ACOUSTICAL ANALYSIS OF TANBUR, A TURKISH LONG-NECKED LUTE

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ABSTRACT

The analysis of historical or ethnical musical instruments can provide means to verify and broaden our knowledge on musical acoustics. The Turkish tanbur, a member of evidently the oldest group of lute instruments, is a good example. Some important features of the instrument include its body resonator (a wooden hemispherical shell covered with a shallow plate) without a sound hole, its violin-like bridge, and its paired strings with an unusual tuning scheme. In this study we introduce the tanbur and discuss the results of an acoustical analysis of the instrument. The analysis data consists of various sound recordings and measurements realized in an anechoic chamber. Using time-frequency analysis techniques, we capture some of the acoustically important features of the tanbur, such as linear and nonlinear string vibration behavior. We interpret the analysis results combining and comparing with the research results available on string instruments of the western world.

1 INTRODUCTION

The acoustics of western string instruments is a widely studied topic [1]. However, some of the more primitive traditional string instruments exhibit many important and unique characteristics, and they can be regarded as interesting acoustical systems by their own right. The tanbur, a Turkish long-necked lute, depicted in Fig. 1, is a typical example of such a system.

The tanbur is one of the most important instruments in classical Turkish art music and has been used to investigate the mode structure (called *makam*) [3] of this music form. However, there is no previous publication about the acoustical properties of the instrument to the authors' knowledge. This study aims to introduce the tanbur and present the preliminary results of the acoustical analysis of the instrument. The organization of the paper is as follows. Section 2 introduces the tanbur and overviews its structure. Section 3

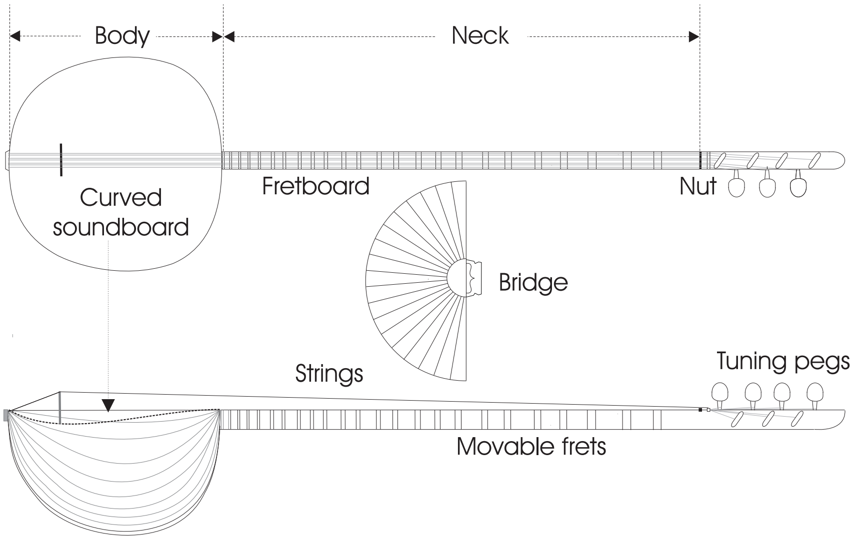

Figure 1: Various constituents of the tanbur. After [2].

describes the impulse response measurements, and discusses the results of the impulse response analysis. Section 4 formulates the nonlinearity of the tanbur string vibrations and shows how it can be observed experimentally. Section 5 draws the conclusions.

2 THE INSTRUMENT

The existence of the long-necked lute in Mesopotamia dates from the Akkadian era (3rd millennium B.C.) [4]. The designation "tanbur" originates from *pandur*, the Sumerian word for long-necked lutes. Throughout the millennia, the instrument migrated between the civilizations of the area, experienced changes in its name, form, and function. The derivatives of the tanbur can be found today in many countries of the Middle-East, Southern-Asia and the Balkans.

An important functional change of the Turkish tanbur occurred in the end of the 17th century, when the instrument was reconstructed for makam studies. The necessity of makam-based intervals resulted in an usual fretboard length (for ease of play of closely-spaced comma intervals) and movable frets (for variation of the makam scales), and these properties made the tanbur the main instrument of the classical Turkish art music. This functional change is usually overlooked in western references [5], and the tanbur is categorized among the other lutes of the area used in folk music.

Fig. 1 shows the various constituents of the instrument. A quasi-hemispheric body shell resembling the shape of a halved apple is made of 17, 21 or 23 thin slices of thickness 2.5 to 3 mm. The slices are usually cut from ebony, rosewood, pearwood, walnut or cherry. The soundboard is made of thin (1.5 to 2 mm) spruce panel. There is neither a sound hole nor braces, so that the thickness of the soundboard has to be carefully adjusted. It should be thick enough to resist the static forces applied by the bridge, but still thin enough for a good sound quality and loudness. The optimum thickness causes the soundboard to curve inwards, forming a shallow top plate. This is a characteristic of the tanbur (see Fig. 1).

The strings are stretched between a raised nut and the bridge. The violin-like bridge is made of rosewood or juniper, and the force is transmitted to the body via the two legs of the bridge. The long neck (73.5 to 84 cm), which is typically made of ebony or juniper, hosts 52-58 movable frets made of gut or nylon. The tanbur has seven strings, six of them are grouped in pairs, and the lowest-pitched string tuned to A1 (55 Hz) is single. The pairs are tuned to A2, D2 and again A2 (or alternatively A2, E2 and A2). The normal playing style involves the use of just the bottom A2 pair, while the other strings serve as resonators. The two A2 pairs are plain steel strings, whereas the remaining three strings

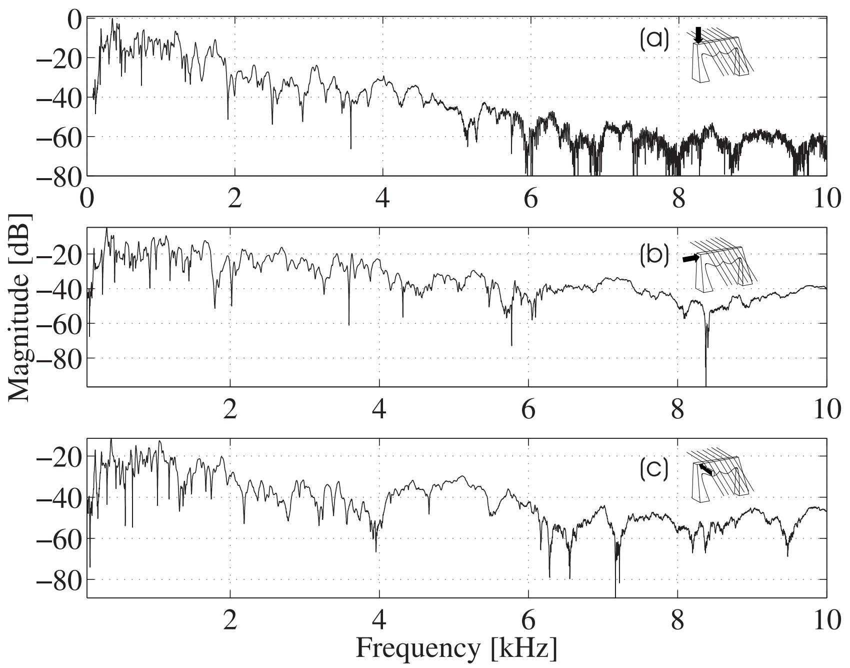

Figure 2: Magnitude spectra of the tanbur body impulse responses: a) The vertical impulse response spectrum b) The horizontal impulse response spectrum c) The longitudinal impulse response spectrum.

are wounded steel or brass. The plectrum is originally made of tortoise shell, nowadays replaced by synthetic material, and its length varies between 9.5 and 13.5 cm.

3 TANBUR BODY IMPULSE RESPONSES

A natural way to start to analyze the body vibration characteristics of any string instrument is to measure its impulse response in an anechoic room [6]. The first experiment with the tanbur was to measure the impulse response of its body for three orthogonal force-impulses applied on the bridge. The force-impulses were approximated using a metallic object with a hard tip. The diameter of the tip was 0.5 mm. The strings were damped, and the responses were recorded with a microphone placed perpendicular to the soundboard with a distance of one meter. The measurements were repeated 25 times for each direction, giving a total of 75 impulse responses. The representatives for each direction were selected using cross-correlation as a measure of similarity within each class. The frequency domain representations of the impulse responses [1] for the three orthogonal directions are shown in Fig. 2. In the rest of this study, these orthogonal directions will be referred as *vertical, horizontal,* and *longitudinal*, following the order from top to bottom in Fig. 2.

The responses in Fig. 2 include the effects of driving point admittance of the bridge, the vibration of body and neck, and the directivity of the radiation pattern. The vertical impulse response is relatively stronger compared to the other directions. The pronounced low-pass characteristics of the body after 400 Hz is evident in Fig. 2. Up to 2 kHz the body is more susceptible to the vertical forces [7], but at higher frequencies the amount of radiation becomes similar in response to horizontal and longitudinal forces.

The peaks up to 1 kHz are shown in Fig. 3, which indicate that the body responds to horizontal and longitudinal driving forces, even in the low frequency range. This issue is

[1] The microphone distance was kept constant throughout the measurements, and the responses were normalized dividing each of them to the average energy of the vertical impulse responses. Since the input was not explicitly controlled, the relationship between the magnitudes of the impulse responses can only provide a rough basis for comparison.

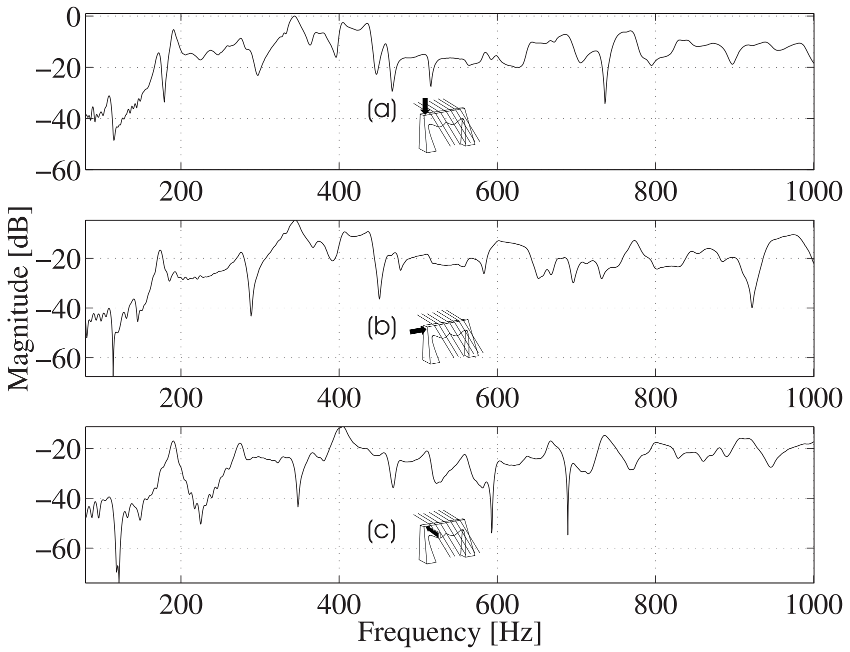

Figure 3: Low-frequency range of the normalized magnitude spectra: a) The vertical impulse response spectrum b) The horizontal impulse response spectrum c) The longitudinal impulse response spectrum.

important for the string vibration analysis of Section 4. The dimensions of the body rise the peak frequencies compared to that of the guitar [7].

3.1 ANALYSIS USING SHORT-TIME FOURIER TRANSFORM (STFT)

The frequency responses provide only time-averaged information, therefore a time-frequency analysis provides more insight about the decay characteristics. Fig. 4 shows the STFT plot of the tanbur body vertical impulse response. Compared to the guitar body response [6, 8], the tanbur body impulse responses decay significantly faster. Fig. 5 shows the decay characteristics of low-frequency components in a more detailed fashion.

From the figure it can be observed that the peaks around 344 Hz and 275 Hz in Fig. 3 decay faster compared to the peak around 191 Hz. The exponential decay characteristics (linear on a dB scale) of the frequency components are hard to notice from Fig. 4 and Fig. 5 because of the ripples. Since the frequency resolution of the STFT methods is limited, two frequencies located very close would exhibit a combined complex decay characteristic. This is indeed the case in STFT plots, for instance, the ripple in the decay around 600 Hz is a result of such a combined decay (c.f. Fig. 3). Another source of the ripple, especially for the ripple observed at low frequencies, is the incompatibility between the analysis window length and the frequency of the decaying sinusoid [6]. At the time instant $t_1 = 0.18$ s, there are only two dominating peaks, located at $f_1 = 191$ Hz and $f_2 = 344$ Hz.

4 NONLINEAR STRING VIBRATIONS

The vibration of the tanbur strings is relatively nonlinear due to the modulation of the tension along the string. As the following analysis shows, the tension modulation exerts a longitudinal force on the bridge which is efficiently radiated as sound from the body. The tension modulation force is nonlinearly related to the vibration of the string.

Fundamental frequency variation and coupling of harmonic modes are among the perceptually most important effects of this nonlinearity. In addition, the radiated sound component due to the tension modulation longitudinal force is pronounced and clearly adds to the character of tanbur tones. The following experiments and measurements have

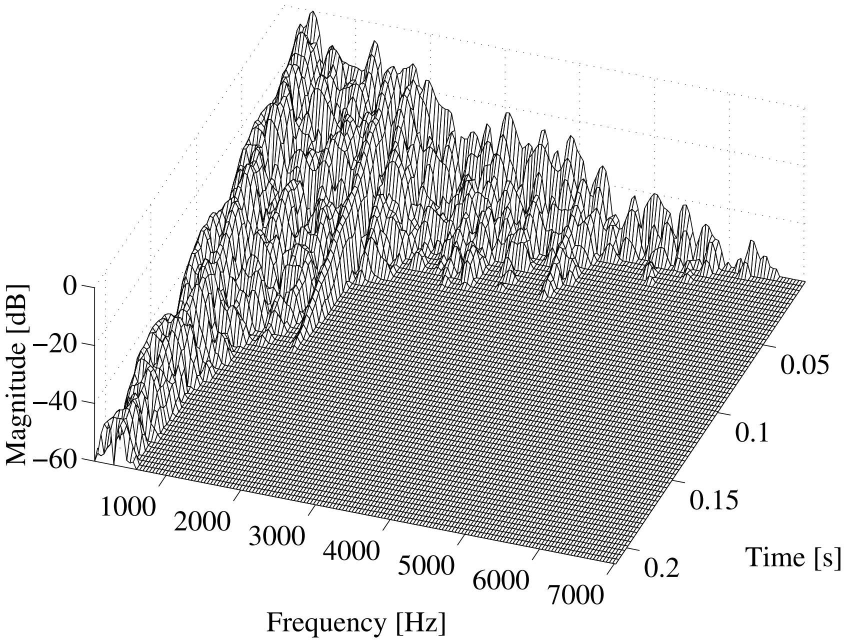

Figure 4: STFT plot of the vertical impulse response. The figure is obtained using 1024 point FFT's with a 25 per cent overlapping Hanning window of 6.85 ms.

been conducted on the highest string of the tanbur. It is made of steel and has a diameter of 0.3 mm and nominal tension of 29.05 N.

4.1 TENSION MODULATION NONLINEARITY

Tension modulation depends essentially on the elongation of the string during vibration. Elongation may be expressed as the deviation from the nominal string length ℓ_{nom} [9]

$$\ell_{\mathrm{dev}} = \int_0^{\ell_{\mathrm{nom}}} \sqrt{1 + \left(\frac{\partial y}{\partial x}\right)^2} dx - \ell_{\mathrm{nom}}, \tag{1}$$

where y is the displacement of the string and x is the spatial coordinate along the string. Tension F_{t} along the string is linearly related to the elongation ℓ_{dev} and it can be expressed as [9]

$$F_{\mathrm{t}} = F_{\mathrm{nom}} + \frac{ES\ell_{\mathrm{dev}}}{\ell_{\mathrm{nom}}}, \tag{2}$$

where F_{nom} is the nominal tension corresponding to the string at rest, E is Young's modulus, and S is the cross-sectional area of the string.

In the linear case, the propagation speed of the transversal wave is $c_{\mathrm{nom}} = \sqrt{F_{\mathrm{nom}}/\rho_{\mathrm{nom}}}$, where ρ_{nom} is the linear mass density along the string at rest. When we assume that the longitudinal wave propagation speed is considerably larger than the transversal propagation speed, the linear mass density and the tension are approximately spatially constant and we may write the propagation speed of the transversal wave as

$$c = \sqrt{\frac{F_{\mathrm{t}}}{\rho}} = \sqrt{\left(\frac{\ell_{\mathrm{nom}} + \ell_{\mathrm{dev}}}{\rho_{\mathrm{nom}}\ell_{\mathrm{nom}}}\right)\left(F_{\mathrm{nom}} + \frac{ES\ell_{\mathrm{dev}}}{\ell_{\mathrm{nom}}}\right)} \tag{3}$$

where ρ is linear mass density of the vibrating string given by $\rho = \rho_{\mathrm{nom}}\ell_{\mathrm{nom}}/(\ell_{\mathrm{nom}} + \ell_{\mathrm{dev}})$. Equation 3 implies that c depends on the elongation of the string. This in turn implies that the string vibration is not strictly speaking periodic. Thus, we use the term effective fundamental period to refer to a short-time average value of the period.

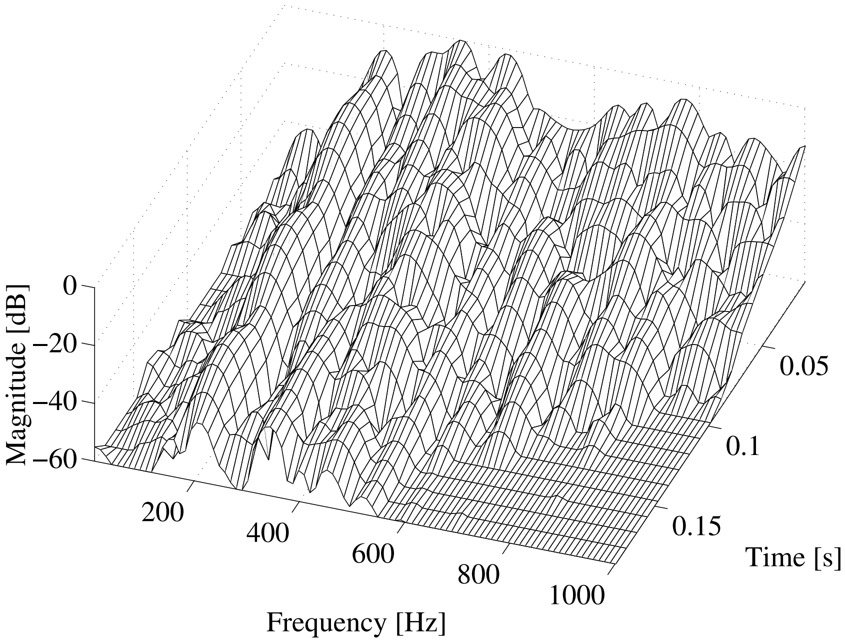

Figure 5: Low-frequency STFT plot of the vertical impulse response. For a better frequency resolution, 4096 point FFT's and a 25 per cent overlapping Hanning window of 2.31 ms are used. At the time instant $t_1 = 0.18$ s, the peaks are located at $f_1 = 191$ Hz and $f_2 = 344$ Hz.

When the elongation is large, the effective fundamental period is expected to be shorter than when the elongation is small, i.e., we expect the fundamental frequency variation to be larger with tones that are plucked hard than with those that are plucked softer. Fig. 6 confirms this by illustrating the fundamental frequency variation of a moderately plucked tone (left) and a hard-plucked tone (right). The trajectories have been obtained using running autocorrelation computation with 73 ms Hamming windows and 18 ms hop-size, and detection of the local maximum corresponding to the fundamental periodicity. In both plots, the fundamental period approaches exponentially 107.5 Hz as the vibration attenuates. When the string is plucked hard, the pitch variation is more than 4 Hz (approximately 4 %), which corresponds to almost one semitone. The moderately plucked tone exhibits a drift of 1 Hz. In the hard-plucked case, the pitch variation is clearly audible as may be perceived in the audio examples available at `http://www.acoustics.hut.fi/~cerkut/tanbur`. From the audio examples it is clear that the pitch variation caused by tension modulation is important for the character of tanbur tones.

4.2 TENSION MODULATION COUPLING

The tension modulation nonlinearity also exerts a longitudinal force on the bridge that is effectively radiated from the body. This phenomenon may be observed by analyzing

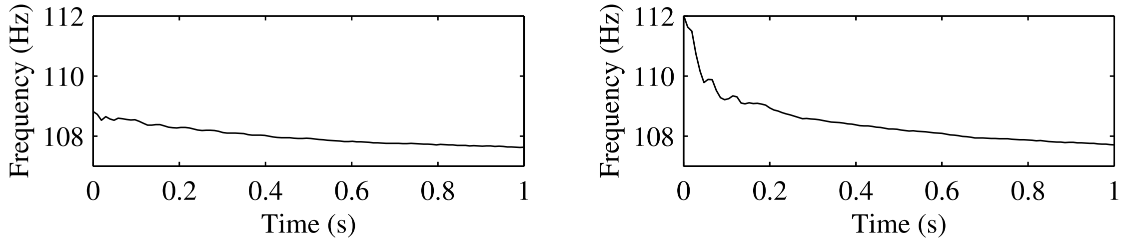

Figure 6: Fundamental frequency drift as detected in tanbur tones plucked moderately (left) and plucked hard (right).

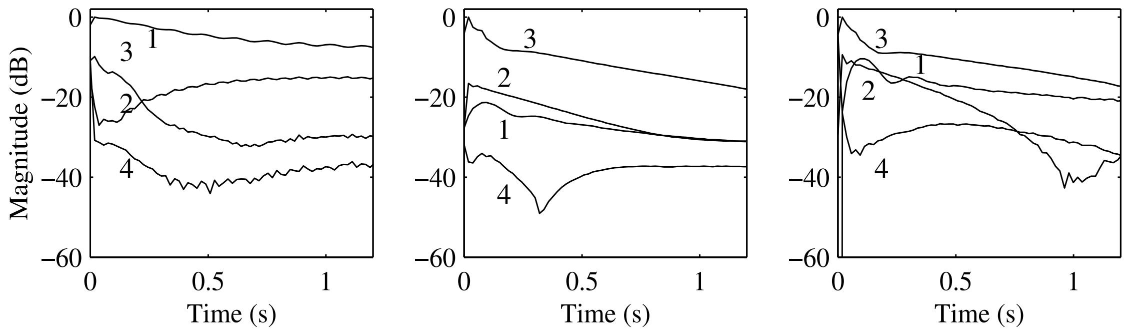

Figure 7: Amplitude envelopes of the four first harmonics of a tanbur tone as detected in string vibration (left), in vibration of the soundboard (middle), and in the radiated sound (right).

the string vibration, acceleration of the soundboard near the bridge, and the radiated sound when the string is plucked at the midpoint so that the initial excitation of the even harmonics is small. The string vibration was detected using a magnetic pickup which is sensitive to the velocity of the string in the transversal plane parallel to the pickup. An accelometer was attached beside the foot of the bridge so that it captures the vertical movement of the soundboard. At the same time, the radiated sound is measured using a condenser microphone. To minimize the disturbances, the experiment was conducted in an anechoic chamber.

Fig. 7 presents results of this experiment. Amplitude envelopes of the harmonics were detected using short-time Fourier analysis. The figures from the left to the right plot the envelopes of the four first harmonics detected in string vibration, in soundboard vibration, and in the radiated sound, respectively. In the string vibration, the first harmonic is most pronounced, as expected. The second harmonic has a relatively low initial level but the amplitude gradually increases with time. This suggests that the vibration modes are nonlinearly coupled so that energy is transferred back to the string at double the frequency of the first harmonic. The third harmonic has a relatively high initial amplitude level that is soon decayed. The body of the instrument has a resonance near the frequency of the third harmonic (f_2 in Fig. 5), which may explain the rapid decrease in the amplitude. In addition, the pickup is only capturing the horizontal polarization of the string vibration, thus it does not provide information on the vertical polarization.

In the soundboard vibration, the second harmonic has a higher initial amplitude level than the first one and also a very sharp attack. Comparing the plots on the left and in the middle, it is clear that a linear system cannot produce such a difference in the behavior of the envelopes of the second harmonic. This suggests that the longitudinal force caused by tension modulation produces the second harmonic in the soundboard vibration. The third harmonic exhibits a two-stage decay which may be explained by the different vibration behavior of the two polarizations [10]. The behavior of the amplitude envelopes in the radiated sound shown on the right is similar to the soundboard vibration although their relative amplitudes are different. This is explained by the coloration of the sound by the resonances of the body of the tanbur.

The experiment of Figures 6 and 7 demonstrates the importance of tension modulation to the tanbur tones. It provides a mechanism for the pluck-excited instrument to produce time variation in the timbre of the tones. Although tension modulation exists in all vibrating strings, in many string instruments it is less pronounced and often discarded, e.g., in computational modeling of the instrument. For instance, in the acoustic guitar the bridge is glued to the top plate of the body which results in a more rigid termination of the string. In addition, in steel-stringed guitars the nominal tension along the string is considerably higher than that of the tanbur strings. Thus, the relative tension modulation is smaller and the variation of pitch is often inaudible.

5 CONCLUSIONS

This paper presented first results of the acoustical analysis of the tanbur. It is shown that, besides to the vertical driving direction, the body responds also to the horizontal and longitudinal directions. The prominent body resonances are found at $f_1 = 191$ Hz and $f_2 = 344$ Hz and this information can be used to calibrate the body models of model-based sound synthesis systems [6]. It is pointed out that the tanbur strings exhibit pronounced nonlinear tension modulation effects, i.e. variation of the fundamental frequency and coupling of the harmonic components. The updated information about the analysis of the tanbur, as well as demonstrative examples are available via WWW at `http://www.acoustics.hut.fi/~cerkut/tanbur`.

In conclusion, the analysis shows that the tanbur features several acoustic properties that are not common in western plucked string instruments. Moreover, the results suggest that the experimental setup and the analysis procedure can also be used to study other plucked string instruments.

The next step for the acoustical analysis of the tanbur is to concentrate on the body vibration characteristics and to extract the modal parameters of the body resonances. The analysis of the curved top plate vibrations and the effects of air-loading on them remain challenging future tasks.

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REFERENCES

[1] N. H. Fletcher and T. D. Rossing, *The Physics of Musical Instruments.* New York, USA: Springer-Verlag, 1991.

[2] C. Acin, *Enstruman Bilimi.* Yenidogan Basimevi, 1994.

[3] K. L. Signell, *Makam: Modal Practice in Turkish Art Music.* Da Capo Pr., Jan. 1986.

[4] F. Jahnel, *Manual of Guitar Technology.* Frankfurt am Main, Germany: Verlag Das Musikinstrument, 1981.

[5] S. Sadie, ed., *The New Grove Dictionary of Musical Instruments.* London, UK: MacMillan Press, 1984.

[6] M. Karjalainen and J. O. Smith, "Body modeling techniques for string instrument synthesis," in *Proceedings of the International Computer Music Conference*, (Hong Kong), pp. 232–239, Aug. 1996.

[7] B. E. Richardson, "String instruments: Plucked," in *Encyclopedia of Acoustics* (M. J. Crocker, ed.), vol. 4, pp. 1627–1634, John Wiley & Sons, Inc., 1997.

[8] T. Tolonen, "Model-based analysis and resynthesis of acoustic guitar tones," Master's thesis, Helsinki University of Technology, Espoo, Finland, Jan. 1998. Report 46, Laboratory of Acoustics and Audio Signal Processing.

[9] K. A. Legge and N. H. Fletcher, "Nonlinear generation of missing modes on a vibrating string," *Journal of the Acoustical Society of America*, vol. 76, pp. 5–12, July 1984.

[10] G. Weinreich, "Coupled piano strings," *Journal of the Acoustical Society of America*, vol. 62, pp. 1474–1484, Dec. 1977.