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VIBRATION ANALYSIS OF TONEWOODS USING FINITE ELEMENT METHODS

JÁNOS LÍSKA[1*], ANDOR MÓDRA[1] AND GÁBOR KÓNYA[1]

[1] Department of Innovative Vehicles and Materials, John von Neumann University, Izsáki út 10., Kecskemét, 6000, Hungary

The acoustic and mechanical properties of tonewoods commonly used in traditional instrument making – such as mahogany, oak, maple, and walnut – play a crucial role in shaping the sound characteristics of musical instruments. The aim of this research is to comprehensively analyze the vibration dynamics of these wood types through experimental measurements and finite element simulations. A further objective is to explore the potential substitution of these materials (primarily their acoustic functions) using advanced additive manufacturing technologies. In the initial phase of the study, harmonic excitation was applied to determine the vibration characteristics of the individual wood specimens. This enabled the quantitative evaluation of parameters such as amplitude, acceleration, damping behavior, and the distribution of natural frequencies. Based on the measured data, parametric material models were constructed in the ANSYS finite element simulation environment to validate the experimental results. During the refinement of the numerical models, special attention was paid to the anisotropic nature of the materials, accurate geometric representation, and realistic implementation of boundary conditions. The long-term goal of the research is to develop an alternative geometry - manufactured using 3D printing technology - that can mimic the mechanical and acoustic functions of traditional tonewoods. The geometric optimization of such prototypes is based on simulation outcomes, while also considering their acoustic performance.

Keywords: tonewoods, Finite Element Analysis (FEA), vibration, additive manufacturing

1. Introduction

The selection of wood species employed in instrument making has long represented one of the most critical aspects of the craft. As a natural, organic composite material, wood exhibits mechanical and acoustic characteristics that fundamentally govern the tonal output, structural reliability, and vibrational response of musical instruments. The acoustic signature of an instrument—including timbre, dynamic range, and decay time—is strongly correlated with the density, elastic modulus, internal friction, and speed of sound in the material [1],[2].

A defining characteristic of wood is its pronounced structural anisotropy: mechanical and acoustic performance varies considerably along the longitudinal (grain), radial, and tangential directions. In the longitudinal orientation, wood typically demonstrates higher stiffness and faster sound propagation, whereas transverse orientations are associated with reduced vibrational transmission and elevated damping. Such direction-dependent behavior is decisive in determining how a given species resonates within an instrument [3].

The most frequently employed tone woods include:

- Mahogany (Swietenia spp.): medium density ($\rho \approx$ 620-690 kg/m³), low internal friction, relatively homogeneous microstructure. Acoustics yields a warm, balanced response dominated by midrange frequencies. Elastic modulus: $E \approx$ 9-12 GPa.
- Maple (Acer spp.): higher density ($\rho \approx$ 630-750 kg/m³), greater stiffness ($E \approx$ 12-14 GPa). Produces a bright tonal response with pronounced high-frequency content. Strongly anisotropic properties.
- Walnut (Juglans spp.): medium density ($\rho \approx$ 550-650 kg/m³), provides balanced resonance combining the warm characteristics of mahogany and the brightness of maple. Elastic modulus: $E \approx$ 10-12 GPa.
- Oak (Quercus spp.): high density ($\rho \approx$ 700-770 kg/m³), mechanically hard and strong ($E \approx$ 12-15 GPa). Acoustically characterized by extended sustain due to low internal damping. Rarely chosen in lutherie despite its robustness.

Vibrational characterization of tone woods is performed using several experimental protocols, including impulse excitation, ultrasonic testing, and modal analysis. These techniques enable the

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*Correspondence: liska.janos@nje.hu

Table 1: Material properties

Material	Density (ρ) [kg/m³]	Young-modulus (E) [MPa]	Poisson's ratio (ν)
Oak	726	22000	0,37
Maple	685	19000	0,35
Walnut	597	17000	0,35
Mahogany	685	13000	0,36

Figure 1: Measured mass of examined bodies

determination of eigenfrequencies, damping coefficients, and mode shapes [4].

Standardized procedures relevant to wood testing include:

- ISO 3129:2019 – Sampling and general requirements for physical and mechanical testing of wood [5]
- ISO 13061-4:2014 – Determination of modulus of elasticity in static bending [6]
- ASTM E1876-15:2016 – Dynamic determination of Young's modulus and shear modulus by resonance methods [7]

Although no tonewood-specific standards exist, these international frameworks ensure reproducibility and comparability of data.

Over the past two decades, finite element analysis (FEA/FEM) has become a central methodology for the investigation of tonewoods and instrument bodies. Its strength lies in the ability to incorporate material anisotropy, heterogeneous microstructures, and realistic boundary conditions, all of which are challenging to reproduce experimentally.

Experimental datasets including amplitude, acceleration, damping factors, and frequency response functions can be employed to validate numerical models. Conversely, simulations enable systematic parametric studies that would be cost-prohibitive or practically unfeasible under laboratory conditions [8]. In this context, FEM serves as a bridge between traditional empirical knowledge in lutherie and modern materials science, providing a rigorous framework for evaluating the vibrational dynamics of wood.

The acoustic function of musical instruments is inherently based on vibrational energy transfer: primary oscillations generated by strings, membranes, or air columns are amplified, spectrally modified, and reinforced along the material's eigenfrequencies. Modal analysis facilitates the mapping of characteristic mode shapes of the resonant body, endowing each instrument with its unique acoustic identity. The integration of experimental and computational approaches thus not only advances the materials science perspective on musical acoustics but also supports the preservation and refinement of instrument-making traditions.

2. Experiments

The experiments were based on international standards, which we reproduced based on our equipment and circumstances.

2.1. Equipment and devices

During the experiments we used TRUTH B2030A studio monitor, quick-release clamps, mounting stand, Focusrite Scarlett Solo 4th Gen audio interface, The T.bone SC-450 studio microphone and wooden bodies.

Softwares used during the measurements: Audacity, Praat, MS Excel. During the experiments we had 21 degrees Celsius and humidity was around 43%. The samples were already there 24 hours before the measurement.

2.2. Measurement method

During the measurements, wooden bodies were fixed to a mounting stand, with the opposite end of each body coupled to the membrane of a loudspeaker. A frequency sweep from 0–1000 Hz was generated through the speaker. Since the loudspeaker membrane and the bodies were in direct physical contact, they performed vibratory motion together. It was observed that at certain frequencies only very small amplitudes were produced, indicating that the bodies attenuated the vibration. At other frequencies, however, significantly larger amplitudes appeared, showing that the bodies resonated together with the loudspeaker. The sound from the loudspeaker was recorded using a microphone. Because the acoustic power is proportional to the amplitude of the loudspeaker membrane, it was possible to determine when both the membrane and the bodies exhibited large amplitudes. From this, the amplification and damping points for specific frequencies could be identified.

Identical geometrical bodies were first manufactured from four wood types: oak, maple, walnut, and mahogany. Their key properties are listed in *Table 1*. For better simulated results we measured the density of the woods (*Figure 1*). During the measurements we used a highly precise digital scale. The moisture content of the tested samples was below 12%.

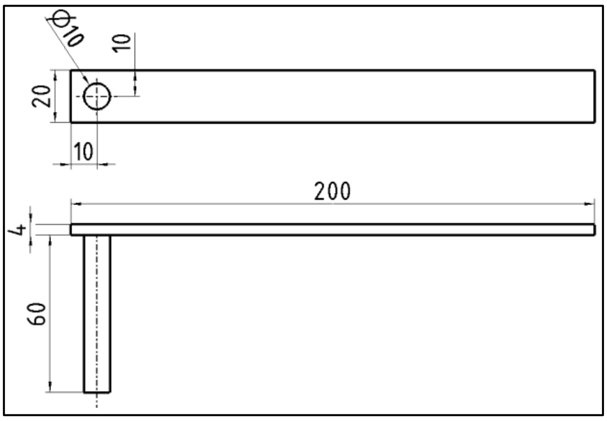


Figure 2: Dimensions of the body

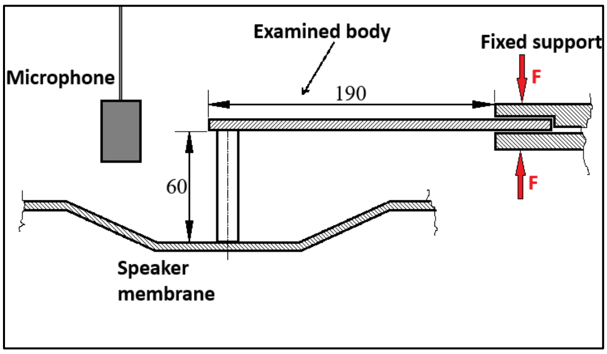


Figure 3: Schematic representation of the measurement

Figure 4: Experimental setup

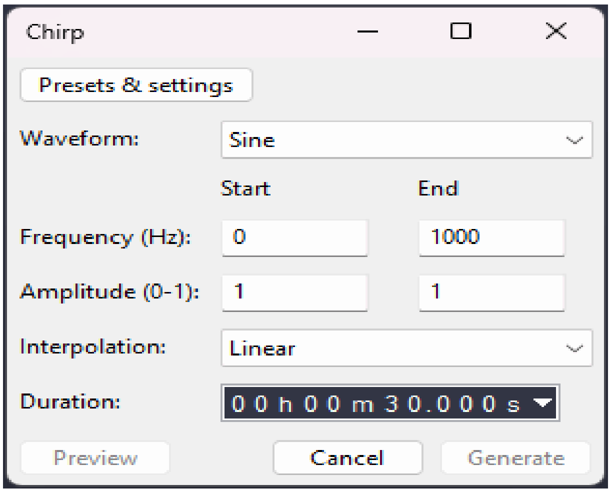


Figure 5: Frequency sweep parameters in Audacity

The measurement setup is illustrated in *Figures 2-4*. The microphone was positioned ~100 mm from the middle of the speaker membrane. The frequency sweep from 0–1000 Hz was generated using Audacity with the settings shown in *Figure 5*.

The first measurement was performed without samples. This reference measurement was necessary to capture the individual characteristics of the loudspeaker and its environment, which could later be filtered out from subsequent recordings. After this, the measurements were repeated for each of the four wooden samples. The audio files were recorded in Audacity alongside the generated sweep, ensuring temporal alignment of all recordings.

3. Processing of data

3.1. Converting sound to a visual diagram

The recordings were obtained in WAV format and then converted into numerical data for subsequent analysis. The resulting text files were imported into Excel, where the following operations were performed. The absolute value of each time series was taken, since the loudspeaker produces oscillatory motion: every positive half-period of amplitude is followed by a corresponding negative half-period. To make the data graphically interpretable, the signals were rectified to positive values.

Next, an envelope curve was constructed to trace the outer boundary of the amplitude range. This was achieved using the sliding window maximum method, in which local maxima were computed within small intervals and assigned to their respective time cells. With nearly one million data rows, the resulting envelope curves were sufficiently smooth and not visibly “stepped.” This procedure was performed for all-time series, including the reference (unloaded) loudspeaker. In this way, the unique response of the bare loudspeaker was obtained, which was then used to normalize the time series corresponding to each body. The resulting ratios were plotted on graphs, clearly showing in which frequency ranges amplitude peaks occurred and where significant damping effects were observed for each wood type.

4. Finite element analysis

4.1. Software and Configuration

The finite element simulations were conducted using Ansys Workbench 2025, while the more complex 3D modeling tasks were carried out with PTC Creo 8.0. For subsequent data analysis and evaluation, Microsoft Excel was employed to process and visualize the results.

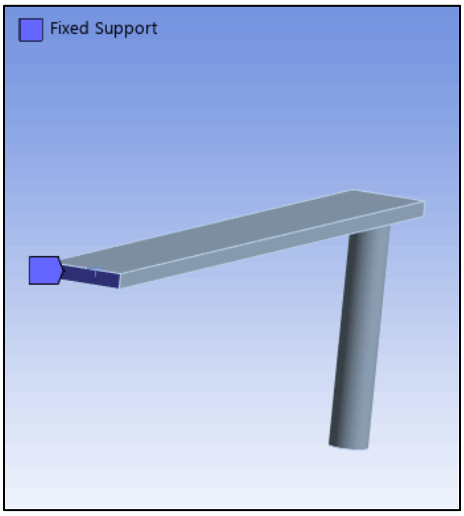


Figure 6: Fixed support constraint

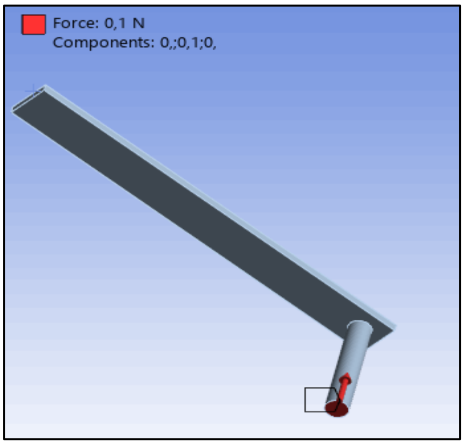


Figure 7: Static force preload

4.2. Configuration and virtual environment

The simulation was carried out using the same geometry as the physical measurements. The simulation configuration and execution were conducted using the Static Structural, Modal Analysis, and Harmonic Response modules within Ansys.

4.3. Constraints

When defining the constraints, care was taken to simulate the phenomenon in a realistic manner. Since the last 10 mm section of the body was clamped, the active vibrating length was not 200 mm but 190 mm. As the material volume between the jaws of the clamp does not significantly contribute to the vibration, the following simplification was introduced: a 190 mm long body was modeled, with the fixed support applied at its end as illustrated in *Figure 6*.

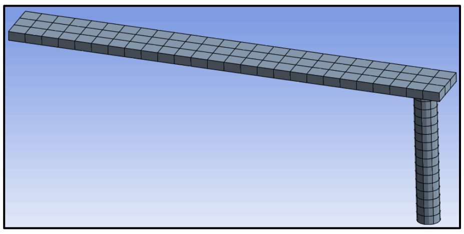


Figure 8: Meshing of the body

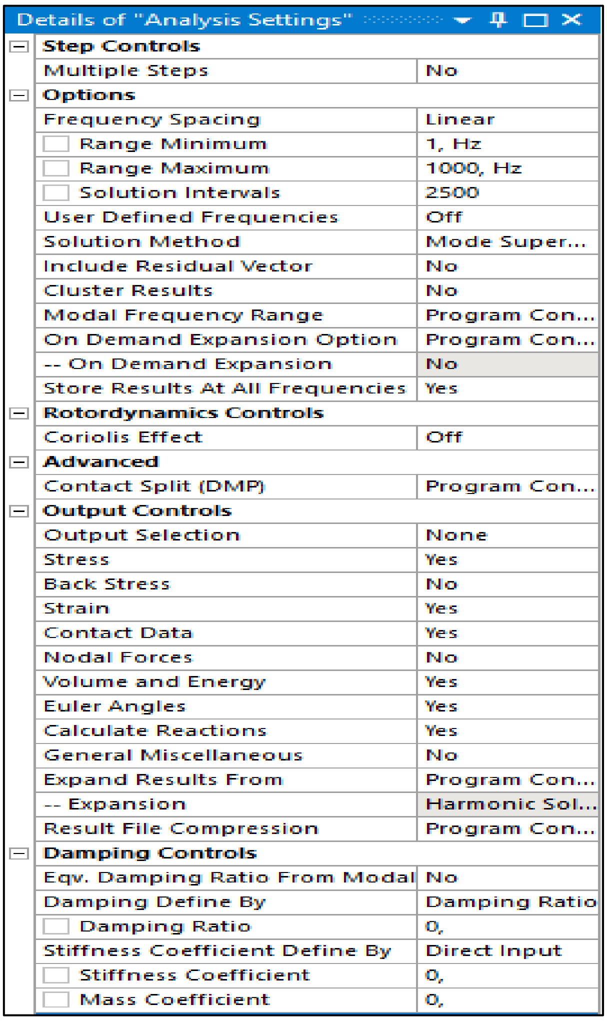
Details of "Mesh"	
Display	
Defaults	
Physics Preference	Mechanical
Element Order	Program Controlled
Element Size	Default
Sizing	
Use Adaptive Sizing	Yes
Resolution	3
Mesh Defeaturing	Yes
Defeature Size	Default
Transition	Fast
Span Angle Center	Coarse
Initial Size Seed	Assembly
Bounding Box Diagonal	201,48 mm
Average Surface Area	1257,6 mm²
Minimum Edge Length	4, mm
Quality	
Check Mesh Quality	Yes, Errors
Error Limits	Aggressive Mechanical
Target Element Quality	Default (5,e-002)
Smoothing	High
Mesh Metric	None
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0,272
Maximum Layers	5
Growth Rate	1,2
Inflation Algorithm	Pre
Inflation Element Type	Wedges
View Advanced Options	No
Advanced	
Number of CPUs for Par...	Program Controlled
Straight Sided Elements	No
Rigid Body Behavior	Dimensionally Reduced
Triangle Surface Mesher	Program Controlled
Topology Checking	Yes
Pinch Tolerance	Please Define
Generate Pinch on Refr...	No
Automatic Methods	
Sheet Body Method	Quad Dominant
Sweepable Body Method	Sweep

Figure 9: Mesh settings of the body

The end of the body was loaded with an upward-directed force of 0.1 N (*Figure 7*). This was necessary to ensure that the body was clamped with a slight preload against the loudspeaker membrane, thereby preventing undesired bouncing between the two surfaces.

4.4. Meshing of the body

The meshing of the body and the mesh settings for the analysis are shown in *Figures 8* and *9*.



Details of "Analysis Settings"	
Step Controls	
Multiple Steps	No
Options	
Frequency Spacing	Linear
Range Minimum	1, Hz
Range Maximum	1000, Hz
Solution Intervals	2500
User Defined Frequencies	Off
Solution Method	Mode Super...
Include Residual Vector	No
Cluster Results	No
Modal Frequency Range	Program Con...
On Demand Expansion Option	Program Con...
-- On Demand Expansion	No
Store Results At All Frequencies	Yes
Rotordynamics Controls	
Coriolis Effect	Off
Advanced	
Contact Split (DMP)	Program Con...
Output Controls	
Output Selection	None
Stress	Yes
Back Stress	No
Strain	Yes
Contact Data	Yes
Nodal Forces	No
Volume and Energy	Yes
Euler Angles	Yes
Calculate Reactions	Yes
General Miscellaneous	No
Expand Results From	Program Con...
-- Expansion	Harmonic Sol...
Result File Compression	Program Con...
Damping Controls	
Eqv. Damping Ratio From Modal	No
Damping Define By	Damping Ratio
Damping Ratio	0,
Stiffness Coefficient Define By	Direct Input
Stiffness Coefficient	0,
Mass Coefficient	0,

Figure 10: Harmonic response analysis settings

4.5. Materials and body contacts

The material assignment of the bodies was carried out in accordance with the physical specimens. Virtual wood materials were created using the values listed in *Table 1*. Their densities were obtained from our own measurements (mass/volume), while the remaining properties were taken from literature sources. Since the physical specimen used in the measurements consisted of two bodies, the model was also constructed accordingly.

4.6. Analysis settings for Harmonic Response

The analysis settings for Harmonic Response are illustrated in *Figures 10* and *11*.

5. Results

The results of physical and simulated measurements can be seen in *Figures 12-20*.

The results of the physical and numerical investigations revealed a strong correlation between the acoustic and mechanical properties of the different wood species. Based on density measurements, oak exhibited the highest value among the four analyzed materials ($\rho = 726$ kg/m^3), whereas walnut proved to be the lightest ($\rho = 597$ kg/m^3). The Young's modulus also showed substantial variation: the stiffness of oak and maple ($E = 22{,}000$ MPa and 19,000 MPa, respectively) was significantly higher than that of walnut ($E = 17{,}000$ MPa) and mahogany ($E = 13{,}000$ MPa).

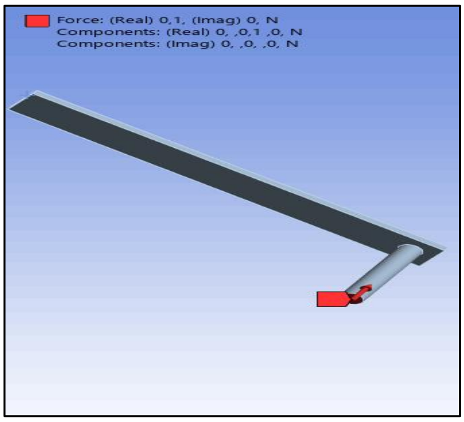


Figure 11: Harmonic response Force components

Within the 0–1000 Hz range, the frequency response revealed species-specific amplification and damping characteristics. Maple and oak displayed pronounced amplitude peaks between 600–850 Hz, which indicate a bright, sparkling tonal quality at higher frequencies. In contrast, walnut exhibited a balanced response curve with moderate resonances across both low and high ranges, confirming its intermediate acoustic character. Mahogany, on the other hand, showed its most significant amplitude increase within 250–450 Hz, where amplitude values nearly doubled compared to the reference loudspeaker, reflecting the wood's warm, deep tonal coloration.

The results of the finite element simulations closely matched those of the experimental measurements. For example, in the case of oak, the principal resonance peak occurred at approximately 800 Hz (simulation) and 690 Hz (experiment), whereas for maple it was observed at 920 Hz (simulation) and 805 Hz (experiment). The main amplification range of mahogany appeared around 360 Hz in the simulation, which correlated well with the 420 Hz experimental peak. Discrepancies between simulation and measurement (generally <5–15%) were primarily attributed to the natural heterogeneity of wood materials and the inherent limitations of accurately modeling anisotropy.

In summary, the findings support that oak and maple are particularly suitable for certain musical instrument applications due to their bright, high-frequency tonal qualities, while mahogany enhances low- and mid-frequency resonances, contributing to a warm tonal character. Walnut's balanced response, in turn, allows for versatile applications.

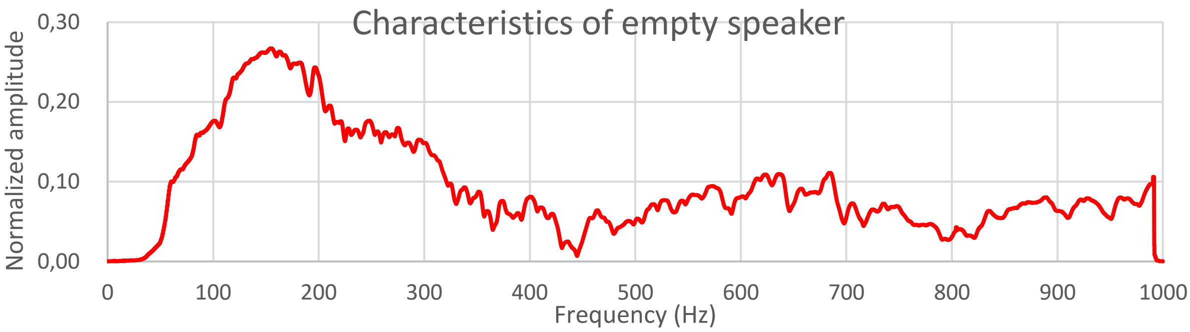


Figure 12: Empty speaker measurement for correction

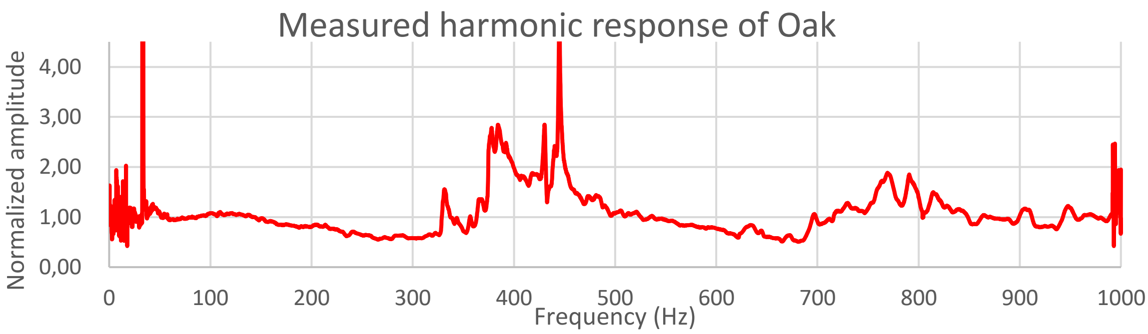


Figure 13: Measured harmonic response of oak body

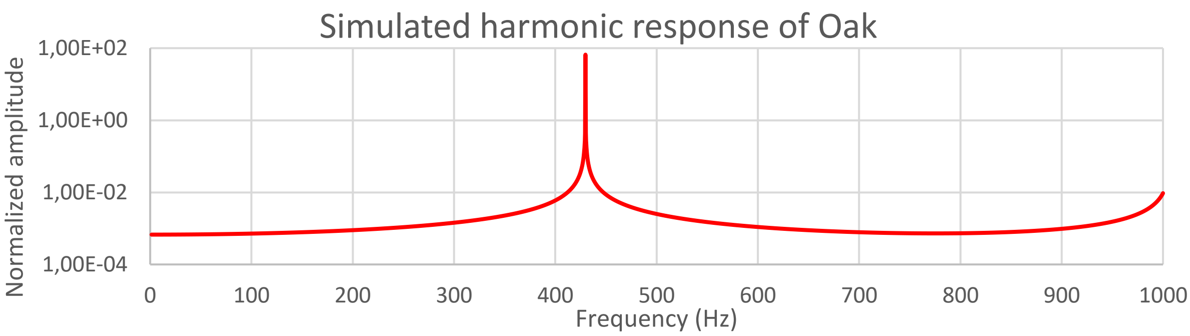


Figure 14: Simulated harmonic response of oak body

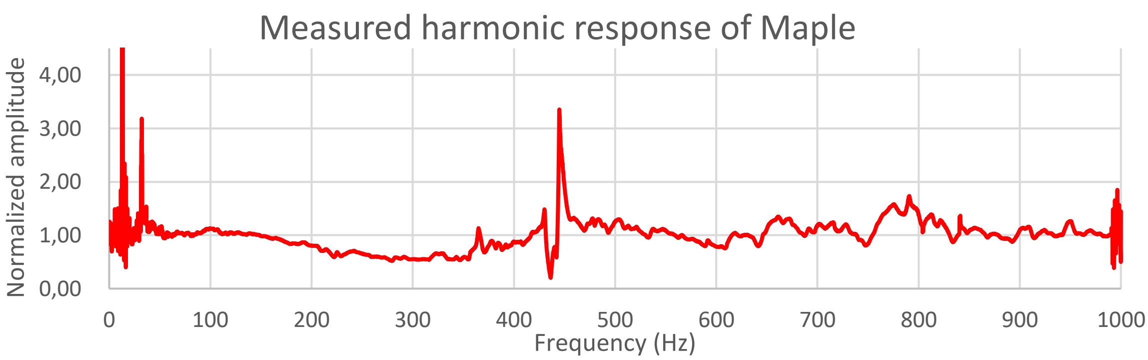


Figure 15: Measured harmonic response of maple body

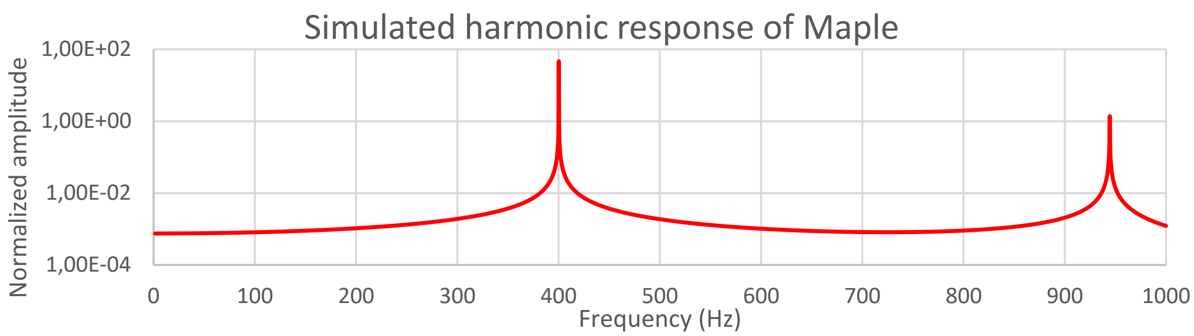


Figure 16: Simulated harmonic response of maple body

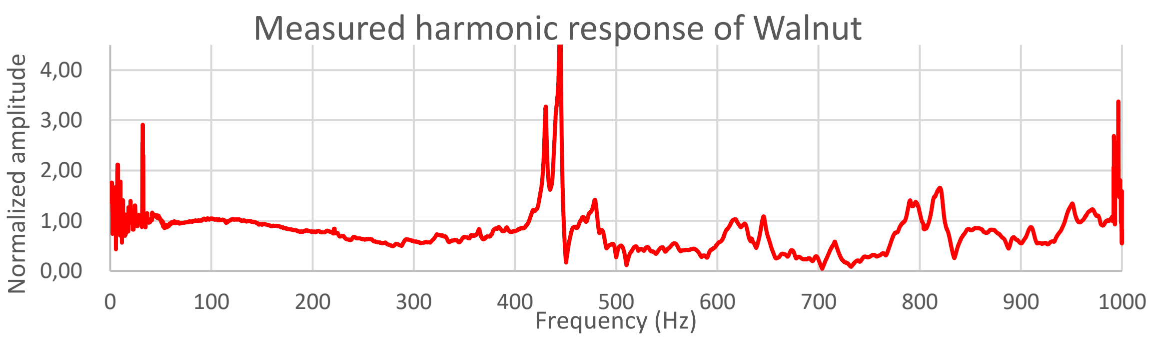


Figure 17: Measured harmonic response of walnut body

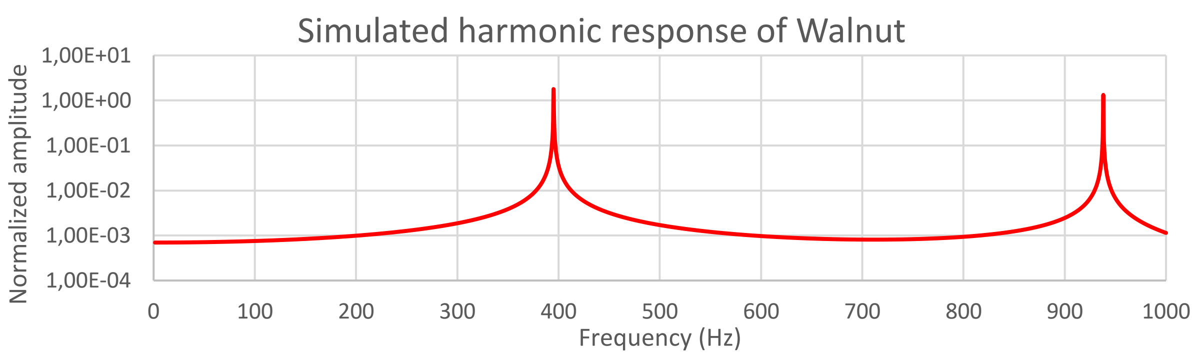


Figure 18: Simulated harmonic response of walnut body

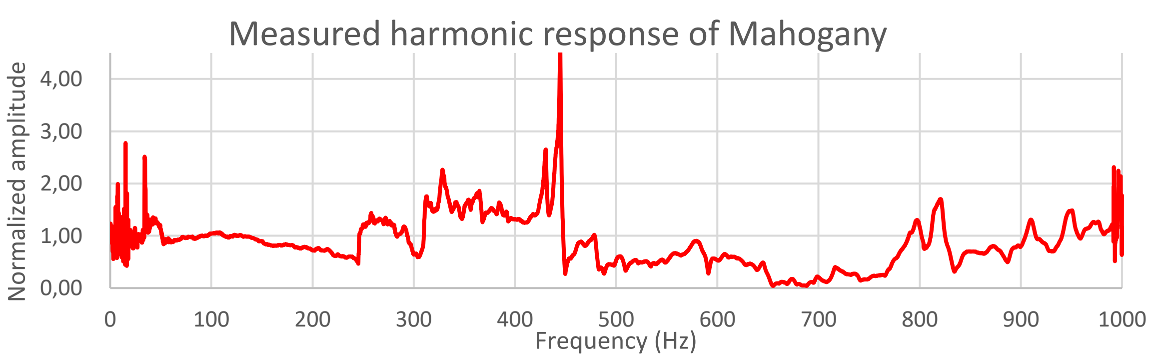


Figure 19: Measured harmonic response of mahogany body

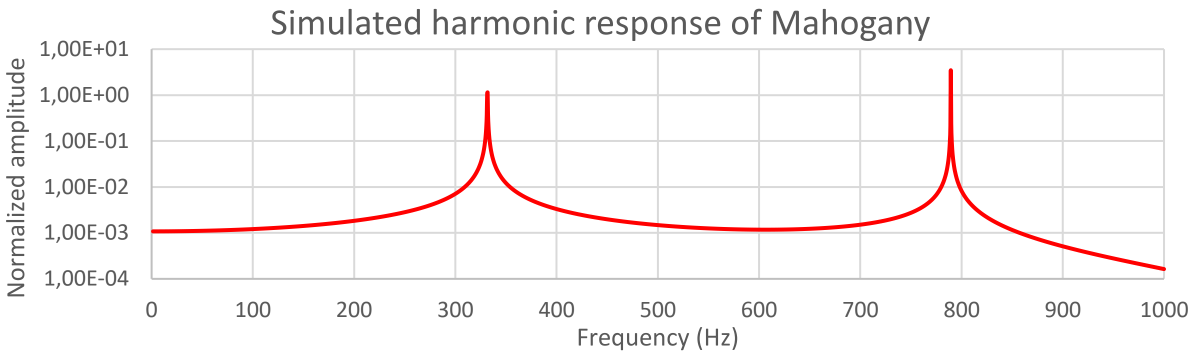


Figure 20: Simulated harmonic response of mahogany body

6. Conclusion

As can be seen, the measurements and simulations proved to be quite successful, with only minor deviations observed. The amplification and attenuation points in the experimental results appear at slightly different locations compared to the simulations, but this discrepancy arises from the unknown properties of the material. The exact Young's modulus of the real wood samples is not known, nor are details of their internal structure, age, or the climate in which the trees grew. All of these factors significantly influence the tonal character of tonewoods. Nevertheless, it is evident that maple, oak, and walnut produce a brighter, more sparkling sound. This is the reason, for example, why bass guitars are often made from maple: if they were constructed from a deeper-toned wood, the sound of the instrument would be overly deep, boomy, and lacking character.

In the case of mahogany, however, it can be observed—particularly in the experimental results—that significantly higher amplitudes occur in the lower and mid-frequency ranges (250–450 Hz). This confirms the warm tonal quality of mahogany, which is why it is widely favored in guitar making, as it provides a warm, rich sound profile.

Acknowledgement

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REFERENCES

[1] Bucur, V.: Handbook of materials for string musical instruments (Springer) 2016, ISBN: 9783319320786

[2] Wegst, U.G.K.: Wood for sound, *Am. J. Bot.*, 2006, **93**(10), 1439–1448, DOI: 10.3732/ajb.93.10.1439

[3] Hietala, M.; Niinimäki, J.; Oksman, K.: The use of twin-screw extrusion in processing of wood: The effect of processing parameter and pretreatment, *BioRes.*, 2011, **6**(4), 4615–4625

[4] Jha, N.K.; Das, D.; Tripathi, A.; Hota, R.N.: Acoustic damping: Analytical prediction with experimental validation of mixed porosity liners and analytical investigation of conical liners, *Appl. Acoust.*, 2019, **150**, 179–189, DOI: 10.1016/j.apacoust.2019.02.006

[5] ISO 3129:2019 Wood —Sampling methods and general requirements for physical and mechanical testing of small clear wood specimens

[6] ISO 13061-4:2014 Physical and mechanical properties of wood — Test methods for small clear wood specimens, Part 4: Determination of modulus of elasticity in static bending

[7] ASTM E1876-15:2016 Standard test method for dynamic Young's modulus, Shear modulus, and Poisson's ratio by impulse excitation of vibration (ASTM International)

[8] Saeed, Z.; Firrone, C.M.; Berruti, T.M.: Joint identification through hybrid models improved by correlations, *J. Sound Vibr.*, 2021, **494**, 115889, DOI: 10.1016/j.jsv.2020.115889