Design and Analysis of a Modified Kantele with Increased Loudness

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Summary
The kantele, an ancient plucked string instrument, belongs to the family of zithers, and it is still used in traditional folk music in Finland, Northwest Russia, and the Baltic countries. Design rules for making the kantele louder are proposed and confirming analysis results are presented. A description of the main characteristics of the traditional design of the kantele is given, so that it supports the presentation of the design rules and analysis results. The design rules to make a plucked string instrument louder are (I) increase the string tension, (II) increase the radiation surface, and (III) isolate the top plate from the sound-box with an air gap. Rules (I) and (II) are almost self evident, for musical acousticians. Rule (III) on the other hand is more unique, since it enables a freely vibrating top plate. The design rules are confirmed by comparing the traditional design with the new one, through several methodological aspects. Results from the analysis are drawn from both analytical treatments and acoustical measurements. The effect that the new design has on the instrument's dynamic range and perception is investigated through a playability test with several professional kantele players. Results from two listening tests are presented that support the assumption of an increase in loudness for the new kantele design. Loud plucks of the modified design are, on the average, perceived as 3 dB louder than in the traditional design. The design ideas are also applicable to other string instruments.

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1. Introduction

There is a great variety in the number of strings, 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. Figure 1 shows a traditional 10-string Finnish kantele. The narrow end, on the right in Figure 1, is called the ‘ ponsi’. At the right end of Figure 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 Figure 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 in concerts, but the traditional Finnish models are usually too quiet 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.

Figure 1. The traditional 10-string kantele, top view and angled bottom view.

For a few hundred years now, a trend among luthiers has been to make louder musical instruments. This is to meet the requirement of large concert halls. A stepwise example of this loudness development can be seen by following the emergence of the piano: clavichord → harpsichord → piano [3]. Another example of gradual development is

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the violin, whose neck is now longer, the strings are under higher tension, and the bass bar, or sound bar, is tuned better, than during the baroque era [3]. Both the classical guitar (de Torres) and the modern flute (Boehm) are examples of a single instrument builder who made significant changes [3]. This work continues within these lines, by thriving to make (at first) louder kanteles.

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 [3], 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 contrast to fixed edges, one of the objectives in the new kantele design is to have a freely vibrating top plate, so that the edges are not fixed.

The idea for a freely vibrating top plate comes from the old 5-string museum kanteles: some of them have a closed box while 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 [4]. Our practical experiments showed that the old bottomless design could be further improved by incorporating a reinforcement 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.

Based on the ideas and experiments done with several kanteles by Jyrki Pölkki, 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 isolation of the top plate from the soundbox with an air gap enables the creation of a freely vibrating top plate.

The first kanteles of the new design were built in 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 sound deeper in quality and stronger in amplitude than those of the comparable, good-quality traditional models. An 11-string kantele, used in this research and produced according to the new design rules, is shown in Figure 2. By comparing Figures 1 and 2 the extension of the radiation surface can be noted. Figure 3 illustrates the concept of isolating the top plate from the soundbox with an air gap. Panes (a) and (b) depict the side views of the traditional and modified designs, respectively. The air gap continues trough out, between the top plate and the box. Figure 3 (b) shows how an air gap is left through out the edges of the instrument, and how one of four wood screws attaches the soundbox to the rest of the instrument.

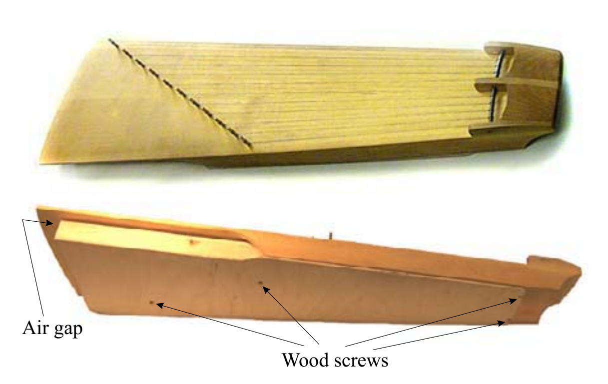

Figure 2. The modified 11-string kantele, top view and angled bottom view.

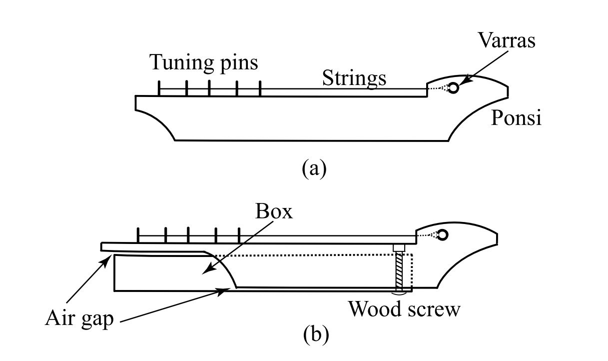

Figure 3. Side views of (a) the traditional and (b) the modified kantele.

We investigate the question of increased loudness, due to the proposed design rules, through both objective and subjective evaluation. We have conducted acoustical measurements and two listening tests, and a playability test. 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 two listening tests, that compare the

Table I. The fundamental frequencies f_0 (Hz), string lengths L_n and L_m (cm), relative length and tension change percentages, $L\%$ and $T\%$, respectively, of the normal (index n) and modified (m) kantele. Note that the modified kantele has one extra string (#S2).

S#	Tuning	f_0	L_n	L_m	$L\%$	$T\%$
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

relative loudness of the two designs, 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 I. In order to achieve the diatonic scale, an additional string has been added in the modified design (String 2 in Table I). In the new design, the tension of the string has been increased up to approximately 70% of its breaking point, which is significantly closer to the breaking point than in the traditional design as can be seen from Table I. Since the same set of strings is used for both designs, the relative tension change is obtained using equation (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

$$f(L) = T\frac{\mathrm{d}z}{\mathrm{d}x}\bigg|_{x=L}, \tag{2}$$

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 $\mathrm{d}z/\mathrm{d}x$ 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 4.6) and inserting the tension change values of Table I into equation (2), we conclude that the force input to the modified design is increased 20% ($\pm 4\%$) on the average. The deviation of $\pm 4\%$ originates from the $\pm$ 1 mm error in the displacement estimate.

Depending on the mechanical input admittance $Y(\omega)$ of the tuning pin, this force component sets the instrument body into motion. The admittance 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 [4]). However, at some frequency regions the radiating surface might split into antiphasic regions, separated by nodal lines [5]. This would suggest a decrease in radiation efficiency improvement, for some vibrational modes. This subject is a world of its own, and is thus out of the scope of this article, and therefore left for interesting future work.

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 investigation.

Recall that the power spectral density is defined as

$$p(\omega) = \Re e\{F^*(\omega)V(\omega)\} = |F(\omega)|^2 \Re e\{Y(\omega)\}, \quad (3)$$

where ω is the angular frequency, and $\Re e$ stands for the real part and * for the complex conjugate of the function at hand. Within a frequency range $\omega \in [\omega_1, \omega_2]$, the total power is calculated by

$$P = \int_{\omega_1}^{\omega_2} p(\omega)\,\mathrm{d}\omega. \quad (4)$$

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 magnet on the 5th tuning pin of each instrument and exerted a force on the tuning pin using the calibrated force transducer of the WinMLS - Violin toolbox system [6]. The very small magnet (2 mm×2 mm×2 mm) is attached to the tuning pin with bee wax. The force exerted to the magnet is produced by an electro-magnetic coil. The magnet is placed halfway inside the coil, so that half of it is outside the coil. The coil is driven by a signal from the sound card output.

We measured the velocity of the body at a point in the vicinity of the tuning pin with a laser vibrometer. The strings were damped, and the instruments were supported as in typical playing condition. The admittance characteristics were calculated using the WinMLS. We experimented with different excitation signals (Maximum-Length Sequence (MLS) [7] and sine sweeps), and varied the number of averaged trials. In all cases we obtained coherent admittance characteristics. However, the results obtained with MLS exhibited an anomaly in frequencies below 100 Hz. Therefore, we finally used linear sine sweeps as the excitation signal and took an average of five individual trials. We also recorded the excitation force, as required by equation (3).

This method allowed us to obtain reliable admittance functions for both designs between 100–10000 Hz, compared to 100–2000 Hz obtained in our previous experiments [8]. The admittance functions thus obtained are illustrated in the top part of Figure 4, where the dotted curve indicates the admittance function of the traditional design, and the solid curve indicates the admittance function of the modified design. The phases of these responses are illustrated in the middle pane. The two admittance functions differ mostly at low frequencies below 1000 Hz. The modified design exhibits two strong resonances under 200 Hz, whereas the lowest resonance of the traditional design occurs around 235 Hz. In addition, the modified design has a higher density of resonances.

The power spectral densities that are shown at the bottom part of Figure 4 are obtained by multiplying the corresponding force magnitude spectrum squared by the real part of each admittance function, as given in equation (3). The numerical integration of the densities between 100 Hz

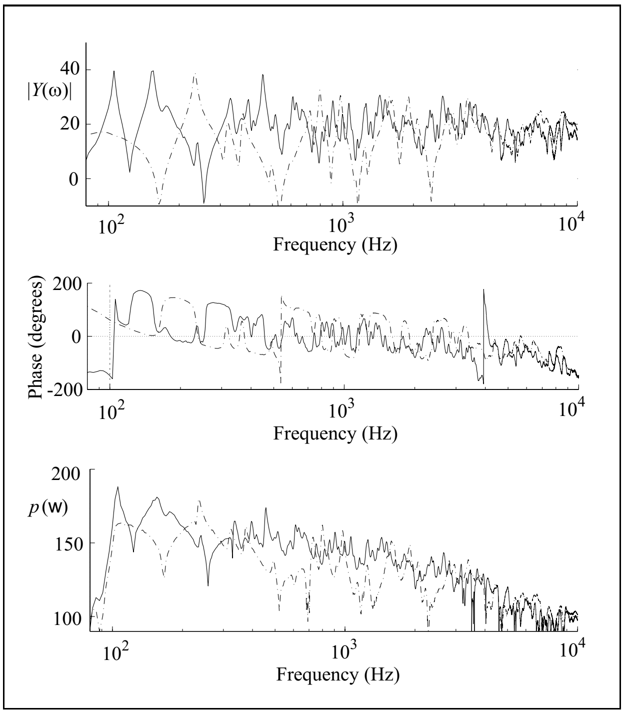

Figure 4. The admittance moduli (top), the phase of the admittance moduli (middle), and the power spectral densities (bottom) of the traditional (dashed) and modified (solid) designs.

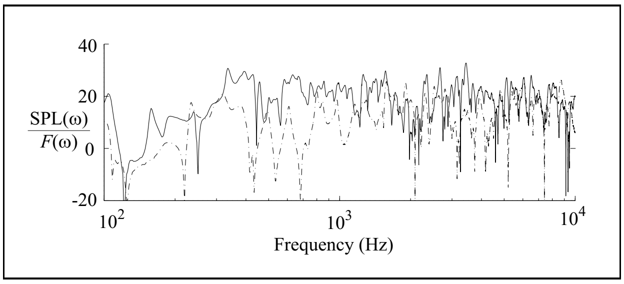

Figure 5. Comparison of the transfer functions of the modified (solid) and traditional (dashed) designs.

and 10000 Hz according to equation (4) indicates that the total input power, at the measured tuning pin, is increased by 28% in the modified design.

3.2. Radiation

The final step in the energy flow chain is the conversion of the mechanical vibrations to the acoustical waves. The radiation property differences between the designs were investigated in the following manner. Both instruments were excited by the force transducer used in the previous experiment in an anechoic chamber. The sound field was measured with a microphone (B&K 4145), placed one meter above the top plate of each instrument. The results of this experiment are illustrated in Figure 5, which shows the force to SPL transfer functions of the traditional (dashed curve) and modified (solid curve) kantele.

Similar to the admittance measurements, but more pronounced here, the radiation characteristics differ mostly at low frequencies. In particular, below 1000 Hz the radiation characteristics of the modified design are more pronounced. This is the case almost everywhere, except around the lowest resonance of the traditional design at 235 Hz. Again, the results are valid for the measurement point. In addition, 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 Figure 5, one cannot conclude that the modified design is louder. We will revisit the estimation of the loudness in Section 4 when discussing the listening test and its results.

4. Listening Tests and Playability

To investigate the perceived loudness of the two kantele designs, two separate listening tests were conducted. In the first one, live playing conditions were simulated by having a player play the instruments behind a curtain, in a controlled fashion and controlled environment. In the second test, recorded tones of both kanteles were played to the testee, with the purpose to tune the perceived loudness of two tones to be equal. The listening tests and their results will be described below.

4.1. Description of Live Playing Listening Test

To investigate the perceived loudness of the two kantele designs, a listening test was conducted. A kantele player played the same short musical excerpt (4 to 6 seconds) in a row with two kanteles. The listener was asked to judge which excerpt sounded louder. The excerpts were also permitted to be judged as equally loud. The playing occurred behind an acoustically transparent curtain to prevent the listeners from seeing which kantele was being played. The kantele to be used in each excerpt was handed to the player. Before the test the players had a chance to get familiar with both instruments. They were not, however, told that the objective of the new design was to make it louder. The test was arranged in the listening room of the Acoustics Laboratory at Helsinki University of Technology [9]. This high standard listening room has a very low noise level and short reverberation time, and it meets the ITU-R BS.1116 standard. Dimensions of the room are length 6.25 m, width 5.60 m, height 2.95 m, volume 103 m^3, and area 35 m^2.

The short musical excerpts covered the playing styles of the kantele, i.e., strumming and plucking. The three excerpts used constituted of playing two chords by strumming all the strings, playing an arpeggio by plucking the high pitched strings (S# 1, 4, 6), and playing an arpeggio by plucking the low pitched strings (S# 11, 9, 7). Three different playing dynamic levels were used: piano pianissimo (*pp*), mezzoforte (*mf*), and forte fortissimo (*ff*). These dynamic levels correspond to very soft, normal, and extremely loud playing. Moreover, mezzoforte stands for normal playing, interpreted by the player as a mid-way between the softest and loudest on a given instrument, not targeting to a specific sound level. This means that a dynamic level to be played is relative within the instrument, for all instruments.

Four professional kantele players and four non-players participated in the listening test. When the player did not play he/she listened, and this way seven subjects answered to four sets of questions. Each set included 21 excerpt pairs (two kanteles), which comprised of the combinations of 3 short excerpts and 3 playing levels, each played twice, and 3 blank trials where the kanteles were the same (3x3x2+3). To prevent biasing or learning of excerpt patterns, the order of the excerpts was randomized. All in all 84 excerpt pairs were listened to.

4.2. Live Playing Listening Test Results

Figure 6 displays the listening test results as bar graphs. The black and white bars represent the cases when the modified and traditional design were considered to be louder, respectively. The grey bars represent perception of equal loudness. The x-axis shows the played dynamic level and the y-axis shows the percentage of corresponding answers. The different playing styles are depicted in different panes, so that (a), (b), and (c) display the strumming, plucking low pitched strings, and plucking high pitched strings, respectively.

In all cases, except for one, the modified design was considered to be louder. In the case of piano plucking of high strings (c), the modified design got a smaller percentage than both other options. This could suggest an increment in dynamic range for plucked high strings. The relatively even matched result for piano plucking of the low strings [pane (b)] suggests there are no significant differences in this case. Why piano strumming does not have as evenly distributed answers as piano plucking cases, could be explained by the difficulty to play evenly and quietly by strumming. In general, the results for strumming are the most well-defined.

The listening test results shown in Figure 6 strongly support the assumption that the modified design is louder. The blank trials, when the kanteles were the same, are removed from the displayed results. Furthermore, the ratio of correct and incorrect blank trial answers is 1.12. This indicates random spreading of the blank trials. In contrast, as can be seen from Figure 6, the listening results are well-defined. This means that the listening test result are reliable and not random.

Next we summarize the verbal and written comments gathered from the testees. The most defined differences in loudness were reported in the case of strumming and in forte playing in general. The notable differences were smaller in piano playing. These comments support the results obtained for piano playing shown in Figure 6 (b) and (c). The players also reported that the loudness difference was more notable while playing.

In spite of the results described above, determining the perceived loudness of two different instruments is not straightforward and in this case some of the reasons are the following. The amount of audible pitch glide [10] was

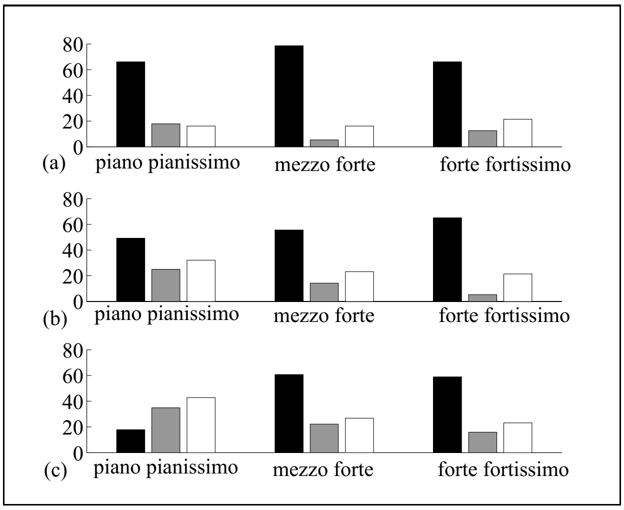

Figure 6. Listening test results as bar graphs for (a) strumming, (b) plucking the low strings, and (c) plucking the high strings, respectively. The y-axis indicates the percentage of cumulated answers and x-axis indicates the played dynamic level. The black bars represent the answers when the new design was considered louder, the grey bars when both designs were considered equally loud, and the white bars when the old design was perceived louder.

reported to be larger in the traditional design. Here pitch glide stands for a decrease in the fundamental frequency of the string just after it has been excited. Based on the comments, a string instrument with a pitch glide can be associated with an instrument being played stronger than an instrument without a pitch glide. This association is, however, a different matter than the perceived loudness, but can easily be understood as a factor making the assessment more complicated. The dissimilarities in the amount of pitch glide can be explained by the smaller tension in the strings of the traditional design. This is because a smaller tension allows larger relative tension modulation, and the larger tension modulation again produces larger pitch glide. For discussions on tension modulation and pitch glide see, e.g., [11, 12, 2]. The effect of pitch glide on the perception of loudness will be discussed further in the context of the next listening test.

The testees also reported of deviations between the instruments in the timbre and attack, which also add to the tonal differences of the instruments. Time-varying characteristics of a signal makes the determination of equal loudness between two signals challenging ([13, 14, 15]). All the factors described above made the determination of the loudness slightly difficult, but not impossible. In fact, the objective was to find out whether the modified design is perceived as being louder than the traditional one, and the listening test results indicate that this was accomplished.

4.3. Description of Equal Loudness Listening Test

In the second listening test, two recorded tones were played to the testee by using headphones. The test subject was able to control the gain of the latter tone, in a range of $\pm$ 9 dB, in steps of 0.5 dB. The aim was to set the perceived loudness of the sample pair to be equal. The recorded tones were forte fortissimo tones plucked 1/6 th of the string length, recorded in anechoic conditions with a microphone (B&K 4145), placed one meter in front of the player. The purpose was to investigate the perception between the two kanteles in very sterile or controlled conditions. In addition, the test enabled to have a look upon the affect of pitch drift on perceived loudness.

As mentioned above, gliding of the pitch after the initial pluck, occurs pronouncedly in the traditional design. To remove some suspicion over the effect pitch drift has on perceived loudness, the pitch drifts in the recorded pluck samples were compensated. The method used for compensation will be elaborated below, but first the rest of the test specifics will be described.

The play list in the test consisted of 1.5 second long sample pairs, of the same string of each kantele. The testee could control the gain of the latter sample. The playing of each pair was started by the test subject, and the pair could be listened for as many times as needed. Both playing orders were covered (2×10 pairs), so that first the sample of traditional design was played and then the modified one and vice versa. Both pitch-compensated and original samples were used (2×10 pairs) and 6 blank trials were included (46 pairs in all).

4.4. Compensation of Pitch Drift

As mentioned above, gliding of the pitch after the initial pluck occurs pronouncedly in the traditional design. To remove some suspicion over the effect pitch drift has on perceived loudness, the pitch drifts in the recorded pluck samples were compensated. The compensation was implemented by applying fractional delayed time-varying sampling rate conversion to the samples [16, 17], which was inversely proportional to the pitch drift. When using a constant sampling rate during playback, the pitch glide is not present.

For compensating the pitch glide, firstly, the fundamental frequency was estimated by using the YIN algorithm [18], an autocorrelation-based method. The results were smoothed out with a 10th order median filter, and after this up-sampled, since the frequency estimation was done in frames with a hop-size of 128 samples. A reference fundamental frequency estimation was chosen from the steady state portion. The time-varying pitch estimation was normalized with this reference frequency value. The inverse of this was used as a time varying step-size function, $D(i)$, for the pitch compensation. When the pitch of the original sample is larger than the reference pitch, a step-size smaller than one is obtained, $D(i) < 1$. As a result, shorter steps will compensate the originally higher pitch to the frequency of the reference pitch. Each new sample in the pitch compensated vector was interpolated by the coefficients given by a 10-point sinc function. In other words, the new sample value was constructed from the sum of the sinc function values weighted by the corresponding sample values of the original signal.

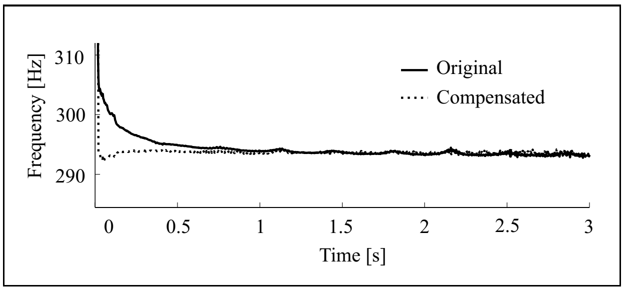

Figure 7. The fundamental frequency as a function of time for a forte fortissimo pluck on the 4th string on the traditional design, before (solid) and after (dotted) compensation of pitch glide.

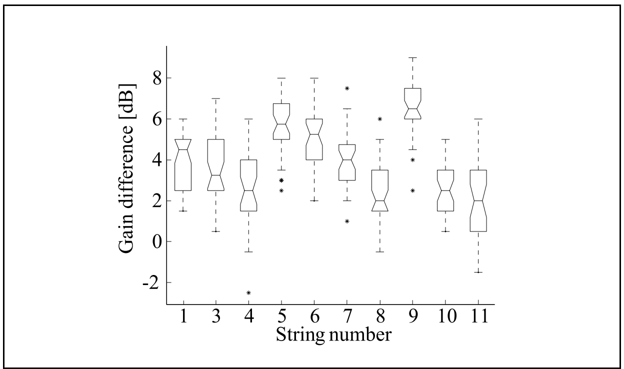

Figure 8. Equal loudness listening test results. X-axis indicates string number and y-axis the difference in the controlled gain between the two kantele designs.

Figure 7 shows the fundamental frequency as a function of time for the 4th string on the traditional design. The fundamental frequency for the original sample is shown with a solid line and the compensated one with a dotted line. Figure 7 illustrates how the drastic pitch glide until 0.5 seconds has been removed. The very beginning of both samples still have a glitch, but this is due to analysis artifacts and the fact that during the very beginning of the attack pitch definition is practically impossible. The pitch glides were successfully compensated from all the samples. No other audible differences were produced by the pitch glide compensation.

4.5. Equal Loudness Listening Test Results

Figure 8 displays the results obtained from the equal loudness listening test. It includes all the played pairs, both playing order and both pitch drift characteristics, except the blank trials. The x-axis indicates the string number, and the y-axis is the amount of gain difference from the traditional to the modified design. More precisely, when the modified design has been the latter sample played, the absolute value of the gain has been taken. In other words, the y-axis indicates how many decibels the traditional sample has been increased or the absolute value of decrease in the case of the modified design, to make both samples sound equal in loudness.

In Figure 8 each box has lines at the upper (75%) and lower (25%) quartile values. The median value is indicated between these values with a line at the center of the hourglass shaped part of each box. The whiskers (- - -) show the extent of the rest of the data. Outliers, displayed with the star symbol (*), are data points with values beyond the end of the whiskers.

Figure 8 shows that the median value for all strings is equal or larger than 2 dB. The mean over all the strings is 2.98 dB with a standard deviation,σ, of 1.92. Thus, the result of the listening test is that, on the average, the gain of the traditional design has to be increased 3 dB to be perceived as equally loud as the modified design.

In addition, the results suggest that the pitch glide does not strongly effect the perception of loudness since the mean of the difference between the compensated and original samples is -0.09 dB, with σ = 1.11. In contrast, the playing order of the samples has a considerable significance to the results. The mean of the difference between playing order samples is 2.02 dB, with σ = 1.31. More specifically, when the louder sample is the latter one the difference in perceived loudness is larger than when the louder sample is played first. This could be explained by the fact that it is perceived closer to the time of final judgement.

4.6. Playability

In pursuance of making the listening test, comments on the playability of the kanteles were gathered from the professional players. In addition, playing of the dynamic range was recorded in anechoic conditions.

The extended wing of the modified design imposes a change in the playing position of the left hand. This was taken note on, but the players could rather well adapt to this new playing position. One player also noted that the 11-string design sounds like a kantele equipped with a microphone and electric amplification. This is probably because of the vibration of the extended part of the top plate, which changes the location of the acoustic center.

The players felt that the modified kantele could handle a larger input force without changing the sound of the instrument. Here changing of the sound refers to the pitch glide, i.e., the modified version could be played louder without introducing pitch glides. In other words, the dynamic range was reported to have been widened.

This widening of the dynamic range was confirmed by recordings made in an anechoic chamber, with a microphone (B&K 4145) at the distance of one meter from the instrument in regular playing position. A sequence of tones was recorded while increasing the loudness at each step. The player felt that in the traditional design the top part of the dynamic range was saturated earlier than in the modified one. In the dynamics test, the loudest SPL was increased approximately by 9 dB with the modified design.

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 (with an uncertainty estimate of ± 1 mm for the displacement). These initial slope estimates were used in Section 2.1 to calculate the input power.

5. Discussion and 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 experiments for quantitative description of the improvement. We found that, in the measured point, the total input power is increased by 28% in the modified instrument. In addition, we have reported results of two listening tests. On the average, forte fortissimo plucks of the modified design are perceived as 3 dB louder than in the traditional design.

The new design ideas naturally can be applied to other stringed instruments. The tuning of the string parameters (tension, length) is easy to realise in any string instruments. Using extensively thicker strings, however, slightly affects the tonal characteristics of the instrument. The use of free edge plates with a separate bottom does not seem to appear in other musical instruments. It should be possible to apply these principles to other instruments whose sound radiation is based on a plate. At the time of writing this paper (November 2004), we have not conducted experiments with instruments other than the kantele. The future plans include both the guitar and the piano.

Interesting future directions include an 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. Detailed analysis of free edge vibration in musical instruments is an especially interesting issue, when considering radiation efficiency. In addition, the acoustic intensity measurements could provide a quantitative description of the radiation efficiency in the new design.

The conducted measurements and experiments suggest that the proposed design guidelines do increase the loudness of the kantele. This makes it easier for kantele players to reach larger audiences with their music.

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