Modal analysis of membrane string instruments: finite element modeling and experimental investigation

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ABSTRACT
Membrane string instruments play a considerable role in several live traditions, examples of which are Persian and Turkish music. A selected sample of such instruments was subject to a series of experiments, with a membrane as the resonating top being an animal skin. Mechanical vibrations of the resonance box were measured using a roving hammer as excitation. Then, the dynamic response was treated in a modal post-processing stage in order to extract the modal data, i.e. natural frequencies, mode shapes with a high level of accuracy. The experimental data were employed to compare with the finite element model to have a first image of the instrument's behavior, assuming orthotropic properties for wood.

Keywords: Vibroacoustics, String Instrument, Mode Shapes. I-INCE Classification of Subjects Number 72.9

1. INTRODUCTION

Sounds radiated by musical instruments as sources for pleasant noise have been studied in the past few decades. String instruments and the air within and around them are complex structural acoustic systems, both in terms of structure and the fluid structure interaction. The string sound alone has a minor role in the sound output, since the radiated sound is mostly generated by the body and cavity of the instrument [1]; meaning that the whole instrument acts as a filter, converting the excitation force of the strings to sound and radiating it. In the lack of a scientific guideline to make a high-quality instrument, fine tuning of many musical instruments including the tar and kamancheh relies completely on the perceptual knowledge of luthiers, which is susceptible to unrepairable errors. Knowing the modal properties of the tar and kamancheh as two most important membrane string instruments in several musical live traditions is also a prerequisite if one wants to make “tonal copies” of a particular high-quality instrument. There is no scientific attempt found in the literature to analyze these types of instruments except for the recent reports published by the authors of the current paper, [2], [4] and [5]. Figure 1 shows how the vibration of each component is coupled with the others.

![Figure 1](image)

Figure 1 – Components of membrane string instruments (similar chart can be found in [2])

Tar and kamancheh are introduced in [2] and [4]. For kamancheh, a bowed spike fiddle, the sphere-like body is closed with a circular membrane stretched on the opening. Quite similar versions to the type shown in Figure 2-a are common in Turkish and Azerbaijani music as well as several other cultures.

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In this paper, vibrating mode shapes of both instruments’ resonating box are shown and the mode shapes of the membranes for each of them are reported. The results are considered to be of great help for further thorough analysis of the whole systems, both in terms of fixing the faults of a given instrument and upgrading the general shape of each type. Besides, as many skilled instrument-makers need to get their hands on a standard modal map so as to guide them through developing a scientific-based method of making the instruments and the fine-tuning that comes afterwards, the current report is supposed to be a minor step on the long way of meeting their needs. As the tar and kamancheh makers have historically followed what their masters had experimentally taught them, no scientific data has been derived and to the best knowledge of the authors, this study could open up the possibility to further analyze the membrane string instruments thoroughly.

2. EXPERIMENTAL ANALYSIS

The experimental modal analysis was done using impulse hammer and accelerometers for the bodies and Scanning Laser Doppler Vibrometer and a shaker for the membranes. In the case of bodies, the mount to hang the instrument consisted of strings for the free-free boundary conditions. For the case of membranes, the instrument was fixed on a foam, approximating the condition in which it is played. In each case, a force transducer was used to measure the force at the point of application, i.e. the hitting point for hammer and the bridge tip for shaker excitation. Pseudo random excitation was applied for tar membrane and in the case of kamancheh membrane, white noise was applied in order to simulate the continuous excitation while playing the fiddle by the bow. The setup details for the bodies can be seen in Figure 3.
Experimental modal analysis was performed for the bodies’ vibration at first, across a frequency range from 10 Hz to 1 kHz and for the membranes between 150 Hz to 3 kHz. The time signal windowing was chosen as hanning window method so as to make sure that the signals are fitted to zero at the start and end points of each period. Natural frequencies and vibration mode shapes were derived in the frequency range using stability method of fitting. Sample frequency responses for tar membrane and kamancheh sound box can be seen in Figure 4. As it is obvious in the figure, the neck vibration is also taken into account in order to see the connection of its vibrations to the resonating box.

![Figure 4 – Modal analysis preliminary results: (a) Tar membrane in ME’SCOPEVES™; (b) Kamancheh box](image)

3. **NUMERICAL ANALYSIS**

Structures were model in the modal section in ANSYS® Workbench. In case of tar box, due to complexities, 3D laser scanner was used for creating the surface geometry and after being imported into the software, a uniform thickness was applied on advice by instrument-makers. Apart from the details of the model which were reported in the authors’ previous paper [4], a component assumed to be the membrane was also added in order to get the idea of the way the box and the membrane are vibrating together. Figure 5 shows sample results of the tar box with no membrane, where orthotropic material properties were set according to [3].

![Figure 5 – Mode shapes of tar box](image)
4. RESULTS AND DISCUSSION

Figure 6 shows few chosen vibrating mode shapes of the kamancheh membrane which show agreement in shape but not in frequency range. As previously mentioned by the authors [4], the agreement between experimental and simulation results for the sound box confirms the possibility of modeling the instrument and that the attempt to derive the modal map of the whole system would be possible. However, the attempt for simulating the membrane and cavity have given merely preliminary results so far.

For the case of membranes, it has to be noted that the numerical simulation is still not complete both in terms of parameter assumptions and modeling details. Table 1 brings a musically important frequency for each of the analyses. Specifically in the case of tar membrane, the pitch standard result does not meet the expectations and therefore, measurements must be repeated. Since the membranes are animal skin and their mechanical properties are yet to be figured out, one should further develop the numerical model in order to investigate the agreement percentage.

<table>
<thead>
<tr>
<th>Modal Analysis</th>
<th>Frequency of pitch standard</th>
<th>Agreement (experimental/numerical) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tar box</td>
<td>419</td>
<td>4</td>
</tr>
<tr>
<td>Kamancheh box</td>
<td>423</td>
<td>2</td>
</tr>
<tr>
<td>Tar membrane</td>
<td>514</td>
<td>-</td>
</tr>
<tr>
<td>Kamancheh membrane</td>
<td>442</td>
<td>-</td>
</tr>
</tbody>
</table>
5. SUMMARY

Modal analysis was performed on two membrane musical instruments, tar and kamancheh, using Scanning LDV and shakers for the membranes and data recording and analyzing systems for the sound boxes. The dynamic responses measured were treated in a modal post-processing stage and natural frequencies and mode shapes were derived. Numerical analysis was done in ANSYS® Workbench and orthotropic mechanical properties were set according to the literature. Results of the experiments and simulations show a degree of matching, confirming the possibility to further develop the analysis for detailed investigation. One goal for such an investigation is that it could create possibilities such as creating the components of the instruments out of manufacturable materials such as composites, similar to a prior study done on a type of kemane in [5].

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REFERENCES