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Acoustic performance assessment of composite materials in musical instrument construction

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ABSTRACT

The aim of this study was to compare the vibroacoustic characteristics of two guitars, the bodies of which were made of carbon-epoxy composites. The article presents vibroacoustic tests of the string and body carried out using microphones and accelerometers. The object of the research were electric guitars with different composite bodies. The phenomena occurring in the instrument during the creation and projection of sound were described. The measurements were performed using various signal representations. A method of stimulating the instrument was proposed, which allowed for performing the tests in a repeatable manner. The methodology of the measurements, as well as the algorithm for analyzing the measurements performed using the selected method were described. Finally, the obtained results from all modalities and conclusions from the analyses were presented.

Keywords: electric guitar body, carbon-epoxy composites, acoustic properties.

INTRODUCTION

Recently, approximately 20 years ago, an alternative to standard guitars made of specially prepared wood (e.g. mahogany, maple, cedar) appeared in the form of plucked instruments made of polymer composites. The first to appear were acoustic instruments, the sound of which is strictly dependent on the materials used. In the case of electric guitars, the sound depends on both the materials used and the electronics used. Considering the required properties of the materials, carbon-epoxy composites are a particularly interesting solution. This is primarily related to the stiffness of the material, which translates into vibroacoustic characteristics [1].

Contemporary research on the acoustic characteristics of electric guitars focuses on both classical aspects of sound physics and material innovations that can affect the quality and sound of the instrument. Traditionally, electric guitar bodies were made of various types of wood, such as mahogany or maple, which affect the resonance, sustain and tone of the instrument [2, 3]. Due to the changing requirements of musicians, the search for new sounds, higher resistance to weather conditions, especially humidity, as well as the availability and time of specific wood conditioning, more and more work is being carried out to produce instruments from polymer materials and their composites, primarily carbon-epoxy laminates [4–8]. The characteristics of polymer composites are determined by the properties of the components used, the form and content of reinforcing fibers and the manufacturing technology [9–12].

The material used for the body significantly influences key acoustic parameters of an electric guitar, such as resonant frequencies, vibrations, and damping properties [13]. Studies have shown that composite bodies can offer longer sustain and a more stable sound than wooden bodies, which is particularly desirable in modern musical styles [13]. It is also worth noting that the use of composites opens the possibilities for personalizing the sound by adjusting the density and structure of the materials used in the construction of the instrument [14, 15].

Studies on guitars with carbon composite bodies have shown that these instruments exhibit more stable resonant frequencies and better sound projection compared to traditional wooden guitars. The use of composites allows precise control over acoustic properties by modifying the material structure, resulting in a consistent tone regardless of environmental conditions [16].

The Dutch company Aristides Instruments produces electric guitars using a material called Arium, a specialized blend of resins and microscopic glass particles. These instruments offer uniform acoustic properties and enhanced durability, which is difficult to achieve with traditional wooden materials.

The application of composites in guitar construction opens new possibilities for sound customization. By adjusting the density and structure of composite materials, luthiers can tailor the tonal characteristics of an instrument to the specific needs of musicians – something that is more challenging with traditional wooden guitar bodies [17].

Numerous studies and practical applications indicate that the use of composite materials in electric guitar bodies can lead to instruments with improved and more predictable acoustic properties compared to traditional wooden guitars.

In the context of research techniques, modern analysis methods, such as numerical modeling (FEM), resonance measurements and impedance analysis, are enabling precise determination, which allow for precise determination of the influence of the structure and material of the body on the acoustics of the guitar [18, 19]. Owing to the use of these methods, it is possible to better understand the differences between composite and wooden guitar bodies, which contributes to the development of knowledge and technology in the field of luthiery and production of electric guitars. In the available literature, it is difficult to find studies on comparative studies between laminated guitars and guitars cast from carbon-epoxy composites.

The aim of the work was to compare the acoustic characteristics of electric guitars differing in body construction and the materials used for their manufacture. In the work, two electric guitars were tested: a semi-acoustic semi-hollow type (laminated) and a fully electric solid-body type (gravity cast), which were made in the Polymer Materials Processing Laboratory of the Department of Theoretical and Applied Mechanics of the Silesian University of Technology and next subjected to acoustic tests in Institute of Machine Design Fundamentals of Warsaw University of Technology.

The semi-hollow body electric guitar, the construction of which is based on a body with an empty resonance chamber, allowing for a warm and full sound, is valued for its uniqueness in creating characteristic sounds, ideal for jazz or blues. Semi-hollow guitars are a group of guitars the body of which is not completely empty; they either have a solid body in part, or a block of wood that passes through the middle along the axis of the strings. Hollow body models are characterized by a larger body size, but have a lighter construction, which makes them more comfortable during long recording sessions or concerts. Semi-hollow body guitars are more difficult instruments to make than solid-body guitars. These are guitars for the people with developed musical taste, i.e. for guitarists who do not play all types of music [20].

Solid-body electric guitars (collectively called full-body) are commonly associated with rock and metal sounds. The body construction provides a powerful sound and long-lasting sustain, which allows for a wide range of sounds. These types of guitars are also valued for their stability and durability, making them an ideal choice for concert and studio musicians. Their solid construction provides excellent sound transmission and minimizes problems with "feedback," or uncontrolled feedback, allowing for a clean sound even at high volumes. These guitars are also relatively easy to repair and maintain, making them an excellent choice for those just starting out with electric guitars [10].

The soundboard or body has an indirect influence on the vibration of the strings, which affects the timbre of the sound. There are known designs in which the front plate is not loaded, leading to the acoustic sound of an electric guitar. Another factor influencing the timbre and pitch is the type and thickness of the strings. The thinner the string, the higher the tone and vice versa.

The aim of the study was to determine the differences between the presented instruments, analyze their sound and vibration characteristics, and gain insights to optimize the measurement process for future experiments.

MATERIALS AND METHODS

Preparation of research objects

Two electric guitars were tested: a laminated semi-hollow and a gravity-cast solid-body, both featuring bodies made from carbon-epoxy composites.

The choice of carbon fiber and the techniques of laminating and casting for the construction of electric guitar bodies is based on the unique properties of this material and the advantages of its processing methods. Carbon fiber is exceptionally durable and resistant to environmental changes, such as temperature and humidity, making it an excellent alternative to traditional materials like wood. The laminating technique allows for the creation of a body that is both lightweight and highly durable, ensuring the stability and longevity of an instrument. Moreover, research has shown that the use of carbon fiber provides surprisingly good acoustic properties, making it an intriguing option for electric guitar construction. The sound and tone of a carbon fiber guitar are louder and more resonant than those of a wooden guitar. This allows musicians to have better control over all notes. The material directly influences sound quality, which is confirmed in this context. In wooden guitars, the sound is often more muted, and when trying to produce higher notes, it can sometimes break or become less clear. An additional advantage of carbon fiber is its aesthetic appeal – the distinctive weave pattern of the fabric, preserved with resin, gives the instrument a modern, carbon-inspired style that impresses with its precision and unique appearance. Unlike wood, the grain of which varies and is susceptible to external factors, carbon fiber maintains its structure and appearance for many years, offering a fresh perspective in guitar design.

The guitar bodies were fabricated using a folded, custom-designed mold created in Autodesk Inventor Professional 2022 and milled from fine-grained MDF. The guitar components (e.g., neck, bridge, etc.) were commercially sourced. The general construction of the electric guitar is illustrated in the diagram shown in Figure 1.

For the production of guitars, the LG 420 FR epoxy resin was used in combination with the HG 400 hardener. This particular resin system was chosen due to its excellent mechanical properties, high durability, and fire resistance, which enhances the safety and longevity of the instrument. Additionally, LG 420 FR provides outstanding adhesion to carbon fiber, ensuring a strong and stable composite structure. The combination with HG 400 hardener allows for optimal curing characteristics, resulting in a rigid, yet slightly flexible final product, which contributes to better vibration transfer and, consequently, improved acoustic performance. Furthermore, this resin system demonstrates excellent resistance to environmental factors, such as humidity and temperature fluctuations, ensuring the guitar remains structurally stable and sonically consistent over time. The components were mixed in a weight ratio of 100:30. The relevant parameters are listed in Table 1.

The semi-hollow guitar utilized a 240 g/m² carbon fabric (GRM Systems sp. z o.o., Olomouc, Czech Republic) with a plain weave as reinforcement (4 layers). The outer layer consisted of a 240 g/m² carbon fabric with red aluminum threads, also in a plain weave (1 layer). The beam was fabricated through gravity casting using an epoxy composite reinforced with 3 mm cut carbon fibers (GRM Systems s.r.o., Olomouc, Czech Republic).

This proposed construction was designed to enhance the resonance of an instrument and minimize feedback, while the combination of a maple neck and an epoxy-carbon body ensures a loud, resonant sound. The result is a distinctive tonal

Figure 1. General scheme of an electric guitar

Table1. Resin and hardener system parameters

Properties	Units	LG420HR	HG400
Density	g/cm^3	1.18–1.23	0.94
Viscosity	mPa.s	600-900	20–30
Epoxy equivalent	mol/1kg	156–165	
Epoxy index	-	0.60–0.64	
Amina number	Mg KOH/g	-	480–550
Properties of matrix			
Gel time	hours	3–5	
Flexural strength	MPa	110–120	
Flexural modulus	MPa	2700–3300	
Tensile strength	MPa	65–75	
Compressive strength	MPa	120-140	
Elongation	%	6–8	
Shore hardness D	oSh D	85	

quality that sets it apart from solid-body constructions. The semi-hollow guitar was manufactured through vacuum-assisted lamination (Fig. 2).

The finished semi-hollow guitar with all required components installed is shown in Figure 3. The solid or full-body guitar was fabricated using gravity casting with an epoxy resin reinforced with 3 mm cut carbon fibers (GRM Systems s.r.o., Olomouc, Czech Republic). The cut carbon fibers constituted 30% of the

a) b) c)

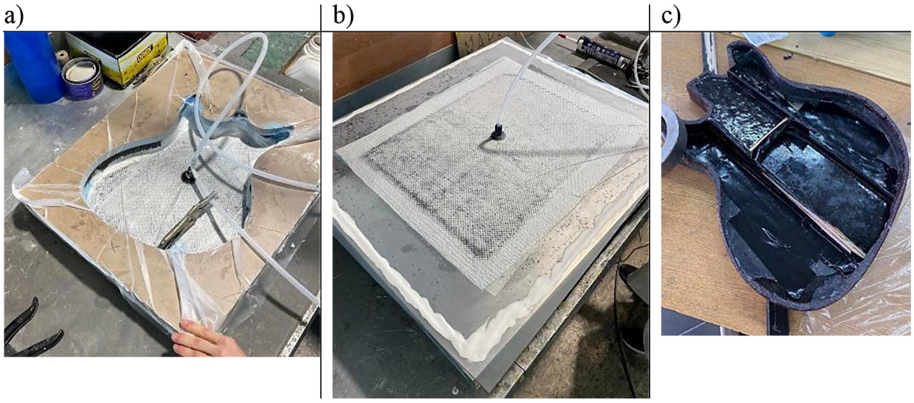

Figure 2. Manufacturing process of a) sound box, b) closing plate; c) beam

Figure 3. Semi-hollow body electric guitar

composite by weight. The guitar body was cast using the same mold as the semi-hollow body guitar. Figure 3, 4 illustrates the manufacturing process, while Figure 5 shows the completed solid-body guitar.

The body of stringed instruments plays a crucial role in sound amplification and has a significant impact its tonal qualities, influenced by both the body shape and the material used in its construction. To protect the guitars from environmental effects, the body is coated with a UV-resistant, two-component transparent polyurethane varnish.

RESEARCH METHODS

The tests were conducted in an acoustic chamber at the Vibroacoustic Laboratory, Institute of Fundamentals of Machine Construction, Warsaw University of Technology. The objective of the research was to determine the influence of the structure and materials body used on selected acoustic characteristics. As part of the work, the sound spectrum of the tested instruments was analyzed. The research was performed without the use of compression or other sound pre-processing techniques. The attack envelope speed (ATTACK) graphs for both guitars were compared. Observations of the sound propagation graphs revealed no significant differences in the signals produced by the tested instruments.

Numerous features of sound waves have been mathematically described, such as wave speed on a stretched string, wave energy and power, and wave interference. However, for stringed instruments like guitars, the materials and shape of the body are as important as the sound itself. The study involved stimulating the strings of the tested instruments using a repeatable mechanism, followed by recording the length of the sound wave, its propagation, and decay. The main aim of the of the research was to measure the vibrations of each guitar body, i.e. the response to stimulation caused by plucking the string.

a) b)

Figure 4. Manufacturing of a solid-body guitar a) casting the guitar; b) milling

Figure 5. Solid-body electric guitar

The measurement setup included the following components: a Fender Blues Junior Tweed tube guitar amplifier, a B&K LAN XI 3160 A042 measurement module with analog-to-digital converter, and a disk array.

The signals were captured using Bruel and Kjaer BK Connect software, and the preliminary analysis was performed in the MATLAB environment. The following equipment was used for signal recording: a B&K type 4958 microphone (to measure sound over the strings), a B&K type 4189 A-021 microphone (to measure sound at the amplifier), a B&K type 4508 accelerometer (to measure vertical vibrations), and a B&K type 4507 accelerometer (to measure longitudinal vibrations).

The measurements were conducted in an anechoic chamber to ensure consistent conditions across all measurements and eliminate unwanted environmental noise. The guitar being tested was secured in a dedicated stand designed specifically for accurate measurements. The stand held the instrument stationary throughout the procedure, allowing for the attachment of a custom-designed arm to simulate the string. To measure vibration of the top plate, the holder was designed to avoid contact with the upper part of the guitar. Instead, a custom stand was developed to secure the instrument by gently clamping its sides.

An automated string simulation mechanism was created to achieve consistent and repeatable string plucking during measurement. A guitar pick was attached to the arm, mimicking the motion of a human hand plucking the string. Figure 6 shows the measurement setup, including the visible arm used to simulate the strings.

The distance between the microphone and the string during the measurement was maintained at 5 mm. This was the minimum safe distance to ensure that neither the device inducing string vibrations nor the string itself made contact with the microphone head. The microphone was positioned as close as possible to the strings to minimize potential interference from external sources.

The microphone used specifically designed for precise free-field measurements, suitable for the conditions requiring a highly sensitive instrument. Additionally, an accelerometer was placed on the bridge, adjacent to the excited string. Since the bridge transmits string vibrations to the guitar body, the oscillations at this location are expected to be more pronounced than those on the soundboard.

Figure 7 presents a schematic diagram of the measuring system's arrangement during signal recording. The program used captured 30-second audio files and accelerometer data of the same duration. This duration was chosen to ensure the recording included the sound decay phase. A set of signals was recorded from two composite electric guitars and one wooden guitar, which served as a reference. Each guitar was tested three times to minimize irregularities during recording and to average the measurement results.

The preparation measurement points were appropriately planned. Measuring sound just above the string allowed the response of the guitar itself to be assessed after excitation. Similarly,

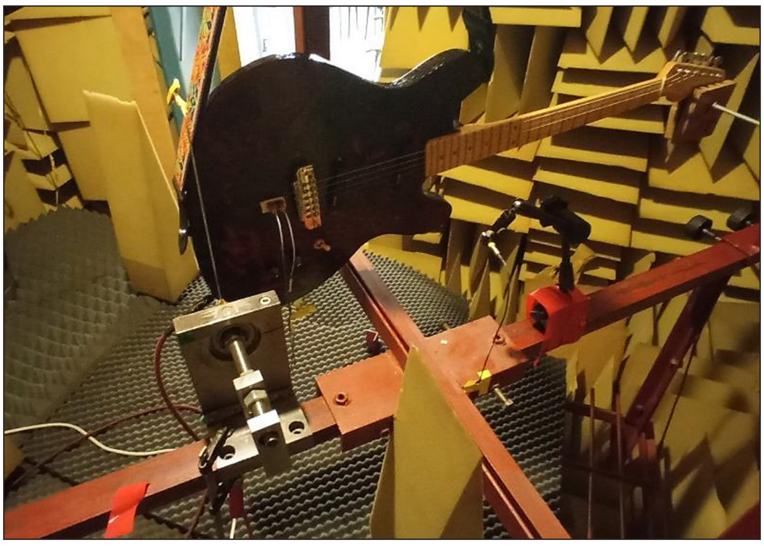

Figure 6. View of the research station

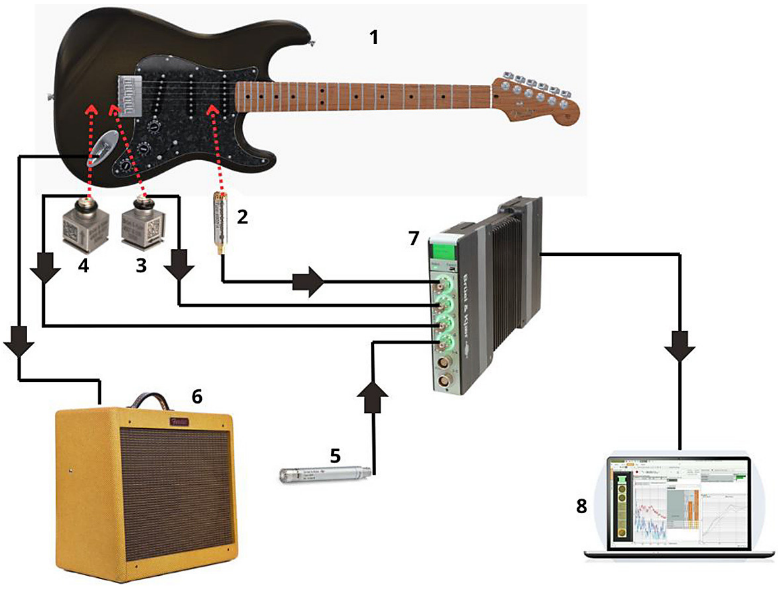

Figure 7. Scheme of arrangement of the elements of the measurement system: 1 – electric guitar, 2 – B&K type 4958 microphone, 3 – B&K type 4507 accelerometer, 4 – B&K type 4508 accelerometer, 5 – B&K type 4189 A-021 microphone, 6 - guitar amplifier, 7 – B&K LAN XI BK Connect and MATLAB 3160 A042, 8 – PC with installed BK Connect software

measuring the signal just before the amplifier speaker, under identical settings, ensured reproducibility of results. Although the amplifier slightly distorts the instrument signal, maintaining consistent EQ settings minimizes its impact on the comparative analysis of the instruments. The measurements of longitudinal and transverse vibrations on the instrument bodies aimed to evaluate how the body vibrates in response to string excitation. This approach provided additional insights into the physical behavior of the instruments under test conditions.

RESULTS

When comparing the response characteristics of the strings on both guitars, it can be observed that the sound level of the strings on the solid-body guitar (Fig. 8, blue line) is higher than that of the semi-hollow guitar across the entire range of analyzed electric guitar frequencies (Fig. 8, red line).

Since the semi-hollow guitar has a small resonance chamber, the expected result should be the opposite. However, given identical measurement conditions and string excitation, it can be concluded that the nature of these variations and the sound level values for each guitar directly result from the construction of their bodies and their resonance properties, favoring the solid-body guitar.

By analyzing the acceleration spectrum of transverse vibrations for both instruments, it can be stated that the solid-body guitar (Fig. 9, blue line) exhibits greater body resonance across almost the entire frequency range. In the semi-hollow guitar (Fig. 9, red line), the damping rate of vibrations is significantly higher, and its disrupted waveform, characterized by multiple harmonics at various frequencies compared to the solid-body guitar, results from the structural characteristics of the examined instrument—primarily the construction of the body as well as the resonance of individual hardware components.

This observation aligns with the impressions of the musician testing these instruments before the measurements began. Contrary to initial expectations, the guitar with a solid body exhibited better resonance. The fretboards of the guitars used in the preliminary tests were made of different materials: maple (solid-body guitar) and rosewood (semi-hollow guitar), meaning their resonance properties were not solely dependent on the body parameters.

In the future, the authors plan to repeat the study, taking into account the experience gained during this experiment. This time, they intend to use identical and detachable electronic hardware, string mounting in the body, and necks that can be

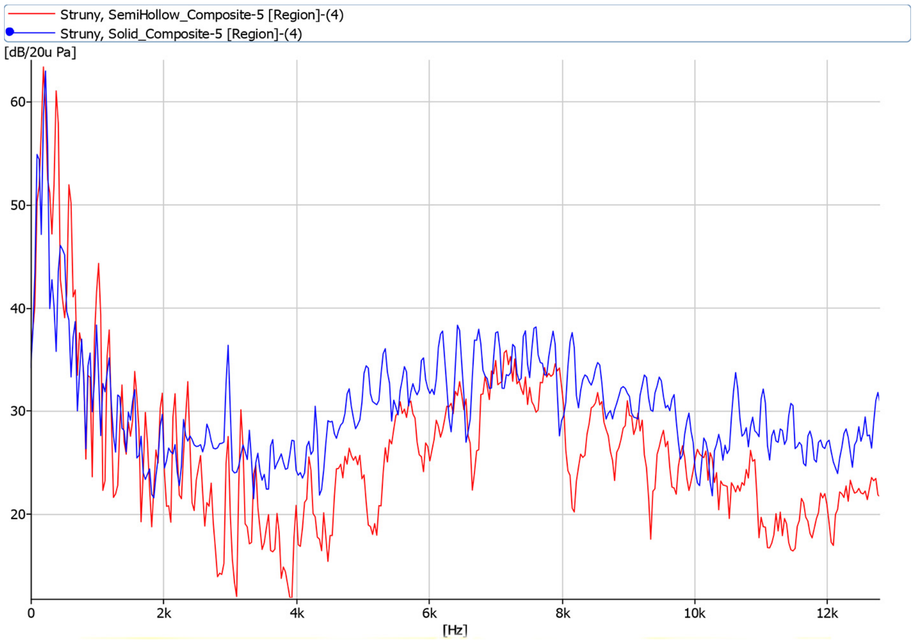

Figure 8. Comparison of strings responses between semi-hollow and solid-body electric guitars

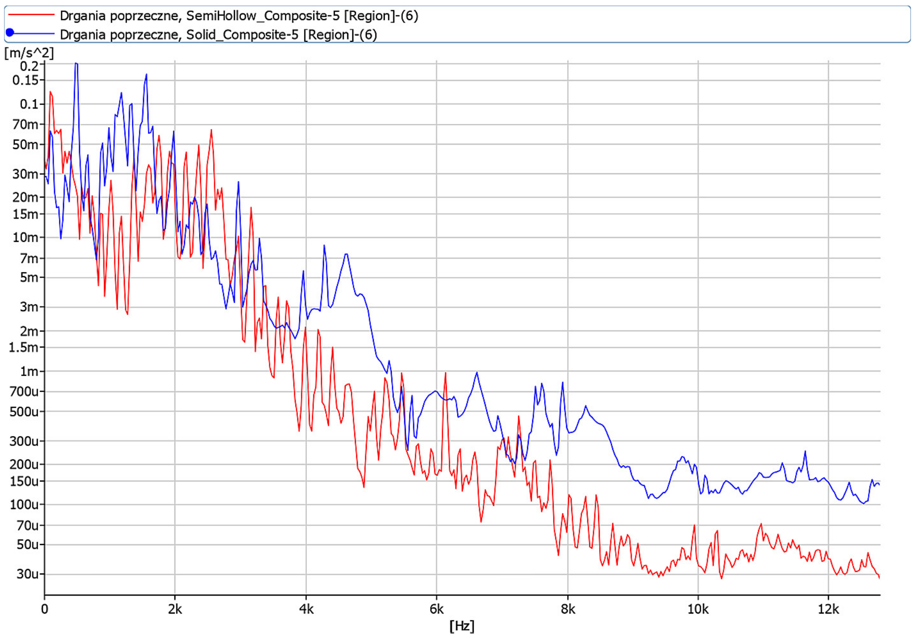

Figure 9. Comparison of transverse vibrations of semi-hollow and solid-body electric guitars

transferred from one instrument to another during measurements. This approach aims to isolate the influence of the body properties from other instrument components.

When analyzing the longitudinal vibration patterns of the instrument bodies, it can be observed that at low frequencies, greater vibrations occur in the semi-hollow guitar (Fig. 10, red line). Above 4000 Hz, the vibrations of the solid-body guitar (blue line) exceed those of the semi-hollow guitar, for which, similar to transverse vibrations, they decay more quickly.

When comparing the response spectra of the strings in a semi-hollow guitar (Fig. 11) and a solid-body guitar (Fig. 12), significant differences can be observed. The sound levels at frequencies around 500 Hz are similar, but for the range of approximately 1000–1500 Hz, the sound levels of the solid-body guitar for these frequencies fluctuate around 60 dB(A). The

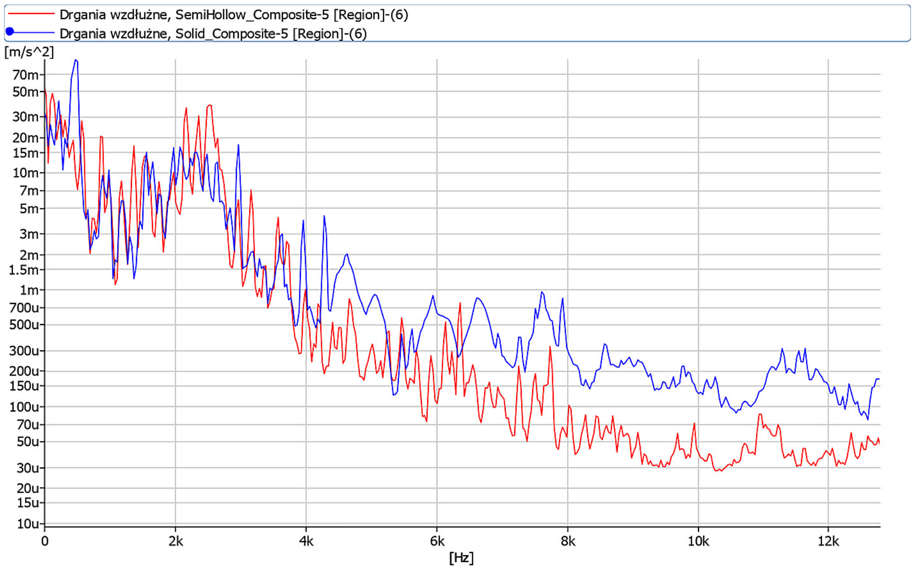

Figure 10. Longitudinal vibrations of semi-hollow and solid-body electric guitars

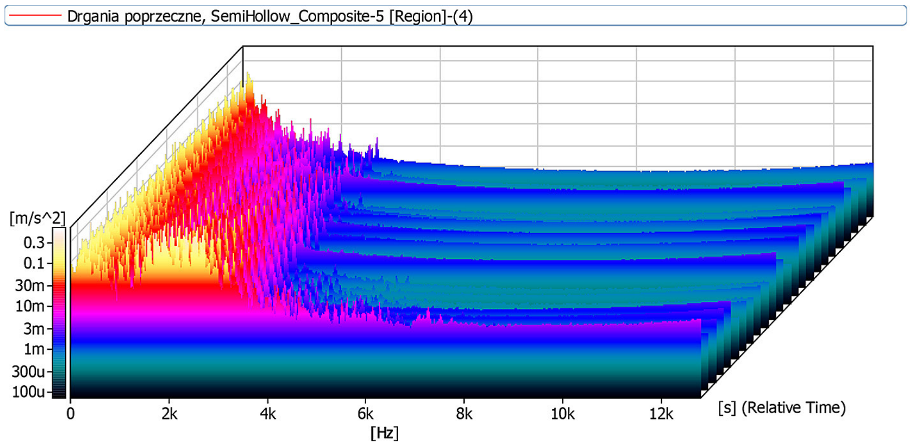

Figure 11. Transverse vibrations autospectrum for the composite semi-hollow electric guitar

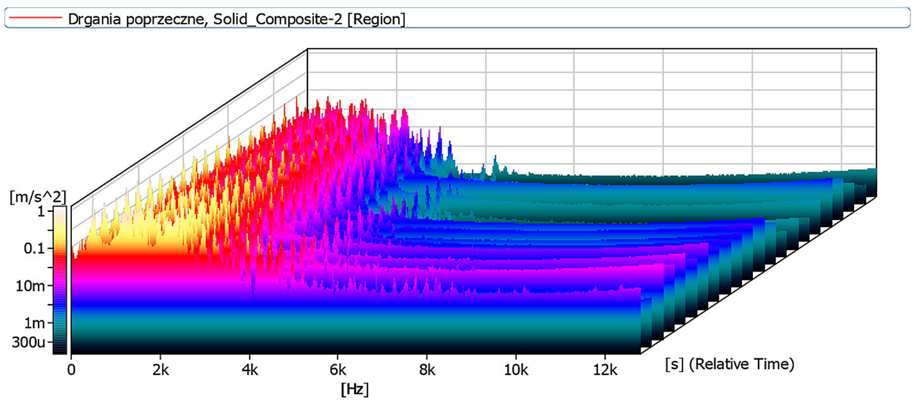

Figure 12. Transverse vibrations autospectrum for the composite solid-body electric guitar

most notable differences can be seen in the 2–4 kHz range, where the semi-hollow guitar attenuates frequencies at 2600 Hz and 3700 Hz, whereas the solid-body guitar amplifies these frequencies. Similarly, frequencies around 5 kHz are amplified by the solid-body guitar while being attenuated in the semi-hollow guitar. The solid-body guitar also amplifies the

10–12 kHz frequency range significantly better than the semi-hollow guitar. On the other hand, the semi-hollow guitar enhances frequencies around 1800 Hz and 7 kHz.

Observing the spectral waveforms for the solid-body guitar (both the acoustic signal from the microphone above the strings and the vibration signal from the body), a beating effect appears in the signal after a short period of time. This effect is most noticeable in the acoustic signal waveform shown in Figure 16. It was observed as the amplitude of individual frequencies

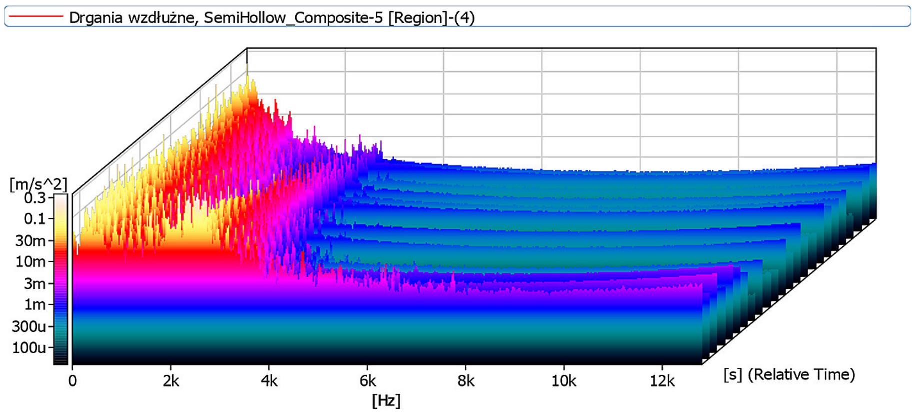

Figure 13. Longitudinal vibrations autospectrum for the composite semi-hollow electric guitar

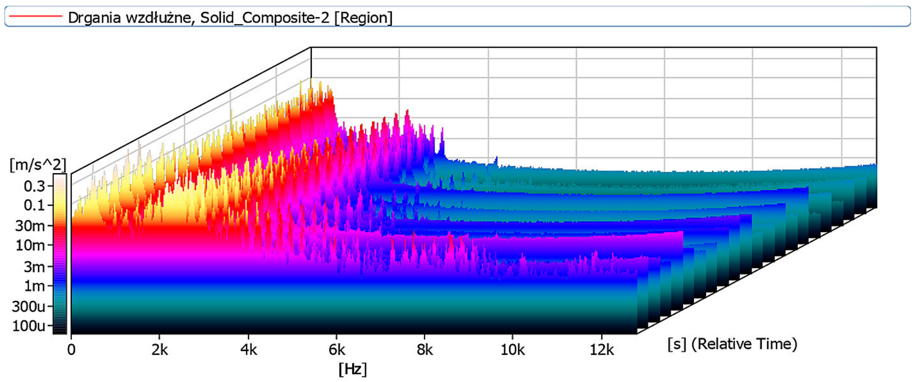

Figure 14. Longitudinal vibrations autospectrum for the composite solid-body electric guitar

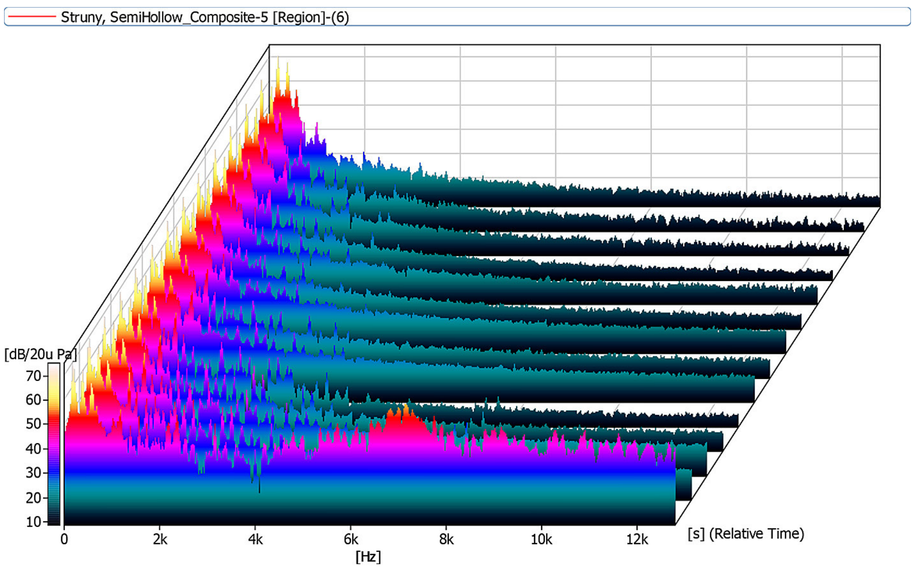

Figure 15. Strings response autospectrum of the semi-hollow electric guitar

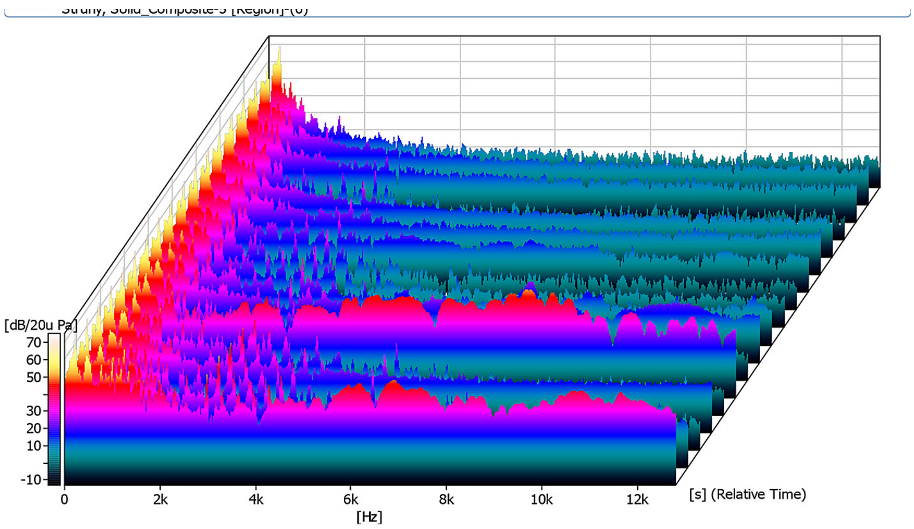

Figure 16. Strings response autospectrum of the solid-body electric guitar

diminished, and the fact that it occurs only in this type of guitar is directly related to the instrument construction. A similar delayed excitation can be seen in the vibration signal of the solid-body guitar (Fig. 12 and Fig. 14), whereas in the semi-hollow guitar (Fig. 11 and Fig. 13), a more uniform decay of vibrations in both planes can be observed.

It should be noted that during the tests, all strings were simultaneously excited to induce maximum body vibrations and replicate the actual conditions of stage performance. Each string was tuned accurately using a guitar tuner, with a standardized tuning to the reference note A at a frequency of 440 Hz. This standard ensures that even if the specific tuning (e.g., E-A-D-G-B-E for standard guitars) does not include the note A at 440 Hz, it will still appear as a higher-order harmonic component. For example, in the case of the tested instruments tuned to the standard pattern, the note A5 (where "5" indicates the fifth string, counting from the first and thinnest) has a fundamental frequency of f_{A5} = 110 Hz. In this context, f = 440 Hz represents the fourth harmonic for the A sound.

All of signals were analyzed in BK Connect software that allows the authors to extract only the desired window of signal decreasing the impact of signal noise.

CONCLUSIONS

The primary conclusion from the experiment and analysis of the results is that both the solid-body guitar and the semi-hollow guitar (with a reduced soundbox) are distinct instruments not only in appearance but also in sound. These differences stem directly from their respective construction and production technologies. However, based on the study of only two composite guitars and one wooden reference guitar, it is challenging to establish a clear metric for determining how to modify the materials or structure of the composite to achieve a "better" sound. The concept of "better" is inherently subjective; preferences vary among musicians. For instance, one musician might favor a guitar with "more bottom" – a sound spectrum dominated by lower frequencies, as seen in the solid-body guitar. In contrast, another might prefer the sound of a hollow-body guitar, appreciating how "the soundbox influences the overall tone".

Based on the conducted research, it is difficult to determine the cause of this behavior in the guitar bodies, where the solid-body guitar exhibits a beating effect, manifesting as a delayed excitation of a frequency band, while the guitar with a reduced resonance chamber does not. In the next article, an extended study will be presented, featuring precise signal acquisition and current measurement from the electrical circuit instead of measuring acoustic pressure in front of the amplifier. To determine whether the observed phenomenon is influenced by the guitar body itself or another component, the experiments should be repeated while incorporating the insights gained from this study.

It can be affirmed that instruments differ from one another. However, the measurements conducted thus far do not provide definitive insights into how the choice of body material and construction method impacts the overall sound. This underscores the need for continued research with enhanced measurement techniques.

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