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EVALUATION OF RESIDUAL STRAINS ON ACOUSTIC QUALITY OF GUITAR

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Abstract

This paper aims to assess how the residual deformations of the guitar neck influence the quality of the musical instrument, knowing that wood is a material whose rheological behavior is influenced by many factors, including humidity, temperature, duration, intensity and how is applied the forces. Thus, it were analyzed two types of classical guitar - standard, without deformations and the other type with deformations of the guitar neck. Were determined flatness deviations of the neck by measuring the distance between strings and fretboard, at 12th fret by means of standardize device. Subsequently, each type of guitar was tested acoustically, recording frequency and harmonics. In the case of guitar characterized by residual deformations, acoustic characteristics (octaves, harmonics, amplitude) were significantly altered due to strings length modifications.

Key words: *residual strain; guitar; bending; acoustic properties.*

INTRODUCTION

The guitar is a complex which involves numerous mechanical wood processes. After mechanical processing of wood from assemblies of classical guitar structure, residual stresses occurs leading to deviations from flatness and straightness. The reasons that cause residual deformations are technological - produced during technological processes due to defective regulation of machine tools, thickness variations of different parts; anisotropic structure of wood used in the structure of the guitar neck leading to deformations out of the rigidity conditions; mechanical - rheological phenomena appearance wood relaxation after being subjected to mechanical stresses during mechanical wood processing, physical conditions - moisture content of wood, humidity and ambient temperature, the heat produced by tools machine which modified the moisture content at the surface of wood product etc. (Stanciu 2014,1). Residual stresses acting on the geometric integrity producing strains that changes the tone of musical instrument and in terms of technology are considered defects.

OBJECTIVE

The objective of this paper is to assess acoustic guitars with and without residual deformations of the neck and identify how these residual deformations affect the tone of the musical instrument through an analysis of the six-string acoustic octaves.

RESIDUAL STRESS OF WOOD FROM GUITAR NECK - THEORETICAL APPROACH

Most of residual stresses and strains occur in the neck of the guitar which is a laminated cantilever beam of constant strength, subjected to bending and torsion, being made of solid wood species such as maple, beech, mahogany. Such a beam is feasible only when on the structure it can

define only a combination of load. The existence of other combinations of load would not allow a beam of constant strength, even if during the playing, the neck is subjected to periodic external forces.
Thus, just in rest, but loaded with forces/couple by strings, the guitar's neck meets the criteria of constant strength beam. Complexity of the mechanical and dynamic phenomenon increases with the internal efforts from the neck structure developed during the interpretation, respective the cyclic loading. Strings tension produce bending and torsion of the neck, top plate and acoustic body of guitar. This is due to the following factors: arrangement of strings on bridge; thicknesses and different materials of the six strings; static stresses of each chord; variable stresses of strings developed by changing the length of the vibrating string when id pressing the chord on fret during playing; the intensity of cyclic forces of strings that subject guitar to periodic cyclic stresses.

The tension in the string varies depending on the material and string diameter. The strings are tightened to produce six tones with frequencies known (Fig.1): N_6 – 82.4*Hz* (noted in my music - E2), N_5 – 110*Hz* (denoted in music Sol - A2), N_4 – 146.83*Hz* (denoted Re - D3); N_3 - 196*Hz* (Sol - G3), N_2 - 246.9*Hz* (Si - B3); N_1 - 329.2*Hz* (Mi - E4).

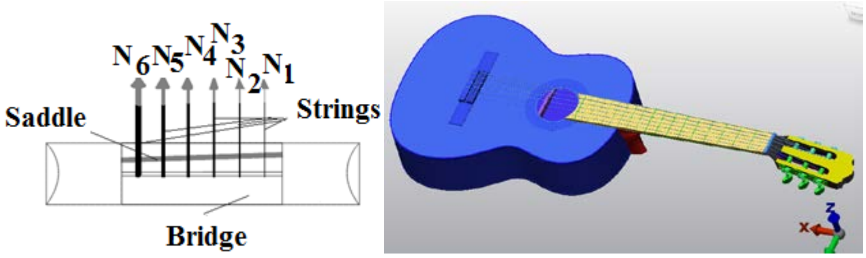


Fig. 1.
The arrangement of strings on bridge

Due to its anisotropic structure with three symmetric planes, the maximum directions of wood strain do not coincide with the direction of maximum stress. The correlation between loads and displacements, and between stress and strain is plotted as characteristic curves, $\sigma = f(x)$. The shape of these curves for different loading and for different planes of wood (LR – longitudinal radial, LT – longitudinal tangential, RT – radial tangential) or in different directions, highlight elasticity area (the straight zone), the proportionality (where is valid the Hooke's law $\sigma = E^*\varepsilon$), the flow and breaking limit. Shape of characteristic curve, σ = f (ε) is dependent by the variation of the forces intensity in time whether they are static or dynamic, constant or variable (with shock) or they are still within certain maximum values and minimal. It notes in particular the influence of fiber inclination against the direction and magnitude of forces, the size of wood structures on the stress flow and the deformation of these parts during mechanical wood processing. In general, the stress and strain state of the wood piece is represented by the specific tensors of stress and strain, given by the relations (1 a; b) (Curtu, 1984):

$$T_\sigma = \begin{pmatrix} \sigma_L & \tau_{RL} & \tau_{TL} \\ \tau_{RL} & \sigma_R & \tau_{RT} \\ \tau_{TL} & \tau_{TR} & \sigma_T \end{pmatrix}; \qquad (1, a)$$

$$T_\varepsilon = \begin{pmatrix} \varepsilon_L & \frac{1}{2}\gamma_{LR} & \frac{1}{2}\gamma_{LT} \\ \frac{1}{2}\gamma_{LR} & \varepsilon_R & \frac{1}{2}\gamma_{RT} \\ \frac{1}{2}\gamma_{TL} & \frac{1}{2}\gamma_{TR} & \varepsilon_T \end{pmatrix} \qquad (1, b)$$

where: σ_L, σ_R *and* σ_T are normal stresses on L, R, T directions; τ_{LR}, τ_{RT} *and* τ_{LT} – tangential stresses in planes LR, RT și LT; ε_L, ε_R and ε_T are the strains and γ_{LR}, γ_{RT} *and* γ_{LT} – shearing strains.

Introducing the tensor of elasticity modules and the tensor of transverse contraction coefficient, resulting:

$$\begin{cases} \varepsilon_L = \dfrac{1}{E_L}(\sigma_L - \nu_{LR}\sigma_R - \nu_{LT}\sigma_T);\ \gamma_{TR} = \dfrac{\tau_{TR}}{G_{TR}}; \\ \varepsilon_L = \dfrac{1}{E_R}(\sigma_R - \nu_{RL}\sigma_L - \nu_{RT}\sigma_T);\ \gamma_{RL} = \dfrac{\tau_{RL}}{G_{RL}}; \\ \varepsilon_L = \dfrac{1}{E_T}(\sigma_T - \nu_{TL}\sigma_L - \nu_{TR}\sigma_R);\ \gamma_{LT} = \dfrac{\tau_{LT}}{G_{TL}}, \end{cases} \tag{2}$$

where: ν_{LR}, ν_{LT}, ν_{RL}... are the Poissons coefficients (first index shows the direction of transverse contraction, the second direction of stress which produces the elongation). From energetic reasons, between coefficients of transverse contraction ν and elasticity modules *E* are the relations:

$$E_L\nu_{RL} = E_R\nu_{LR};\ E_L\nu_{LR} = E_T\nu_{TL};\ E_R\nu_{TR} = E_T\nu_{RT}; \tag{3}$$

Finally the following relationships between stresses and strain results:

$$\begin{cases} \sigma_L = \dfrac{(1-\nu_{RT}\nu_{TR})E_L\varepsilon_L + (\nu_{LR}+\nu_{LT}\nu_{TR})E_R\varepsilon_R + (\nu_{LT}+\nu_{LR}\nu_{RT})E_T\varepsilon_T}{1-\nu_{RT}\nu_{TR}-\nu_{LR}(\nu_{RL}+\nu_{RT}\nu_{TL})-\nu_{LT}(\nu_{TL}+\nu_{RL}\nu_{TR})}; \\ \sigma_R = \dfrac{(\nu_{LR}+\nu_{LT}\nu_{TR})E_L\varepsilon_L + (1-\nu_{LT}\nu_{TL})E_R\varepsilon_R + (\nu_{RT}+\nu_{LT}\nu_{RL})E_T\varepsilon_T}{1-\nu_{RT}\nu_{TR}-\nu_{LR}(\nu_{RL}+\nu_{RT}\nu_{TL})-\nu_{LT}(\nu_{TL}+\nu_{RL}\nu_{TR})}; \\ \sigma_T = \dfrac{(\nu_{TL}+\nu_{RL}\nu_{TR})E_L\varepsilon_L + (\nu_{TR}+\nu_{LR}\nu_{TL})E_R\varepsilon_R + (1-\nu_{RL}\nu_{LR})E_T\varepsilon_T}{1-\nu_{RT}\nu_{TR}-\nu_{LR}(\nu_{RL}+\nu_{RT}\nu_{TL})-\nu_{LT}(\nu_{TL}+\nu_{RL}\nu_{TR})}; \\ \tau_{TR} = G_{TR}\gamma_{TR};\ \tau_{RL} = G_{RL}\gamma_{RL};\ \tau_{LT} = G_{LT}\gamma_{LT}. \end{cases} \tag{4}$$

Wood structure and its rheological behavior under various loads at a certain relative humidity and temperature condition give elastic - plastic features. For elastic plastic materials, characteristic curve does not express all aspects of deformation. Studies have shown that the deformation of wood and the wood-based materials, not simply to an instantaneous change of shape, which occurs after load application, but there is a continuous process of deformation under load, called flow. Under certain environment conditions under prolonged load, the deformations grow and finally the breaking occurs.

ACOUSTIC IMPACT OF REZIDUAL STRAIN

Analyzing the types of defects found that classical guitars (without reinforcing rods of neck guitar) recorded the most common strain in the neck area (approx. 45%), approx. 25% are recorded as deformations of the neck and body of the guitar, 8-10% guitars with joints separation between the neck and body, 20% other defects (Fig. 2).

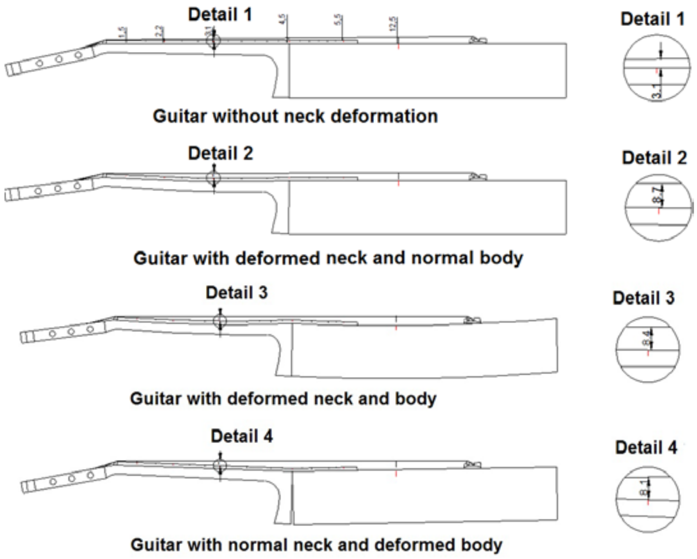
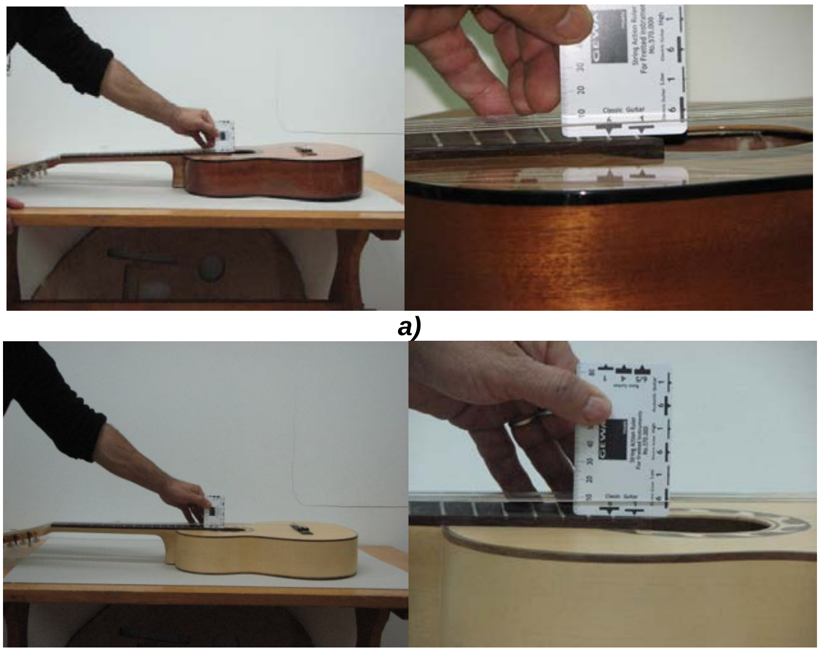


Fig. 2.
Type of guitar deformation

The literature refers to causes which produce the residual deformations such as technological ones (deviations from flatness, straightness, produced during technological processes due to improper adjustment of machine tools); anisotropic structure of wood used in the structure of the guitar neck lead to deformations exceeding maximum strain; rheological phenomena, wood moisture content, relative humidity and environment temperature of storage etc. (Curtu 1993). These deformations affect the functionality of musical instrument and the sound quality. In research conducted, it was analyzed the guitar without deformations of the neck and guitars with deformations over the allowed limit, as presented in Table 1. To measure the distance between each string and fretboard measuring device was used. The first type of guitar does not presented residual deformations, whereas, in the case of the second type of guitar, there was a guitar neck strain by 34% over the standard distance (Fig. 3).



a)

b)

Fig. 3.

Deformation measurement of the analyzed guitars

Table 1

Type of tested guitar

Type of guitar	String	Normal distance between string and fret d_s *mm*	Measurement distance d_m *mm*	Deviation from normal distance $e=d_m-d_s$ *mm*	Specific frequency of free string f_0 *Hz*	Octave (frequency at 12th fret) f_{12} *Hz*
1. Without strain	**mi**	3.5	3.5	0	329.6	659.3
	si	3.6	3.6	0	246.9	493.9
	sol	3.6	3.6	0	196.0	392.0
	re	3.9	3.9	0	146.8	293.7
	la	4	4	0	110.0	220.0
	mi	4	4	0	82.4	164.8
2. With strain	**mi**	**3.5**	**4.7**	**1.2**	329.6	**659.3**
	si	**3.6**	**4.8**	**1.2**	246.9	**493.9**
	sol	**3.6**	**4.8**	**1.2**	196.0	**392.0**
	re	**3.9**	**5.1**	**1.2**	146.8	**293.7**
	la	**4**	**6.2**	**1.2**	110.0	**220.0**
	mi	**4**	**6.2**	**1.2**	82.4	**164.8**

Testing consisted of mechanical excitation of each chord determining the frequency of free vibration simultaneously pressing string at 12th fret, halved the string length and thus obtaining a vibration frequency twice higher than a free string frequency. The emitted sounds were acquired and processed using software TuneIt (Musical Instrument Tuning software). The experimental bench tested consisted of guitar, microphone attached to the top plate of the guitar, computer software for data acquisition and display. The strings were pressed on 12th fret and plucked on the rosette area, the sounds being recorded in real time with microphone (Fig.4). In Fig. 4 are presented harmonic analyses of musical instrument tuning soft.

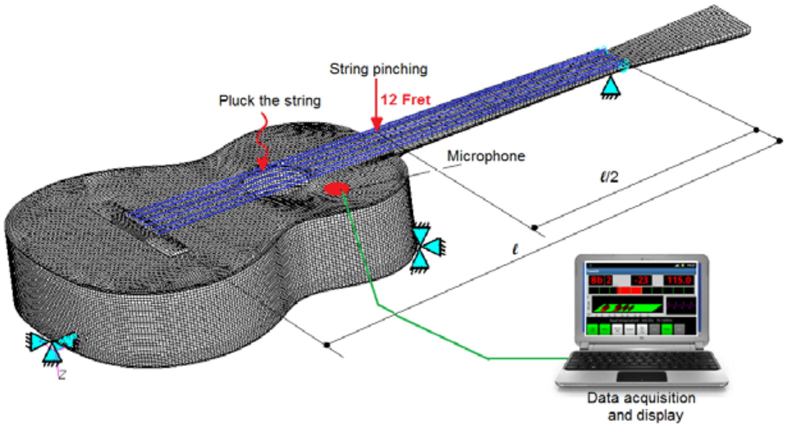


Fig. 4.
Acoustic test bench

a) Normal guitar ***b) Deformed shape of guitar neck***

Fig. 5.
Harmonic analysis

RESULTS AND DISCUSSION

The tests have found that in the case of the distorted neck, deviations from normal values in terms of the harmonics, clarity and accuracy of sound emitted during singing are obvious

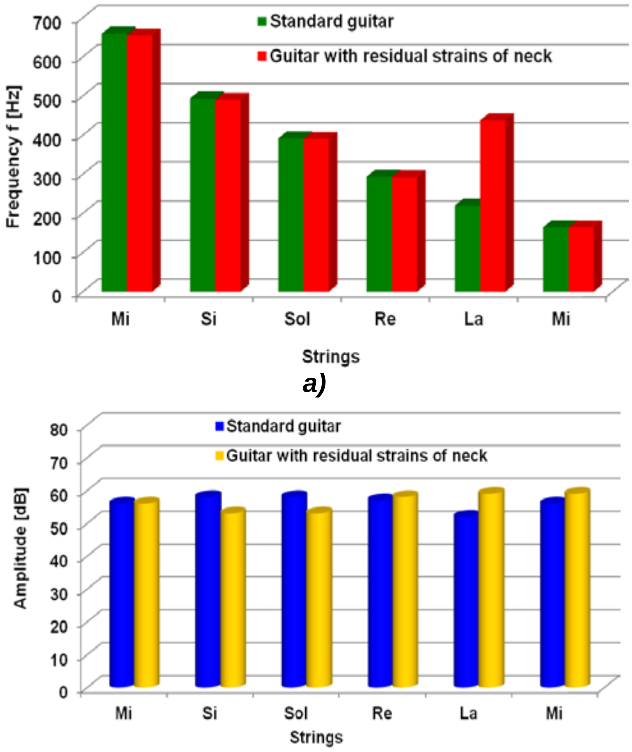
As the string length varies with both deviations and inharmonious are higher, such as in the case of third, quartiles and quintiles. The Table 2 shows the results of the analysis of the 6-string acoustic first octaves.

Table 2

Results of harmony analysis

Type of the tested guitar	**String**	**The measurement frequency at 12th fret** f_{12m} ***Hz***	**Inharmonicity** ***Hz***	**Offset**	**Amplitude** ***A dB***
1. Whitout deformation	**mi**	659.3	0.000	0	-56
	si	493.9	0.000	0	-58
	sol	392.0	0.000	0	-58
	re	293.7	0.001	0	-57
	la	220.0	0.000	0	-52
	mi	164.8	0.005	0	-56
2. With deformation	**mi**	654.3	0.000	-13	-56
	si	490.2	0.014	-13	-53
	sol	390.6	0.000	-6	-53
	re	292.8	0.001	-5	-58
	la	438.0	0.000	-8	-59
	mi	164.1	0.013	-8	-59

These tests prove that acoustic residual deformations of the guitar neck lead to distortion of tones during musical interpretation, thus affecting tone, accuracy, clarity and musical timbre (Fig. 6,a and b).



a)

b)

Fig. 6.

Comparison between standard guitar and guitar with residual strains of neck: a) variation of octaves; b) variation of amplitude

Moreover, if this increase due to cyclical load produced during the singing, the viability of the finished product - the guitar is reduced. To avoid residual deformations of classical guitar neck, there are many ways of reinforcing it, such as the use of reinforcing rods - with different sections, placed under fretboard or eliminating deformations obtained from mechanical processing of wood, or selecting and cutting wood in longitudinal – radial direction (Fig. 7) (Stanciu 2014,2).

The problem of residual strains whatever the reason, be addressed and solved on the basis of the rheological behavior of materials from the guitar neck structure, because these strains are recorded initially on the elastic-plastic domain then in the plastic domain. After the cyclic loading and analyzing the hereditary status of deformed system, the neutral axis of a guitar neck from a current section changes its position, the stresses and strains passing from elastic to visco-plastic behavior.

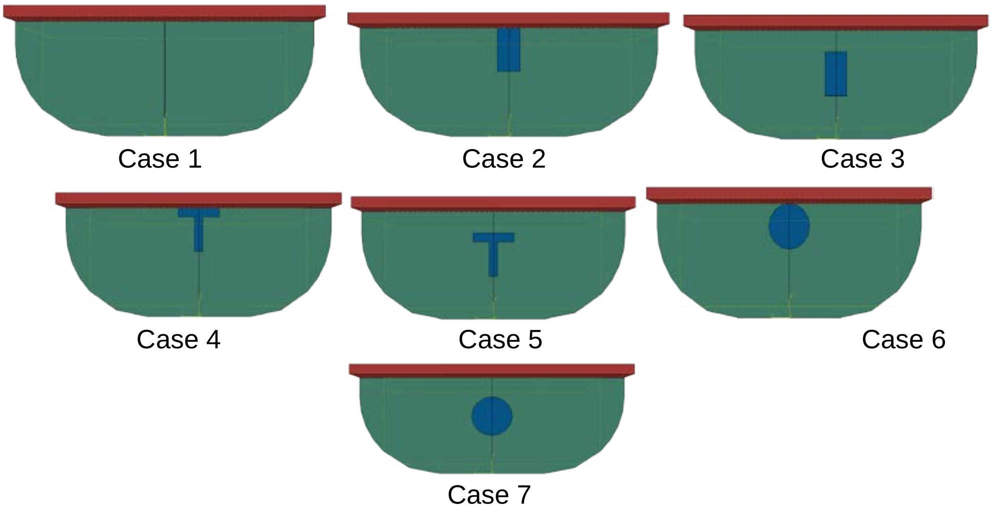

Case 1
Case 2
Case 3
Case 4
Case 5
Case 6
Case 7

Fig. 7.
Types of reinforcement of the guitar neck

In previous studies, the authors analysed with finite element method (FEM), the displacements variation of the seven cases of the guitar neck reinforcement. On the each fret it was successively applied a distributed force of 0,1*N*/*mm2*. The analysis was made in static and dynamic domain and it was found that the maximum displacement is around 1,29*mm* which is comparable with measurements before the acoustic test. In Fig. 8 are presented displacements of guitar obtained in case of modal analysis.

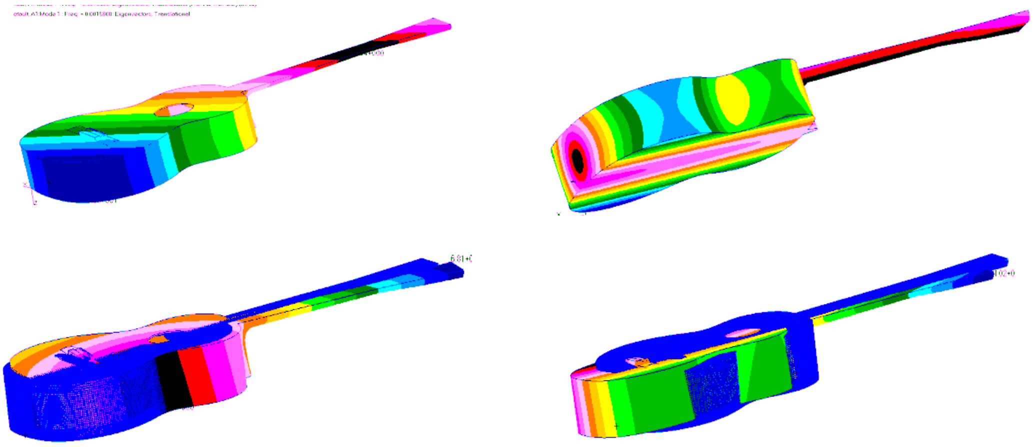


Fig. 8.
Torsional and bending vibrations of classical guitar with simple neck

CONCLUSIONS

The results obtained within the present research demonstrated that an increasing of displacement due to bending of the guitar neck lead to deviation of accurate frequencies, attenuate sounds and poor performance of classical guitar. Residual strains represents a current problem in industry regardless the products being solved by using a proper schedule for mechanical proccessing.

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