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CARBON FIBER BOUZOUKI DESIGN

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ABSTRACT

The scope of the study is the design and prototyping of a musical instrument made from carbon, specifically the bouzouki, which is traditionally manufactured by wood. The use of carbon fiber is expected to facilitate the manufacturing of such a musical instrument, independent of factors that affect wood in an often unpredictable or uncontrollable way, such as inhomogeneities and environmental conditions like humidity and temperature. This approach will also allow for a significant reduction of the production costs, benefiting the broader musical instrument community. We focus on the development of a prototype carbon fiber bouzouki, able to acoustically perform comparably to the traditional wooden bouzouki. It is expected that the results of the presented research will eventually lead to the manufacturing of a carbon fiber bouzouki ready for commercial exploitation, thus setting the basis for the design and manufacturing of other traditional musical instruments from carbon fiber.

Keywords: *musical instruments, bouzouki, vibration, acoustics, composite materials.*

1. INTRODUCTION

Historically, musical instruments have always been part of human culture. The importance of musical instruments is the basis of the field of musical instruments acoustics [1]. Many studies have been performed for the analysis of the vibrational modes of instruments and their relation to the acoustic characteristics. The development of new materials has affected the manufacturing of musical instruments. One of the early studies using new materials was by Haines et al [2]. Bucur [3] has reviewed the use of composite materials for the manufacturing of musical instruments. For the complete study of musical instruments, we have developed an integrated method [4,5], which comprises Electronic Speckle Pattern Interferometry (ESPI), impulse response measurements and finite element method (FEM) modelling and simulations. This method allows for the characterization of musical instruments, made out of classic (e.g. wood) and new materials, based on acoustodynamic criteria.

Bouzouki is a string instrument, which belongs to the broader family of tanbur. The version of the instrument most commonly played in Greece has three or four pairs of strings. Here we present the results for the characterization of a carbon fiber bouzouki. The construction of an instrument of such material is challenging not only due to the requirements of the process, but also because it must eventually be approved by the players. To include subjective criteria imposed by the players/listeners, psychoacoustic tests were also performed.

The paper describes the procedure, which includes the comparison of three wooden bouzoukis and the qualification of one as the best. A wooden bouzouki was the basis of the construction of three instruments of carbon fiber. One of them was qualified via interferometric experimental measurements with reference to the best wooden bouzouki. Furthermore, finite element simulation results of the qualified carbon fiber bouzouki were demonstrated with reference to the traditional wooden

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bouzouki experimental results, providing new findings crucial for the optimization of the manufacturing of the carbon fiber instrument.

2. IMPULSE RESPONSE MEASUREMENTS

Figure 1 shows the experimental setup for the impulse response measurements of a carbon fiber bouzouki. As it may be seen, a grid of measurement points was created on the instrument's top plate. The measurements were performed using the roving hammer method. The location of the response point was chosen to be close to the bridge. An impact hammer (PCB, Model 086E80) excited the instrument, and an accelerometer (PCB, Model TLD352A56) detected the resulting response. A real time multi-analyzer (OROS, Model OR34) calculated the frequency response function (FRF). The ratio of accelerance was used for the estimator H_2, which is given by

$$H_2(\omega) = \frac{G_{yy}(\omega)}{G_{yx}(\omega)} \tag{1}$$

where $G_{yy}(\omega)$ is the auto-spectrum of the acceleration and $G_{yx}(\omega)$ the cross-spectrum between force and acceleration signals. The excitation points are shown in Figure 1 along the tape lines attached to the top plate of the instrument.

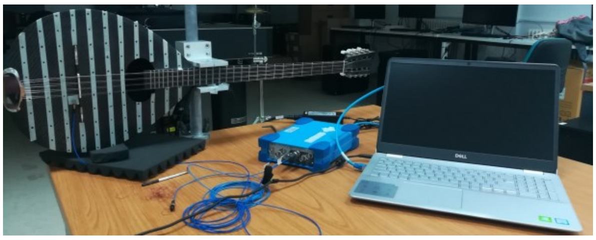

Figure 1. Modal analysis setup.

3. VIBRATIONAL MODES DETERMINATION & VISUALIZATION

Apart from the modal analysis, measurements using Electronic Speckle Pattern Interferometry (ESPI) were also performed. ESPI is a useful method for the determination and visualization of the normal modes and the experimental extraction of the corresponding vibration amplitude distribution. Further information about the application of this technique and its capabilities can be found in [4]. The experimental setup of ESPI is shown in Figure 2. A laser beam of a single longitudinal mode laser (Oxxius, Model LCX 532, 532 nm, 170 mW) is directed to a beam splitter (BM1), after changing height through a periscope (PER) and direction by a mirror (M1). After BM1, two beams follow different paths. The first beam is diverged by two lenses (L1, L2) and illuminates the vibrating bouzouki (OBJ). A signal generator feeds an active loudspeaker, which excites the bouzouki. The intensity of the second beam is controlled by a variable neutral density filter. Two mirrors (M2, M3) guide the beam to a beam expander (EXP). The reflection of the first beam and the beam after the expander are superimposed on the CCD camera detector using a beam splitter (BS2). The resulting speckle interferogram is recorded by the CCD camera and is further analyzed by means of custom-made image analysis software.

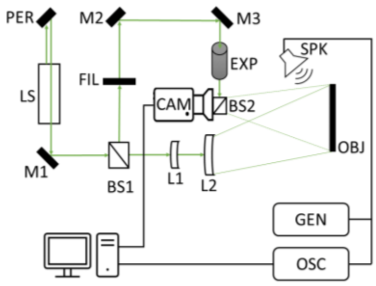

Figure 2. Electronic speckle pattern interferometry experimental setup.

4. PSYCHOACOUSTIC TESTS

Two psychoacoustic tests were performed, one focusing on players/soloists and the other on listeners. The ITU method [6] and the corresponding rating scale was followed. The survey was anonymous, and the filling of a questionnaire was required. In the first set of tests five soloists participated. The players/soloists had different years of experience and the questions they had to answer related to the quality of the sound and the playability of the instrument. Each player/soloist was allowed to rehearse with each instrument as long as wanted. Due to impartiality, during the rehearsal the players/soloists were blindfolded.
The quality of sound was also judged by 60 listeners. Their music background ranged from professionals to not related to music. After listening to 15-minute recordings of the instruments under test, the listeners had to fill in a specially designed questionnaire addressing the points of the

research. More details and sound examples may be found in [5].

5. CARBON FIBER BOUZOUKI MANUFACTURING

A 3D Computer Aided Design (CAD) model of the musical instrument was developed according to the point cloud generated by the 3D scan of a wooden bouzouki (152 points/cm2). Then, the 3D CAD/Computer Aided Manufacturing (CAM) of the molds of each part were developed. Based on the G-code produced by CAM, the molds were manufactured by Computer Numerical Control (CNC) machining and were used for the molding of the carbon fiber bouzouki parts that assembled the musical instrument. The fabrication of the carbon fiber fabric parts was conducted by initially placing the dry carbon fabrics in the mold, then impregnating the fabrics with resin using a vacuum, and by finally heating at a specific temperature and time.
Three corresponding top plates with slightly varying characteristics were manufactured, and three carbon fiber instruments (C01, C02, and C03) were assembled. The manufacturing of the three top plates was performed using Twill and Ud carbon fiber layers. The bridge and the bars of the soundboard of C01 were made from spruce wood in accordance with the wooden bouzouki for the comparison studies [5], while the bridge and the bars of C02 and C03 were manufactured by Twill and Ud carbon fiber layers in varying sequences and fiber directions.

6. MEASUREMENT RESULTS

Impulse response measurements are used for the location of the resonances, which are visualized and also determined using ESPI by frequency scanning around the appearing resonance peaks. Figure 3 shows three vibration modes for the three wooden bouzoukis. For the first bouzouki (W01) the resonances occur at 165 Hz, 500 Hz and 700 Hz. For the second (W02) at 180 Hz, 445 Hz and 695 Hz, and for the third (W03) at 170 Hz, 455 Hz and 695 Hz. Based on the ESPI results in combination to the results of the psychoacoustic tests, the W02 instrument qualified as best for its vibroacoustic behavior [5]. Figure 4 shows the same modes as Figure 3 for the case of the three carbon fiber bouzoukis. The resonances of C01 occur at 160 Hz, 666 Hz and 1080 Hz, for C02 at 165 Hz, 405 Hz and 720 Hz, and for C03, at 165 Hz, 405 Hz and 720 Hz.

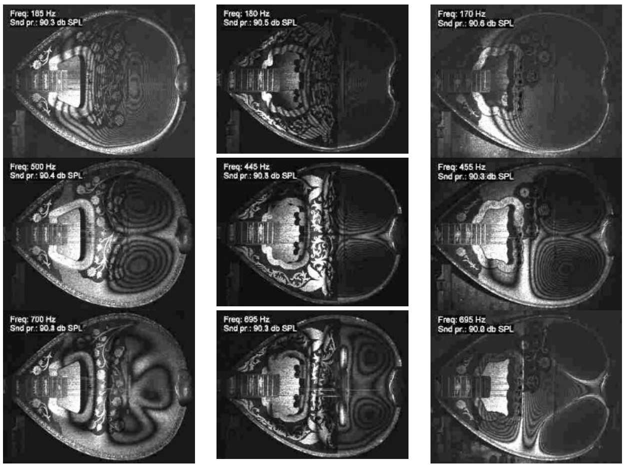

Figure 3. Resonant frequencies of the W01, W02, W03 bouzoukis, from left to right respectively.

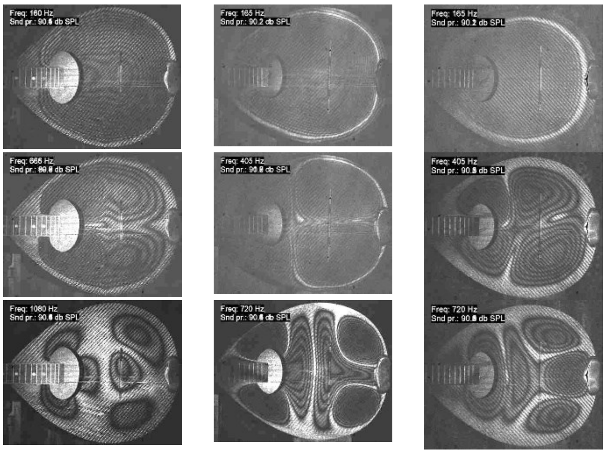

Figure 4. Resonant frequencies of the C01, C02, C03 bouzoukis, from left to right respectively.

ESPI results also demonstrated that the vibrational behavior of the C01 and W02 musical instruments was similar for frequencies up to 1000 Hz, and a good agreement was observed for frequencies higher than 1000 Hz, thus the qualified C01 was modeled via the FEM and different approaches (in geometry and material properties) were considered to optimize the new manufactured carbon fiber bouzouki.

7. NUMERICAL MODELING AND SIMULATION RESULTS

The top plate of C01 was properly discretized, and a FEM model was developed. To follow the experimental conditions and measurements, a FEM prestress static analysis and modal analysis were performed. The developed discretized model of the bouzouki soundboard included the bridge at the front and the two bars at the back side. The material properties used to simulate the Twill [5] and Ud [5] layers were considered, according to the literature values, while spruce [5] material properties for the wooden parts were selected. A total number of approximately 110,000-130,000 elements was considered for the mesh of the developed models. Regarding the boundary conditions, the side of the soundboard that was in contact with the fingerboard and the outer nodes on the edges of the soundboard was considered fixed since this area was in contact and bonded to the full body of the instrument. For the prestress static FEM analysis [5], a tension force of 70 N, as was experimentally measured, was considered for each string.

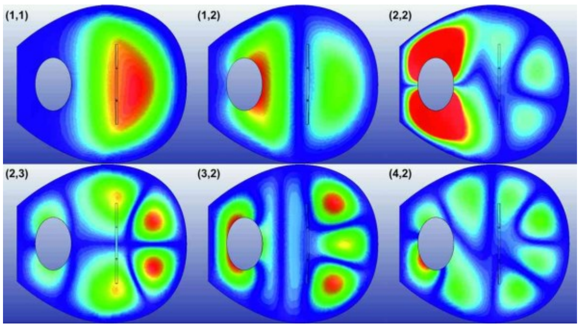

Figure 5. FEM simulation results of six representative modal shapes of the C01 soundboard.

Table 1. Resonant frequencies of W02 and C01

Modes	ESPI W02 (Hz)	FEM C01 (Hz)
(1,1)	185	235
(2,2)	436	445
(2,3)	635	655
(3,2)	710	705
(4,2)	796	820

FEM simulation results, considering the bridge and bars as wooden, were compared to the ESPI experimental results along with impulse response measurements, and a good agreement was found [5]. To optimize the manufacturing process of the bouzouki, the replacement of the wooden bridge and bars with carbon fiber was studied by FEM. A different number of layers for the soundboard, along with different carbon fiber directions, were tested in different developed models. The results of the simulations were compared with the ESPI results of the optimal traditional bouzouki W02. A good agreement with ESPI was found for the model that had four layers (one layer of 0° Twill, then two layers of 0° Ud, and finally, a layer of 0° Twill, 1.16 mm thick in total) and carbon 0° Twill properties for the bridge and bars. Table 1 shows the comparison of five characteristic resonant frequencies for ESPI and FEM, while Figure 5 shows representative modal shapes of the model.

8. CONCLUSIONS

The present study focuses on the development of a prototype carbon fibre bouzouki, able to acoustically perform comparably to a traditional wooden bouzouki. The proposed integrated method, which combines experimental measurements, psychoacoustic tests, and computational simulations, allows for even more research and modifications in the future for the further improvement of the vibrational behaviour, the reduction of the manufacturing time and cost for a variety of carbon fibre instruments, when it goes into industrial production.

9. ACKNOWLEDGMENTS

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