titanium tuning plug, and a flute with a traditional head. All tuning plugs were assembled with a Trevor James Cantabile silver plated concert flute, whose original head joint was made of silver. Notes held long and steady (without *vibrato*) were played on all flutes by a professional flutist. Recordings were made for all six configurations in the full musical scale playable on the flute—from c' (one-lined c, further referred to as C1) to c'''' (four-lined c, further referred to as C4)—playing the notes *piano* and *forte*, one by one, in a sequence along the chromatic scale. Altogether $6 \times 37 \times 2 = 444$ sound samples were recorded, and in each sound sample the same note was sounded three times consecutively.

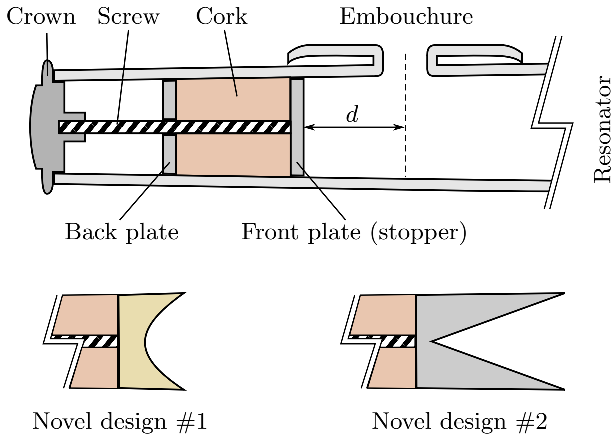

Figure 1: Longitudinal section of the flute head. Top: traditional setup. Bottom: New tuning plugs with different shapes and materials, left: approximate shape of the cocobolo and bone plugs, right: steel, silver, and titanium plugs.

The sounds were recorded in a semi-anechoic chamber using four calibrated condenser microphones. Two microphones were located at a distance of $\approx 20\,\text{cm}$ from the embouchure hole and the open end of the flute, respectively. The other two microphones were placed at a distance of $\approx 150\,\text{cm}$ from the flutist, one opposite and one to the left hand side of the player. The recordings were made using a 24-bit A/D card running at a sampling frequency of $f_\text{s} = 51\,200\,\text{Hz}$.

Each recorded sound was automatically segmented into attack, steady state, and decay parts. The segmentation was performed based on the running r.m.s. of the sound pressure measured by the microphone near the open end of the flute. First, the fundamental frequency was determined from the steady state part of the signal. Beside the mean frequency, its temporal statistics were also calculated by sampling consecutive time windows. A slight fluctuation of the fundamental frequency is natural due to the inevitable instability of the air jet excitation produced by the player. The results of the analysis of the

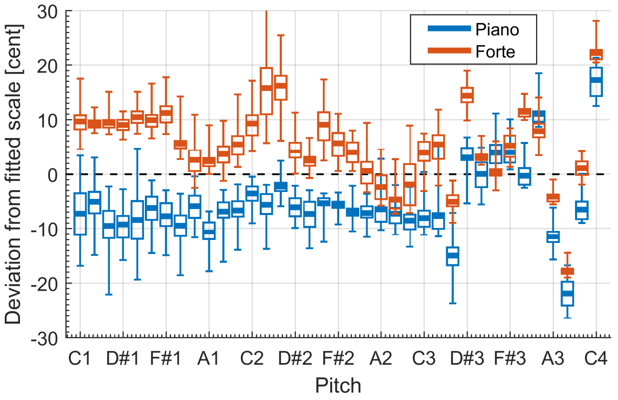

Figure 2: Typical statistics of the observed fundamental frequencies compared to a fitted tempered scale. Thick lines: mean value, boxes: upper and lower quartiles, thin horizontal markers: minimum and maximum.

fundamental frequency are exemplified in Figure 2. The frequencies are shown as deviations from an imaginary tuning resulting from fitting a tempered scale onto the measured frequencies. The properties observable on the diagram were found to be common for all six examined flutes. It is seen that notes played with *piano* dynamics are a few cents below the fitted scale, while the *forte* notes lie above the same scale. As observed, the notes of the first (C1–C#2) and second (D2–C#3) registers are much easier to play in tune and hold steady than that of the third register (D3–C4).

Steady state results

Once the fundamental frequencies were accurately determined, the signals were resampled using a sampling frequency $f_{\mathrm{re}} = 64 \cdot f_1$, with f_1 denoting the mean fundamental frequency of the signal. Then, both the steady and attack segments of each recording were analyzed. From the steady state segments the equivalent loudness, the averaged power spectra, and the spectral centroids were calculated. The equivalent loudness was evaluated by summing the power of the harmonics in the spectrum. The power of non-harmonic components was found to be negligible. Figure 3 shows a typical equivalent loudness curve measured by the near field microphone at the open end of the flute. As seen in the diagram, the switching between registers (overblowing to the 2nd or 3rd mode) also results in a jump of the loudness.

The measured sound pressure levels (SPL) for the different tuning plugs are displayed in Table 1. It is seen that the SPL of notes played with different dynamics in all registers are influenced by both the material and the type of the tuning plug. For example, the steel tuning plug enables higher levels in the middle and upper registers compared to the traditional plug when playing *forte* dynamics, while the levels of *piano* notes in the lower register are not affected significantly. Similar differences are observed when comparing the cocobolo and titanium tuning plugs with the traditional one. The achievable dynamic range (or *forte* to *piano* ratio) is slightly greater

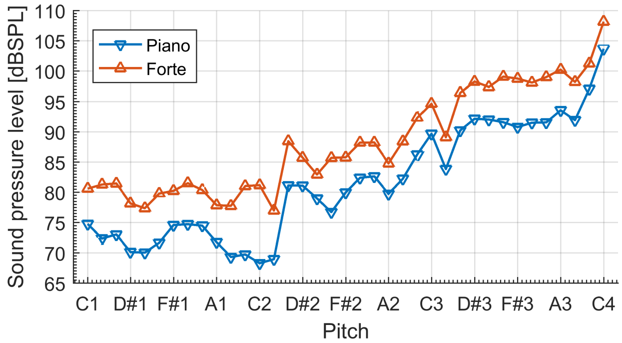

Figure 3: Typical equivalent loudness measured by the microphone near the open end of the flute. The overblowing transitions between registers are clearly visible between the notes C#2–D2 and C#3–D3.

Dynamics	Piano [dBSPL]			Forte [dBSPL]		
Register	1st	2nd	3rd	1st	2nd	3rd
Steel	72.2	85.9	95.7	81.5	92.1	102.3
Cocobolo	72.1	83.8	95.9	79.9	89.6	102.9
Bone	72.2	81.5	94.0	79.0	86.8	98.8
Silver	71.2	82.6	94.8	80.9	88.1	99.9
Titanium	72.0	82.8	94.4	79.9	88.5	100.2
Traditional	71.9	82.3	93.0	80.5	88.1	98.7

Table 1: Average SPL of notes held long played on different flutes measured near the open end over the three registers.

in case of the silver and steel tuning plugs and smaller in case of the bone plug compared to the traditional plug.

The stationary spectrum of each recording was also evaluated. Interestingly, significant differences were found regarding the spectral envelopes of the notes played on different flute heads. Figure 4 shows the amplitudes of the first nine harmonics of the F1 *piano* note. As it is seen, there are remarkable differences between the spectral contents produced by the different tuning plugs. The greatest dissimilarities are observed in case of the 2nd harmonic (octave), where the levels can differ more than 20 dB compared to each other. For the higher harmonics differences up to 15 dB are also observed. Such great differences of the spectral contents also significantly affect the perceived character of the flute sound.

In order to quantify the harmonic content and the timbre of all notes in the steady state the spectral centroids C of the recordings were evaluated using the formula

$$C(X) = \sum_{n=1}^{N_{\mathrm{harm}}} nX(nf_1) \Big/ \sum_{n=1}^{N_{\mathrm{harm}}} X(nf_1), \qquad (1)$$

with X denoting the power spectrum of the signal, f_1 the fundamental frequency, and N_{harm} is the number of harmonics taken into account. In the evaluation N_{harm} was limited by the Nyquist frequency of the sampling.

Table 2 displays the spectral centroid values measured with different flute head configurations averaged over the three registers for *piano* and *forte* dynamics. The

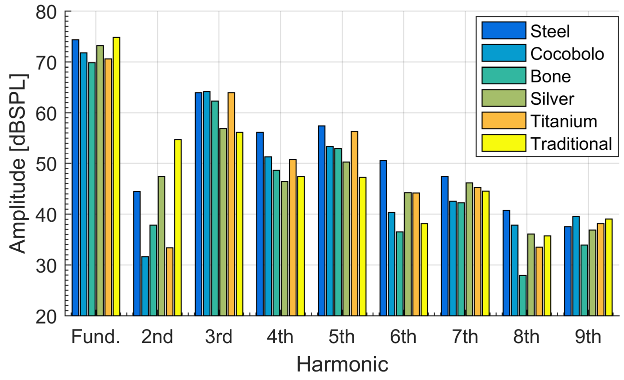

Figure 4: Steady state harmonic amplitudes of the F1 *piano* note played on different flute heads.

Dynamics	Piano			Forte		
Register	1st	2nd	3rd	1st	2nd	3rd
Steel	1.42	1.20	1.02	2.38	1.33	1.04
Cocobolo	1.36	1.22	1.01	2.26	1.38	1.05
Bone	1.33	1.17	1.01	2.12	1.28	1.03
Silver	1.22	1.18	1.03	2.30	1.34	1.06
Titanium	1.39	1.18	1.01	2.31	1.28	1.04
Traditional	1.22	1.21	1.02	2.16	1.41	1.05

Table 2: Average spectral centroids of the held notes played on different flute sets, measured at the open end of the flute over the three registers.

spectral centroids of *forte* notes are significantly greater than that of *piano* notes in all cases. In cases of flutes with steel, cocobolo or titanium tuning plugs the spectral centroids of the produced notes are higher, especially in the lower register, thus, their steady state sound is richer in higher harmonics compared to the traditional flute head. The spectral centroids of the held notes played with bone, silver and traditional plugs are similar.

Transient results

To investigate how notes are started, the attack phases of the sounds were analyzed. The attack phase plays an important role in the perceived quality of the sound, therefore it is worth analyzing the attack phase in an objective manner too. Resampling is important in the evaluation as it enables coherent sampling and avoiding the spectral leakage effect even with a small time window size. Thus, the amplitudes of the harmonics are determined with high accuracy and detailed temporal resolution.

It is a general feature of wind instruments that the attacks are slightly different when the same note is played repeatedly. This renders the objective evaluation of the attack phase more difficult. Therefore, always the fastest attack (from the three consecutive ones) was evaluated, as this can be regarded as the "smoothest" one.

Figure 5 demonstrates the greatest difference between the novel flute heads and the traditional one, observed in case of the note F#1. When played with *piano* dynamics the attack is much slower with the traditional head than

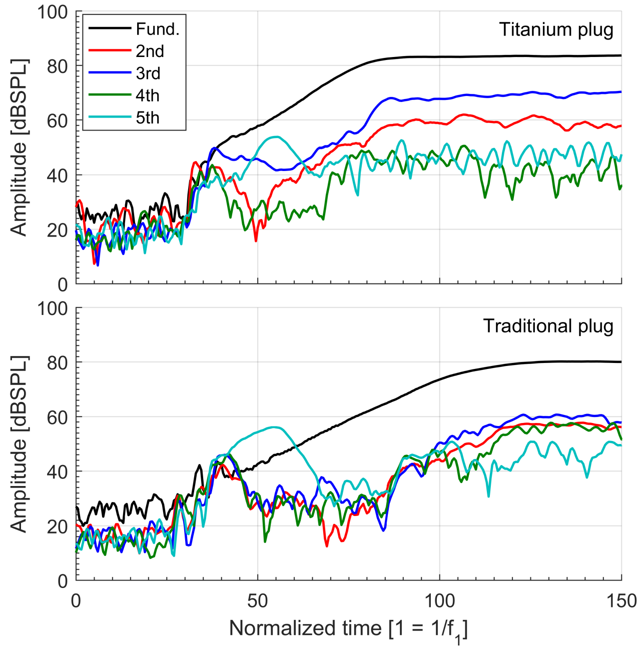

Figure 5: Attacks of note F#1 *piano* played using the titanium (top) and traditional (bottom) tuning plugs.

with any of the new heads. With the traditional head, in case of either dynamics the 5$^{\text{th}}$ harmonic (major third) appears with a significant amplitude in the beginning of the attack. In this case the difference in the attack transients is also well audible. This unique phenomenon was not observed neither when playing the same note with any of the new flute heads or when playing the neighboring F1 or G1 notes.

Acoustical model

In order to examine the effect of the new tuning plugs on the acoustical behavior of the air column, an acoustical waveguide model of the flute was assembled. Figure 6 depicts the model that is composed of straight and conical bore sections, T-models representing open or closed tone holes and radiation impedances at the embouchure (Z_{emb}) and at the open end (Z_{open}). The model enables the calculation of the input admittance function $Y_{\text{in}}(f)$ of the flute, from which the eigenfrequencies of the air column inside the bore can be obtained and the harmonicity of the modes be predicted. The harmonicity of the resonator is worth to be examined as it is expected to have a remarkable influence on the harmonic content of the steady state sound [2].

The the resonator is inherently slightly inharmonic due to the frequency dependence of the tone hole and radiation impedances. It is useful to characterize the latter using length corrections ΔL which are related to the impedance Z and the reflection coefficient R as

$$R = \frac{Z - Z_0}{Z + Z_0} \qquad R = -\left|R\right| \mathrm{e}^{-2\mathrm{j}k\Delta L}, \tag{2}$$

with Z_0 denoting the plane wave impedance of the bore and k the wave number.

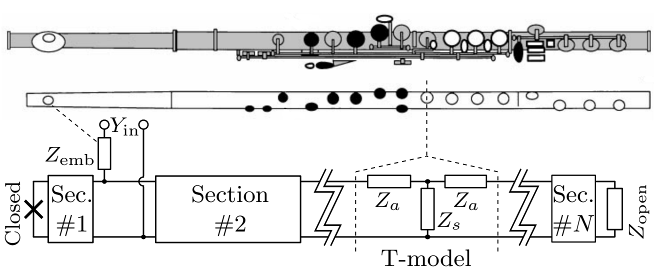

Figure 6: Sketch of the flute (top) its bore (middle) [3] and the acoustical waveguide model (bottom).

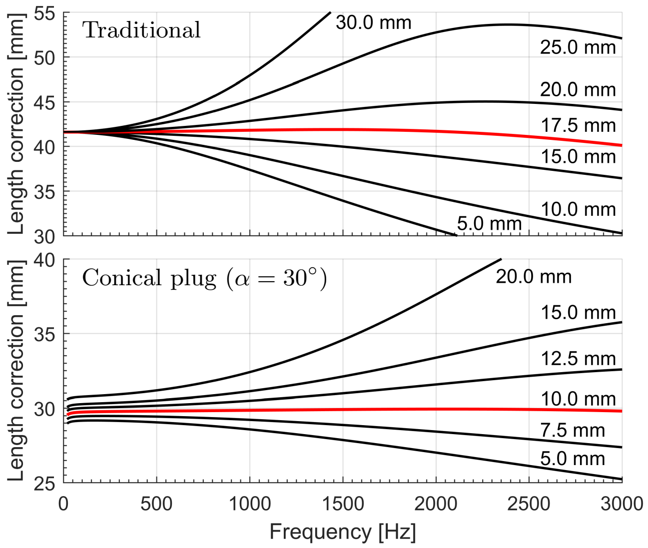

Figure 7: Effect of the distance of the tuning plug from the embouchure hole on the embouchure length correction. Top: traditional (flat) tuning plug. Bottom: novel conical plug.

The length correction of the embouchure has a significant effect on the harmonicity. [1] In the traditional flute head the tuning plug is located at a distance of $d \approx 17.5$ mm from the center of the embouchure hole (see Figure 1). It is shown in the top diagram of Figure 7 that this setup provides $\Delta L(f) \approx$ const in a broad range of frequencies. The bottom diagram of Figure 7 proves that a similar result can be achieved using a novel tuning plug with conical shape. In case of a plug with cone angle $\alpha = 30°$ at $d \approx 10.0$ mm the resulting embouchure correction is even more flat than the same for the traditional plug.

The resulting harmonicity can be quantified using the normalized stretching factors $\mathrm{Str}(n)$

$$\mathrm{Str}(n) = \frac{f_n}{n f_1} - 1, \tag{3}$$

with f_n denoting the nth eigenfrequency. Figure 8 displays the harmonicity of the C1 and G1 notes with different tuning plugs and d values (same as in Figure 7). Due to the effect of tone holes the harmonicity curves are quite different for the two notes with both tuning plugs. For the G1 note a near-optimal harmonicity is achieved by the setups that also provide the constant length corrections. The harmonicity curves lie closer to each other in case of the conical tuning plug, which means that the novel design is less sensitive to the distance d.

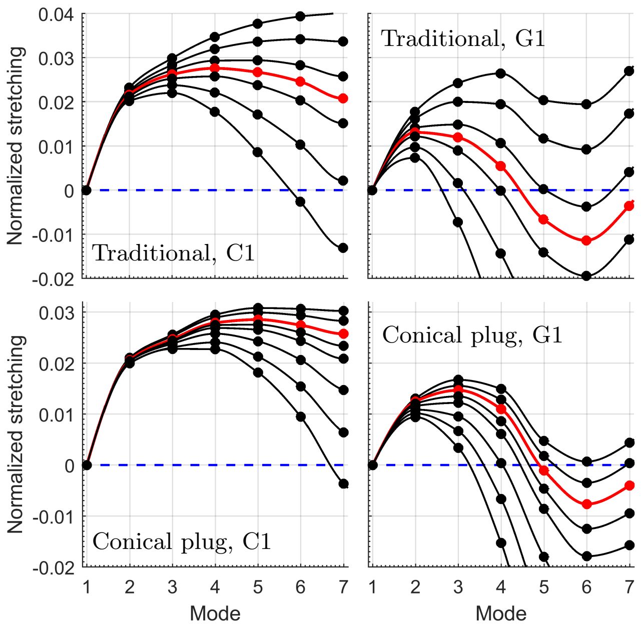

Figure 8: Effect of the distance of the tuning plug from the embouchure hole on the harmonicity of different notes.

The limiting factor in the evaluation of the harmonicity is the embouchure impedance, which is significantly affected by the player. [3] Flute players also change the position of their lips when playing different notes along the scale [4], which renders the evaluation of the impedance more difficult.

The results from the acoustical model confirm that the shape of the tuning plug can have a significant effect on the length corrections and harmonicity of the flute. The relations of the predicted harmonicity and measured sound spectra is to be examined in the future.

Acknowledgments

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