NEW DESIGNS FOR THE KANTELE WITH IMPROVED SOUND RADIATION

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ABSTRACT

The kantele is a plucked string instrument belonging to the family of zithers that are used in traditional folk music in Finland, Northwest Russia, and the Baltic states. We propose design rules for a kantele that has a higher loudness than traditional models and present acoustical analysis results to confirm the amplification. The guidelines for making a plucked string instrument louder are to increase the string tension, to add more radiating surface area, and to isolate the top plate from the sound-box with an air gap. We investigate the increased string tension analytically, and show the benefits of the enlarged radiating surface and the isolated top plate experimentally, by acoustical measurements. The input force and the resulting SPL are measured in an anechoic chamber at several points around the instrument, and the measured SPL values are converted to loudness estimates using a computational model. All results are compared against similar figures for a traditional kantele. A playability test, where a professional kantele player is asked to play as softly and as loudly, as she/he feels comfortable, reveals how much we have been able to widen the dynamic range. Finally, the effect of the structural modifications on the timbre is evaluated.

1. INTRODUCTION

There is a great variety in string quantities, box models, and sizes among the stringed musical instruments that are called the "kantele". A common feature is the special timbre that is caused by the way the steel strings are attached, especially the knot [1, 2]. A kantele has typically 5 to 36 steel strings, which form a fan over the top plate. Fig. 1 shows a traditional 10-string Finnish kantele. The narrow end, on the right in Fig. 1, is called the 'ponsi'. At the right end of Fig. 1, each string is attached by a special knot to a metal rod called the 'varras'. At the wide end of the string fan (on the left in Fig. 1), the strings go around the tuning pins.

For Finns, the kantele is closely connected to the oldest layers of their music and poetry. Nowadays, the kantele is used more and more often in concerts, but the traditional Finnish models are usually not heard without amplification. On the stage, the kantele needs to be louder than traditional models, and it is of interest to examine what can be done without electrical amplification. These are some of the motivations for this research.

Musical instrument makers usually consider designs, where strings are attached to a wooden box that has a sound hole. The main radiator of acoustic energy is the top plate. The mid-part of the top plate is able to vibrate strongly, while the regions at the edges are nearly fixed. There is a long and wide research tradition of stringed instruments with wooden vibrating plates, such as violins, pianos, and guitars, and it helps us to better understand the kantele, too. From the functional point of view, the guitar and the kantele have similarities: they both get an impulsive excitation from the player's finger, and they cannot produce very loud sounds.

In this paper, we propose novel design rules for a kantele that has a higher loudness than traditional models. The main goal of the new design is the improved radiation efficiency. At the same time, an improved balance between the low and high tones is attempted. A large variety of ringing, fluctuating tone colors can be achieved by a skilled kantele player, and we do not want to loose these possibilities when increasing the dynamic range. We investigate the benefits obtained by the increased string tension, an enlarged radiating surface, and an isolated top plate.

The first kanteles of the new design were built in the summer of 1999. Different sizes have been tested: 11-string piccolos one octave higher than the traditional one described above, 5-string models, and two larger 20 or 21-string models with a large compass and deep bass with the lowest tone D2. Based on evaluations by several pairs of ears, all these designs have been promising. Especially the low bass tones sounded deeper in quality and stronger in amplitude than those of the comparable, good-quality traditional models. An 11-string kantele produced according to the new design is shown in Fig. 2.

The idea for a freely vibrating top plate comes from the old 5-string museum kanteles: some of them have a closed box while

Figure 1: *The traditional 10-string kantele.*

Figure 2: *The modified 11-string kantele.*

others are carved from a single piece of wood so that they have a top with sides along its edges, but no bottom. The bottomless design is clearly louder of the two, and it has a warmer timbre. The favorable features of the bottomless model come from an extended radiating area, as reported in [3]. Our practical experiments showed that the old bottomless design could be further improved by taking the idea of a "bottomless box" to the direction of a reinforced plate. An experimental bottom, fixed to the top at the center and separated with a small gap at the boundaries sounded promising. At the same time, the top plate was made 1.5 to 3 times thicker than before. This appeared to help maintaining the characteristics of the attack and the decay of the tone.

The two kanteles under detailed analysis reported in this paper are representatives of large groups of similar instruments. The traditional model is a good one among its type, produced in thousands. The new design is one of about 50 experimental instruments. For these two instruments, we present measurement results that demonstrate their differences and then explain those differences. In Section 2 of this paper, we examine in detail the changes in string tension and body structure. Section 3 reports measurements of the mechanical admittance and radiation efficiency. A playability test and a loudness comparison are presented in Section 4. Section 5 concludes the paper and suggests ideas for future research.

2. DESIGN GUIDELINES

2.1. Guidelines for strings

Our first step towards an improved design was to increase the tension of the strings. In practice, this is equivalent to keeping the fundamental frequencies of the strings constant, and increasing their lengths. The fundamental frequency f of a stretched string is related to its length L and its nominal tension T by the following well-known relation

$$f_0 = \frac{1}{2L}\sqrt{\frac{T}{\rho_{\mathrm{l}}}} \tag{1}$$

where ρ_{l} is the linear mass density of the string. In the modified design, all the string lengths have been increased. The lengths of the strings in both designs are tabulated in Table 1. In order to achieve the diatonic scale, an additional string has been added in the modified design (String 2 in Table 1). Since the same set of strings is used for both designs, the relative tension change is obtained using Eq. (1). On the average, the nominal tension is increased % 27 in the modified design.

The transversal force exerted on the tuning pin at the end of the string is given by

$$f(L) = T\frac{dz}{dx}|_{x=L} \tag{2}$$

where L is the length of the string along the longitudinal direction x and z is the transversal displacement of the string, so that the term $\frac{dz}{dx}$ is the slope of the string. The slope is determined by the player and it is closely related to the tension of the string. Using the initial slopes determined by a professional player in the playing tests (these are discussed in Section 4) and inserting the tension change values of Table 1 into Eq. (2), we conclude that the force input to the modified design is increased 20 % on the average.

Depending on the mechanical input admittance $Y(\omega)$, this force component sets the instrument body into motion. The admittance

S#	Tuning	f_0 (Hz)	L_{n} (cm)	L_{m} (cm)	L%	T%
1	D5	587.3	32.5	34.3	6	11
2	C#5	554.4	-	36.8	-	-
3	B4	493.9	35	39.7	13	29
4	A4	440.0	37.5	42.7	14	30
5	G4	392.0	40.5	45.8	13	28
6	F#4	370.0	43.5	49.5	14	29
7	E4	329.6	47	53.3	13	29
8	D4	293.7	50.5	57.6	14	30
9	C#4	277.2	54.5	62	14	29
10	B3	246.9	58.5	66.7	14	30
11	A3	220	63.5	72.2	14	29

Table 1: *The string lengths L_{n} and L_{m}, fundamental frequencies f_0, relative length and tension change percentages, L% and T%, respectively, of the normal (index n) and modified (m) kantele.*

is determined by the structural properties of the instrument. Therefore, before presenting the measured admittance functions and following the energy flow from the strings to the mechanical vibrations of the body in Section 3, we summarize the structural design guidelines in the next subsection.

2.2. Structural design guidelines

During an earlier set of measurements on a five-string kantele [2], we observed that a considerable amount of the soundboard vibration was being transferred to the sides, and consequently, to the back-plate of the instrument. The preliminary tests on the 10-string kantele also confirm this observation. In a typical performance condition, where the player holds the instrument on his/her lap, the vibrations of the side plates are damped so that some portion of the mechanical energy is lost. The first structural design goal was to reduce this energy loss. This goal is achieved by isolating the top-plate, i.e., by fixing the back-plate to the instrument in the middle area and by leaving the top-plate edges free by a small air gap. Note that this design introduces a cavity, which is further discussed in Section 3.

Another design goal was to improve the radiation efficiency, i.e, the ratio between the input power and sound intensity. This is achieved by increasing the total radiating surface area. The free edges obtained by isolating the top-plate, as discussed above, also add to the total radiating surface. The result is an improvement over the traditional design, where the hinged boundaries of the top-plate do not contribute to the radiation at all (see, for instance, the TV holography measurements reported in [3]).

3. BODY VIBRATIONS AND RADIATION

3.1. Admittance and input power

The mechanical admittance, defined as the ratio of the velocity and the force spectra $Y(\omega) = V(\omega)/F(\omega)$, provides a useful presentation of the body vibration. Since it is also related to the total input power, the measurement of the admittance function has a paramount importance for our discussion.

Recall that the power spectral density is defined as

$$p(\omega) = \Re\{F^*(\omega)V(\omega)\} \tag{3}$$

and within the frequency range $\omega \in [\omega_1, \omega_2]$, the total power is calculated by

$$P = \int_{\omega_1}^{\omega_2} p(\omega)d\omega \tag{4}$$

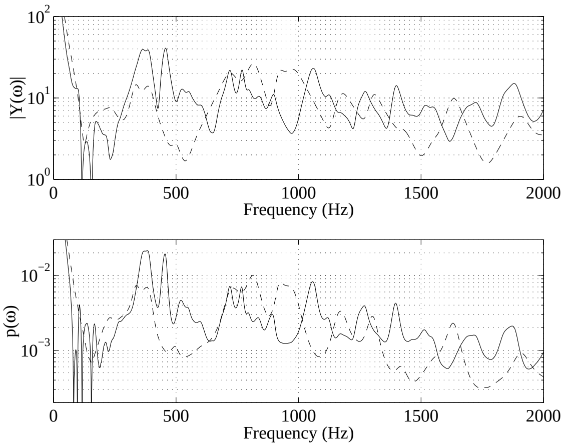

Figure 3: *The admittance moduli (top) and the power spectral densities of the normal (dashed) and modified (solid) designs.*

It can be shown that the power spectral density $p(\omega)$ is related to the real part of the admittance function $\Re\{Y(\omega)\}$ by a weight factor $w(\omega)$, which is the autocorrelation of the input force.

In order to follow the energy flow from the strings to the body and determine the input power for both designs, we conducted the following experiment. We mounted a small accelerometer (PCB 309A) on the top-plate of each instrument near the tuning pin, where String 7 (see Table 1) is terminated. With an impulse hammer (PCB 086C02), we exerted a force on the tuning pin, and measured the acceleration. The instruments were supported as in typical playing condition. We also recorded the autocorrelation of the force. For accuracy, 25 individual hits were averaged. During the measurements, we checked the coherence and only the successful hits were included in the averaging. The accelerance is converted to the velocity by integration.

This method allowed us to obtain admittance functions for both designs up to 2000 Hz. The admittance functions thus obtained are illustrated in the top part of Fig. 3, where the dotted curve indicates the admittance function of the normal design, and the solid curve indicates the admittance function of the modified design. The two admittance functions differ mostly around the low-frequencies (below 500 Hz). Above 750 Hz they are comparable in magnitude, however the modified design has a higher density of the resonances. The power spectral densities that are shown at the bottom part of Fig. 3 are obtained by multiplying the corresponding force autocorrelation by the real part of each admittance function. The numerical integration of the densities between 200 Hz and 2000 Hz according to Eq. (4) indicates that the total input power is increased by 26 % in the modified design.

3.2. Radiation

The final step in the energy flow chain is the transduction of the mechanical vibrations to the acoustical waves. In order to test the radiation properties of the new design, we have conducted the following experiment. Both instruments were excited by the impulse hammer in an anechoic chamber, as described in Sec. 3.1. The sound field was measured with a microphone (B&K 4145), placed one meter above the top plate of each instrument. Simultaneous SPL readings were recorded for microphone calibration. The results of this experiment are illustrated in Fig. 4, which shows the force to SPL transfer functions of the normal (dashed curve) and modified (solid curve) kantele.

In Fig. 4 the modified-design transfer function exhibits two low-frequency peaks that are absent in the admittance plots (see Fig. 3). These peaks are associated with the cavity of the modified design, and will be further discussed in the next subsection. Similar to the admittance measurements, but more pronounced here, the characteristics differ mostly at the low-frequencies (below 500 Hz). It should be noted that the measured SPL is related to but different from the perceived loudness. In other words, by inspecting the radiation characteristics shown in Fig. 4, one cannot conclude that the modified design is louder. We will revisit the estimation of the loudness using a computational model in Section 4.

3.3. Cavity resonances

The cavity introduced in the modified design differs from that of a typical plucked string instrument (e.g., guitar) in the sense that it cannot be considered a simple Helmholtz resonator with a single opening. Although there is a sound hole under the ponsi, a continuous opening under the extended range (see Fig. 2) complicates the determination of the air modes of the instrument. Here, we report a simple experiment, in which we mounted a small loudspeaker near the sound hole under the ponsi. The loudspeaker was driven by a signal generator, and the cavity response was measured with a microphone placed at the continuous opening. During the measurement, the body of the instrument and the strings were damped. A frequency sweep allowed us to roughly determine the frequencies of the cavity resonances by inspecting the microphone signal level. Then, the input frequency was controlled manually, and two lowest cavity resonances was observed around 160 Hz and 270 Hz. The frequencies of these resonances, as well as the observed signal levels, match the characteristics of the lowest peaks in Fig. 4.

4. PLAYABILITY AND LOUDNESS ESTIMATE

A playability test was conducted were both playing and verbal feedback was recorded. The player was asked to play as quietly and as loudly as she felt comfortable with both instruments. Initially, the player had difficulties to adjust her left-hand position because of the extended wing, and to balance the instrument, especially when her right hand is released from it. However, after some warm-up time, she adapted to the conditions imposed by the new design.

The recordings were made in an anechoic chamber, with a microphone (B&K 4145) at the distance of one meter from the instrument, in regular playing position. First we recorded the piano

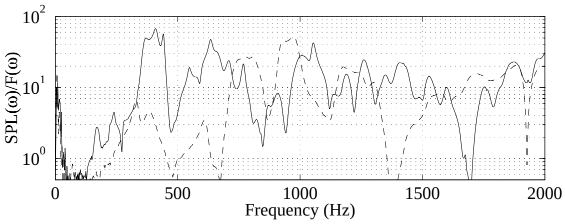

Figure 4: *Comparison of the transfer functions of the modified and normal designs, indicated by solid and dashed curves, respectively.*

and forte playing for approximately two minutes each, on both instruments. Then a set of notes were recorded while increasing the loudness at each step. In addition, the deflection of the string from its rest position was measured in a regular and loud pluck situation. Marks on the instrument were done while the player was asked to deflect the string, but not to release it. The markings were confirmed by visually evaluating a real plucking event, and they have been converted to the initial slope estimates. These initial slope estimates are used in Section 2.1 to calculate the input power.

In the dynamics test, the SPL is increased approximately 9 dB with the modified design. In addition, the dynamic range has been widened, as confirmed by the player. She suggested that the normal design has dynamically saturated in the series of plucks, whereas the new design responded to the increasing dynamics. Our SPL measurements confirmed her suggestion.

In the playability test, the player reported a physical discomfort during the continuous forte playing on both instruments. Therefore, the forte data has been discarded, and piano data has been analyzed. One minute segments have been used for the average RMS power calculation, using 1 ms windows. The SPL values for the normal and modified designs are 66.2 dB and 69.1 dB, respectively, indicating an SPL difference of 2.9 dB.

Short excerpts of the data are analyzed using the HutEar toolbox [4] for loudness estimates based on a computational model proposed in [5]. This model attempts to calculate the average loudness that would be perceived by a large group of listeners with normal hearing. The excitation patterns in the model are calculated from the auditory filter shapes, and they are transformed to specific loudness, i.e., loudness estimates per critical band. The overall loudness (in sones) is calculated by integrating the specific loudness. The estimation results are illustrated in Fig. 5. The model gives overall loudness estimates of 23 and 27 sones, for the normal and modified instruments, respectively. We thus conclude that the loudness is increased in the modified design.

As a last remark, the player noted a difference in the timbre and indicated that the 11-string design sounds like a kantele equipped with a microphone. This is probably because of the vibration of the extended part of the top plate.

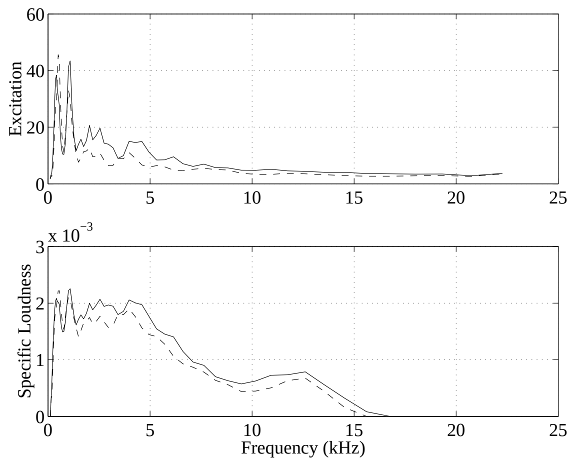

Figure 5: *Comparison of the excitation patterns (top) and the specific loudness estimates (bottom) for the modified and normal designs, indicated by solid and dashed curves, respectively. The estimates are based on the loudness model proposed in [5].*

5. CONCLUSIONS

In this paper, we propose design guidelines for a kantele with a higher loudness than the traditional model. These guidelines include the increase of the tension of the strings, the isolation of the top plate, and the increase of the radiating area. We have confirmed the effectiveness of these rules by following the energy path from the string vibrations to the radiated sound, and by conducting preliminary experiments for quantitative description of the improvement. We found that the total input power is increased by 26 % in the modified instrument, and using a computational model, we concluded that the overall SPL is increased by 2.9 dB. In addition, we have reported results of a preliminary playability test.

The new design ideas naturally can be applied to other stringed instruments. Among all the musical instruments there seem not to be clear examples of free edge plates or a separate bottom of the baffle type. There should not be great problems in trying these principles in other instruments whose sound radiation is based on a plate. At the time of writing this paper (May 2003), we have not conducted experiments with instruments other than the kantele.

Our future directions include a detailed analysis of the vibrations of the body, the air modes within the cavity, and the radiation characteristics of the modified instrument. The analysis of the vibration characteristics using experimental modal analysis or holographic techniques would extend the understanding of the proposed design principles. In addition, the acoustic intensity measurements could provide a quantitative description of the radiation efficiency in the new design. These measurements are left out as challenging future tasks.

6. ACKNOWLEDGMENTS

The authors wish to thank Dr. Marc Schönwiesner for his script[1] that is used for computing the specific and total loudness of the measured signals, and Dr. Arja Kastinen for participating in the playability test. Dr. Aki Härmä is also highly acknowledged for his HutEar toolbox. Henri Penttinen's work has been financially supported by the Pythagoras Graduate School.

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