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Review

Review of Manufacturing Processes and Vibro-Acoustic Assessments of Composite and Alternative Materials for Musical Instruments

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Abstract: The evolution of musical instrument manufacturing has prompted a quest for innovative materials beyond traditional wood. This review explores the utilization of composite materials, 3D-printed materials, and metamaterials as favorable alternatives. The investigation is driven by challenges such as the scarcity of high-quality tonewoods, variations in wood properties, and environmental concerns. Carbon fiber, graphite fiber, ceramic polymers, and nanocomposites present promising alternatives, offering advantages in durability, weight reduction, and customizable acoustics. The integration of 3D printing technology introduces a cutting-edge dimension, enabling intricate, precisely engineered components, optimizing instrument structure, and allowing unprecedented customization. Additionally, this article explores metamaterials, leveraging unique mechanical properties from structural design rather than constituent materials. Metamaterials offer unprecedented capabilities for tailoring instrument vibrational characteristics by providing unparalleled control over sound production. The review provides a thorough analysis, including manufacturing methods for composite materials, metamaterials, and 3D printing in musical instruments. Comprehensive examinations of vibrational and acoustical analyses related to composite materials, 3D-printed materials, and metamaterials, for the evaluation of musical instruments, are presented. This overview, supported by experimental and numerical simulation methods, offers valuable insights for the future development of musical instruments.

Keywords: composite materials; 3D printing technology; metamaterials; manufacturing; vibro-acoustics

1. Introduction

The evolution of musical instrument manufacturing has been a dynamic process, with traditional materials such as wood playing a predominant role for centuries [1,2]. However, the need for innovation in the musical industry has driven researchers and manufacturers to explore alternative materials that offer enhanced performance, sustainability, and versatility. This review article presents the prospects of composite materials, 3D-printed materials, and metamaterials as promising alternatives to conventional wood in the production of musical instruments.

The demand for different materials arises from various challenges faced by the musical instruments industry, including the lack of high-quality tonewoods, the significant variations in both mechanical and acoustical properties of wood internally within a single piece or across the same species [3], environmental concerns, and the quest for achieving specific acoustic properties. Composite materials [4], such as carbon- and graphite fiber-reinforced plastics (CFRPs and GFRPs), ceramic polymers, and nanocomposites, constitute promising alternatives that not only address these challenges, but also offer unique advantages in terms of durability, weight reduction, and customizable acoustic characteristics. CFRPs and GFRPs exhibit exceptional strength-to-weight ratios, leading to instruments with increased durability without compromising on tonal quality. CFRPs, GFRPs, ceramic polymers and nanocomposites offer the potential for finely tuned acoustics, enabling the customization of instruments to meet the preferences of musicians and the demands of different musical genres.

In this work, the integration of 3D printing technology in instrument manufacturing [5] is explored as a cutting-edge approach to creating intricate and precisely engineered components. The ability to design and produce complex geometries with 3D printing not only facilitates the optimization of the instrument structure for enhanced acoustics, but also enables a level of customization previously unattainable with traditional methods.

Moreover, this article delves into the concept of metamaterials [6], which possess unique acoustic/mechanical properties derived from their structural design rather than the properties of the constituent materials. The exploration of metamaterials in musical instrument manufacturing opens new avenues for tailoring the vibrational characteristics of instruments, offering unprecedented control over sound production. In this regard, a novel method to experimentally evaluate the transmitted sound from metamaterial structures is presented.

Considering the dynamic evolution within musical instrument manufacturing, this study seeks to address specific gaps in the existing literature and shed light on key aspects related to manufacturing processes, vibroacoustic assessments, and material choices. The primary objectives of this review are to explore recent advancements, challenges, and opportunities in the utilization of composite materials, 3D-printed materials, and metamaterials for musical instrument manufacturing. A thorough analysis covering manufacturing methods for composite materials used in musical instruments is presented. This also encompasses an exploration of manufacturing techniques for metamaterials and the application of 3D printing technology in the musical instruments industry. Additionally, a comprehensive examination of vibrational and acoustical analyses related to the use of composite materials in musical instruments is conducted. Studies in the literature that concern the vibro-acoustic properties of 3D-printed musical instruments and metamaterials used in musical instruments is also presented, with a detailed description of these phenomena supported by both experimental methods and numerical simulations. This work aims to provide a detailed review of the current state of research in these innovative areas, offering valuable insights for the future of musical instrument design, manufacturing and production.

2. Manufacturing Processes of Musical Instruments Made of Composites and Alternative Materials

The four types of manufacturing processes are casting–molding, machining, joining, and shearing–forming [7]. For the development of musical instruments, the choice of manufacturing methods to be applied depends on the specific requirements of the instrument and the materials involved. To craft an object from a malleable material that initially exists in a fluid, formless, or dissimilar shape from the desired final product, the technique of molding is employed. The mold is necessary for the transition of the bulk material to the final solid state of the object. Molding stands as a primary manufacturing process employed in the manufacturing of solid objects using composite materials. The technique involves shaping and forming composite materials within a mold, allowing them to take on the desired structure and configuration. By utilizing molding, manufacturers can achieve precise and consistent shapes, making it a crucial method for crafting solid objects from composite materials. Machining processes involve removing material from a workpiece to achieve the desired shape. Computer Numerical Control (CNC) machining is commonly used for high-precision instrument making [8]. Milling, turning, and grinding are examples of machining processes suitable for instruments that require precision and fine details. Joining is crucial for assembling different components of an instrument and involves connecting two or more parts to create a complete instrument. Welding, brazing, soldering, and adhesive bonding are common joining methods. Shearing involves cutting or trimming material, and forming involves shaping materials, and thus is suitable for producing components or casings of instruments. Traditionally, instrument making involves shearing to cut sheets of wood into the desired shapes, while forming is typically accomplished using steam to shape the curved and thin components of the instruments.

Engineering tools play a pivotal role in the manufacturing process of musical instruments, ensuring precision, repeatability, and efficient record-keeping. Various computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided engineering (CAE), and reverse engineering tools are integral, either used independently or interconnected based on the available software and hardware [9]. CAD is employed by designers to digitally create the final object and generate detailed drawings of the tools required at each stage of the manufacturing process. CAM programs then produce machine-readable codes for automated machines involved in manufacturing. CAE tools calculate crucial parameters, aiding in the optimization of object design or production processes. This step ensures that the final product meets required specifications. Reverse engineering is a process focused on studying parts to understand how they were made, allowing for recreation or documentation. A non-destructive method involves 3D scanning, where the points of an object are digitally recorded, creating a detailed point cloud from the measurements.

2.1. Composites in Musical Instrument Manufacturing

A composite material is a combination of two or more materials with distinctly different chemical or physical characteristics. Together, they create a new material with enhanced properties and characteristics that neither material can provide on its own [10]. In most composites, one material serves as the matrix, maintaining the shape of the manufacturing and transferring forces to the reinforcement.

The main families of materials are ceramic, organic, and metal. Matrices and reinforcements may be derived from each family, and the creation of a composite material can result from any combination of them. Composites may be categorized based on the matrix or the reinforcement [11]. The widely used matrix category in boats, cars, airplanes, bicycles, instruments, and others, is the organic matrix, specifically the polymer matrix. The main categories of composite reinforcements [11], according to their form, are fiber, particle, and structural reinforcement. Reinforcement-oriented characterizations of a composite, such as CFRPs, GFRPs, flex filament, hemp fibers, and others, or matrix-oriented characterizations like fiber-reinforced polyurethane foam (FRUF) and fiber-reinforced epoxy, can generally describe a composite. It is common to define both materials in the description of a composite, especially in the case of a rare combination like carbon-reinforced polyurethane foam (CF/UF). Carbon Fiber (CF) usually has an epoxy resin matrix, and polyester usually has glass fiber reinforcement [11]. Complex composites, such as “sandwich”, a subcategory of structural reinforced composites [11], can be created from the combination of composites and other materials. In the literature, studies can be found where violins were made from CFRP [12,13]. Soundboards were crafted from glass and carbon fiber-reinforced polyurethane foam [14], as well as from carbon fiber-reinforced synthetic wood [15]. A drum shell [16] and a cello [17,18] were manufactured by carbon fiber-reinforced epoxy (CFRE). Various musical instruments made from CFRE, including violin, viola, cello [19], guitar, bass, ukulele [20], snare drum [21], and piano [22], are commercially available. Furthermore, in the manufacture of a traditional stringed Greek bouzouki [23], CFRE on the top and bottom skin, with a core of polyurethane foam in between was considered. The variety of composites is endless and therefore this study gradually focusses on the most used in the musical instrument manufacturing, such as fiber-reinforced polymer matrices.

The main form of fiber reinforcements consists of plain fibers without any weave. The most common form of reinforcement in fiber-reinforced composites is fabric, which is created from these fibers. Non-woven fabrics [24] consist of layers of fibers usually sewn with an elastic thin thread in a specific direction, such as unidirectional (UD), biaxial, quadraxial, etc. Woven fabrics [25] can be plain, twill, or more complex in their weave pattern. Polymer matrices are divided into two main categories: thermosets and thermoplastics. Thermoplastics typically undergo numerous state transition cycles (solid to liquid) through warming, with this process having a limited impact on their mechanical properties. Thermoplastics find extensive use in mass-produced items; however, their application as a composite matrix in instrument making is limited [26]. In contrast, thermoset matrices solidify during a curing process and cannot be liquefied again. The curing cycle defines the glass transition temperature, Tg, of a thermoset matrix, representing the temperature at which it remains in a solid state without undergoing plastic deformation while retaining its mechanical properties. Thermoset matrices generally exhibit superior mechanical properties compared to thermoplastics. In the realm of instrument making, many instruments described in the literature are manufactured using thermoset polymers, such as epoxy resin [16–18]. The manufacturing process for musical instruments made from fiber-reinforced thermoset polymer matrix materials typically initiates with mold preparation [27–30]. A mold is commonly made from aluminum alloys, and frequently manufactured using automated CNC machines [3,23,28]. Another common approach used in instrument making is the use of composite molds [17].

Basic types of manufacturing processes for musical instruments are open and closed molding. Open molding produces objects with an exposed surface, such as the soundboard of a stringed instrument [3]. On the other hand, closed molding produces objects with a closed surface in at least one direction (of the surface), as seen in the manufacturing of instruments like drums [16,29]. The means of manufacturing and the lay-up process determine the design of the mold. Lay-up [31] is the manufacturing process of a composite product on a mold, typically performed layer by layer on the mold's surface by reinforcement fabrics. Several crucial parameters influence the lay-up process, including the type, the direction and inclination of fabrics and the chosen types, the area and the sequence covered by each layer. The choice of these parameters determines the mechanical properties of the lay-up. For instance, a specimen with a lay-up of UD0/twill/twill/UD0 may exhibit a significantly different bending behavior in the zero-degree direction compared to a lay-up of twill/UD0/UD0/twill. In the former, the UD is in the tensioning–compressing sides, while in the latter, it is closer to the bending neutral line.

Hand lay-up is a common method in polyester parts, which lacks a debulking process but involves a hand roller to press the layers onto the mold surface, and ultimately yields suboptimal mechanical properties in the final product. The matrix impregnation is a pivotal factor in the manufacturing process of musical instruments, which achieves high quality results when prepreg materials are facilitated. Prepregs consist of reinforcement fabrics pre-impregnated with the matrix, remaining in a non-cured state. They find extensive usage in instruments manufacturing [3,4,16,28,32]. The vacuum-assisted resin transfer molding (infusion or VARTM, a subcategory of RTM) [12,17,23], stands out as the second-best process for producing high-quality composite objects. Both prepreg and VARTM processes necessitate the use of vacuum bags for pressing the lamination onto the mold surfaces. The use of a vacuum bag in the lay-up process consistently results in parts with a favorable reinforcement-to-fabric ratio, while the trapped air in the layers is removed. In thermoplastic matrices the most common way of matrix infusion is the injection of the matrix on a closed mold. The easiest process of resin infusion is the manual deposition of it in the lamination, while the curing method for thermoset matrices is crucial. Some resins cure at room temperature, but high-quality resins often require specific cure cycles in ovens with specific rates of temperature rise and cooling [23,28]. Autoclaves [13,16,32] represent the most advanced version of ovens, providing controlled temperature and pressure conditions for an optimized curing process. Machining, joining, and shearing–forming follow for the manufacturing of every part and the assemble of the final instrument is completed. Figure 1 demonstrates the steps for the manufacturing of a violin top plate via a detailed lay-up procedure, while Figure 2 shows the lamination and VARTM processes during the manufacturing of a Greek bouzouki.

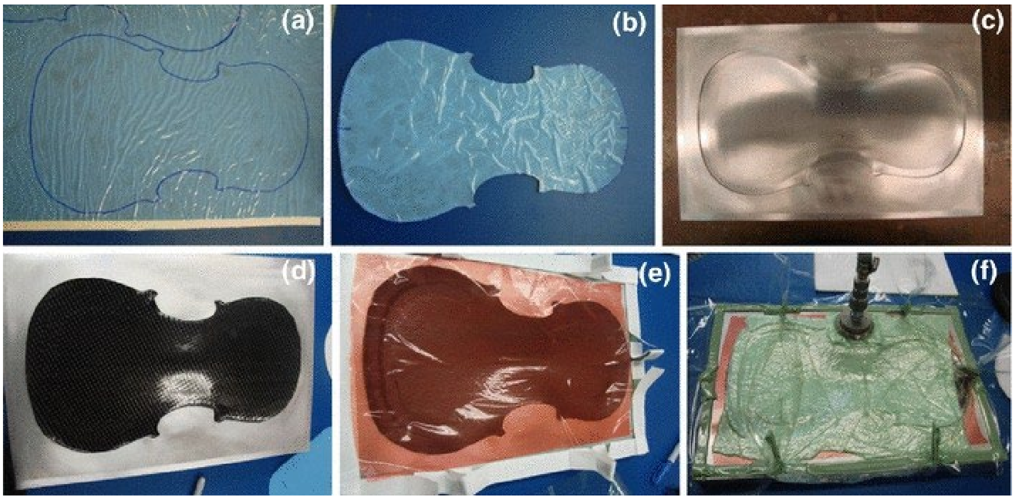


Figure 1. Development of a violin top plate. (**a**) Marked profile of the top plate on prepreg fabric with protective films, (**b**) cut preform of the prepreg, (**c**) treated female mold, (**d**) placement of the fabrics, (**e**) release film on top of the fibers to help the separation of the cured part from the breather and the vacuum bag, (**f**) vacuum bagging. Reprinted from [3] with permission from Spinger Nature. Copyright 2015 Springer Nature.

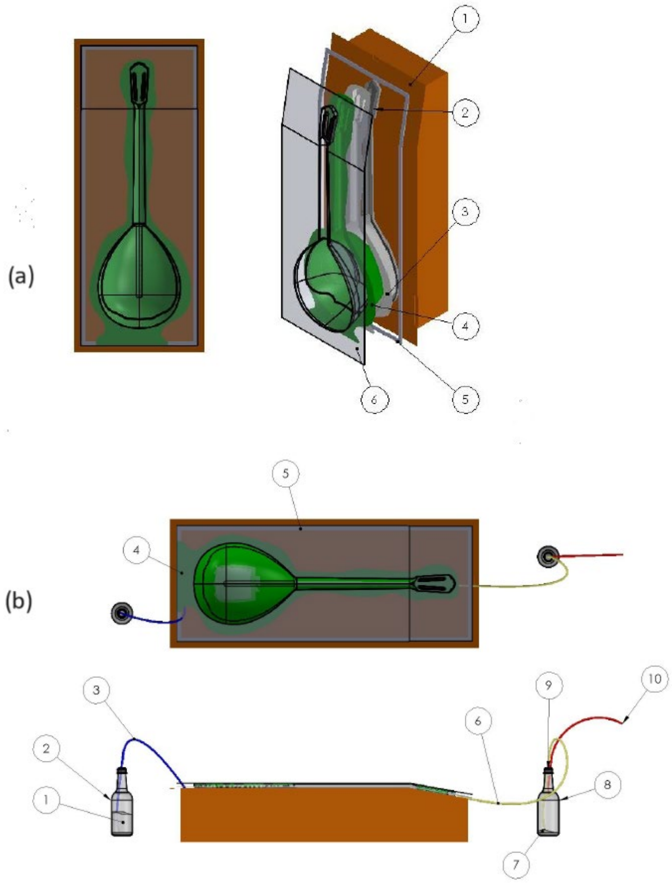


Figure 2. Manufacturing of a Greek bouzouki. (**a**) Lamination process: 1. Mold 2. Final composite lamination 3. Peel ply, expendable detachable fabric that helps to separate the cured composite from the other expendables 4. Green flow, net that helps the air to escape and the resin to infuse the lamination 5. Sealing tape 6. Vacuum bag. (**b**) VARTM process: 1. Resin, 2. Vessel that contains resin 3. Suction tube 4. Complete lamination with expendable materials 5. Sealing tape 6. Overflow resin tube 7. Excess resin 8. Resin trap 9. Sealing tap 10. Vacuum generator tube.

Representative research works in the literature highlight the variety, the advantages, and the machinability of composites, especially when used in musical instrument manufacturing. Ono et al. [15] proposed that carbon fiber-reinforced polyurethane foam (Uf) could serve as a viable replacement for spruce soundboards, contingent upon factors such as the direction of the UD carbon fiber layers, their lay-up stacking sequence, and the volume fraction of fibers to matrix. The manufacture of specimens with different lay-up procedures was described and a completed acoustic guitar with a soundboard made from carbon fiber-reinforced polyurethane foam was presented. The lay-up procedure and lamination stack were described as a symmetric lay-up of [0/90/Uf]s, where the 0 direction corresponds to the grain and the 90 is the cross direction. Acet et al. [33] manufactured a Turkish folk violin, Kemane, using glass fiber and carbon fiber composites with polyester resin, as an alternative to the traditional gourd manufacturing. Ibáñez-Arnal et al. [16] produced a drum shell using a carbon fiber-reinforced epoxy composite laminate. The shell, crafted with an autoclave method, involved the laying of three or more collinear plies. The autoclave process was crucial for eliminating voids generated during the curing process. The drum shell was manufactured using a GFRE mold with an epoxy-based coating finish. Damodaran et al. [29] produced the composite shell for an Indian drum using a sandwich structure. The drum shell consisted of a carbon fiber/epoxy face sheet and a balsa core to which the drumhead was attached. The shell structure was crafted through a combination of wet lay-up and vacuum molding techniques. Figure 3 demonstrates the detailed lay-up procedure and the sequence of manufacturing of the percussion instrument.

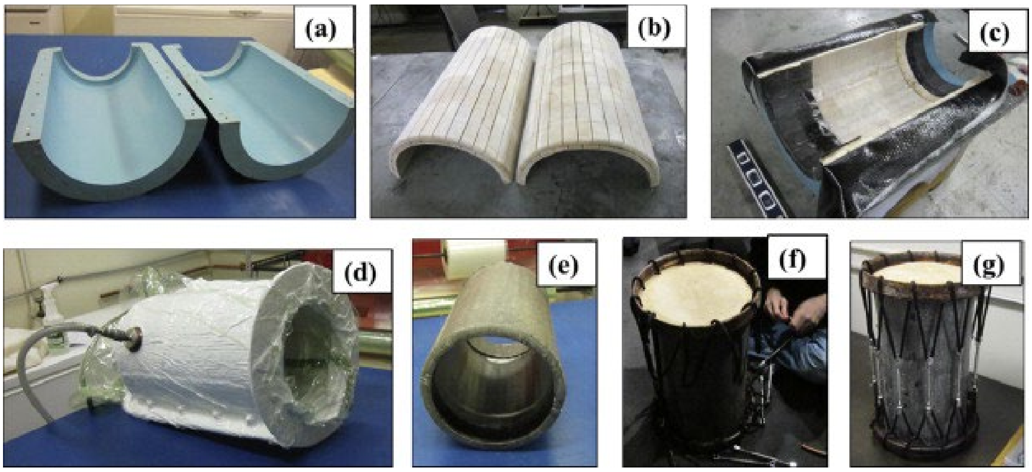


Figure 3. (**a**) Two-part mold; (**b**) prefabricated balsa core; (**c**) placement of carbon fiber; (**d**) vacuum bagging; (**e**) demolded part; (**f**) assembly of drumhead; (**g**) finished drum. Reprinted from [29] with permission from Elsevier. Copyright 2015 Elsevier.

Brezas et al. [23] described the manufacturing process of a carbon fiber bouzouki based on a 3D scan of a wooden bouzouki. They developed a 3D CAD surface model of the musical instrument using the point cloud generated by the 3D scan. The molds for each carbon fiber part were then manufactured by CNC machines based on the G-codes produced by CAM programs. These molds played a crucial role in creating the carbon fiber bouzouki parts, from which the final musical instrument was assembled. The carbon fiber parts underwent proper machining and surface finishing to ensure a precise fit and ease of proper assembly through gluing. The fabrication of carbon fiber fabric parts employed a vacuum-assisted resin transfer (infusion) process, involving specific temperature control and duration. The chosen raw fabrics included (a) 200 g/m^2 Twill, that reinforces the composite in two directions, and (b) 300 g/m^2 UD—providing strength in only one direction to the composite. Three corresponding top plates with slightly varying characteristics were manufactured, resulting in the assembly of three carbon fiber instruments (C01, C02, and C03). The manufacturing of the three top plates involved the use of Twill and UD carbon fiber layers in varying sequences and fiber directions. For comparison purposes, the bridge, and the supporting bars of the soundboard of C01 were made from spruce wood, following the manufacturing of the wooden bouzouki. In contrast, the bars of C02 and C03 were manufactured using UD carbon fibers as local reinforcement layers. Figure 4 shows a finalized carbon bouzouki.

Figure 4. Finalized carbon bouzouki. Reproduced under a Creative Commons Attribution 4.0 International License [23]. Copyright 2023, MDPI.

Duerinck et al. [12] designed and built six composite violins with top plates from different materials. They conducted two experiments with these instruments to examine how experienced listeners judged the timbre across a broad spectrum of possible qualities. The objective was to construct identically all violins except for the top plate, which was made from different materials. To achieve this goal, all prototype violins were crafted by the same luthier. For the back, sides, and neck, a CFRP produced by the VARTM was chosen, offering a quick and reliable way to produce these components in one piece. The soundboards were made from a selection of four composite materials and spruce, added as a reference material. The materials used for the creation of fiber-reinforced composite with the VARTM method included UDFlax: unidirectional flax fiber-reinforced polymer, UDC: unidirectional carbon fiber-reinforced polymer, TwillC: laminate of twill-woven and unidirectional carbon fiber-reinforced polymer, Sandwich: sandwich structure consisting of CFRP skin and an aramid honeycomb core. The TwillC violin was produced twice to check the consistency of the influence of the material and production methods on the sound of the violin. Altogether, these six prototypes exhibited a variety of material properties, including higher damping (UDFlax), different degrees of anisotropy (TwillC and UDC), and a low-weight soundboard (Sandwich). The violin with a soundboard from spruce served as a benchmark material. The reference spruce soundboard was carved by a luthier using templates that matched the arching of the composite plates. The soundboards were given a simplified sound hole design and fitted with a conventional spruce bass bar of high quality. The instruments were then assembled with a bridge, spruce soundpost, Wittner tailpiece, chinrest, fine-tune pegs, and strings. Figure 5 demonstrates the prototype violins.

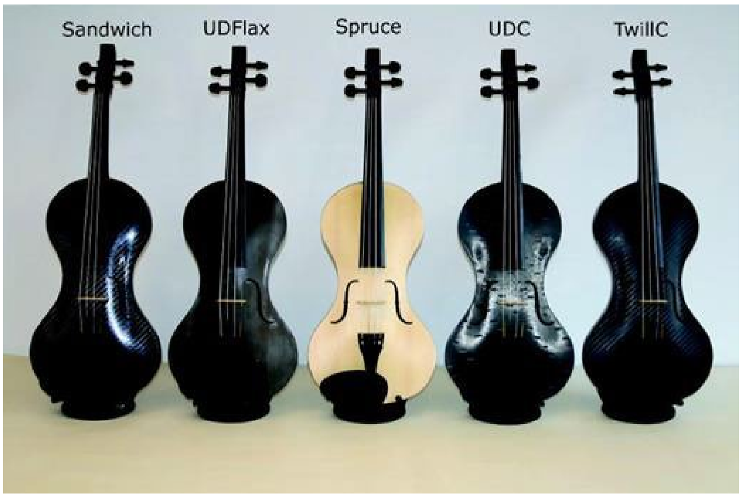


Figure 5. Prototype violins with soundboards from 5 different materials. Reprinted with permission from [12]. Copyright 2020, Acoustical Society of America.

Notable manufacturing processes and tooling were showcased by Phillips et al. [28]. They developed a flax-reinforced sandwich structure, designed to replace wood in the top plates of string musical instruments, particularly focusing on the ukulele. The mechanical properties of Sitka spruce served as a benchmark during the development of new materials. For the manufacturing process, a lay-up method with a two-part closed mold and an internal pressure bladder was employed, producing six prototype monocoque ukuleles. This monocoque design involved creating a single-piece composite object without joining methods, cured entirely in the same cycle. The study specifically considered flax, utilizing unidirectional (FUD-180) and woven (FFA-200) flax prepregs with fiber areal densities of 180 and 172 g/m^2, respectively. Balsa was selected for its low damping properties in a carbon fiber/balsa sandwich structure. The mold, consisting of two nested aluminum plates, was intentionally not sealed to allow resin bleeding during the process. Due to tooling costs, the focus was on developing a manufacturing process applicable to small musical instruments that could be adapted to string instruments of any size. A 3D CAD model, based on ukulele dimensions developed over the years, was created. Considerations for molding included incorporating three-degree draft angles in the vertical sides of the instrument. The two-part closed mold, featuring an internal pressure bladder (mandrel) and a foam core, was designed and CNC-machined out of aluminum 6061. The final step involved sanding and polishing to achieve a refined surface finish. In the development of the pressure bladder, experiments were conducted with both silicone and latex bladders, with the latter proving to be more durable and flexible. A total of six parts were manufactured, and improvements were made to the lay-up process along the way. The preforms were initially based on flat pattern features of the CAD model and were later adjusted to overlap and produce a hollow monocoque composite structure.

2.2. Three-Dimensional Printing in Musical Instrument Manufacturing

Three-dimensional printing technology, as an additive manufacturing process, revolutionizes traditional manufacturing processes by building three-dimensional objects layer by layer from digital models [34,35], allowing for the creation of intricate and complex structures with a high degree of precision. From rapid prototyping to custom manufacturing, 3D printing finds applications across various industries, offering efficiency, cost-effectiveness, and the ability to produce unique designs that may be challenging with conventional processes. The 3D printing process typically involves three fundamental steps. Firstly, a digital model of the physical object is created, by 3D scanning or conventional measurements and design methods, within a Computer-Aided Design (CAD) [36,37] system. The developed digital model serves as the blueprint for the 3D printer to follow. The model is sliced to thin layers, using horizontal cross-sectioning with the help of CAD slicing/editing software features. Each of the generated layers represents a cross-section of the final object and dictates the printing pathway layer by layer. The 3D printer deposits or solidifies the chosen material, whether it is plastic, metal, resin, or another substance, to build up the object following the pathway layer by layer, while manual modifications may be required, depending on the complexity of the printed part.

Over time, various 3D printing techniques have evolved [35,38], including Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM), Fused Filament Fabrication (FFF), and DLS (Digital Light Synthesis). SLA, the most common resin 3D printing process, constructs objects in a vat of liquid polymer. The liquid resin material is solidified into plastic as a computer-controlled laser beam follows a designated trajectory, heating the polymer. Gradually, the object is constructed layer by layer. SLS builds objects using the powder bed fusion process. In this process, a thin layer of powdered polymer is deposited onto the building platform. A laser or UV light fuses together all particles within the area of the first cross-section. After a layer is created, the platform is lowered, and the process is repeated, producing the object layer by layer. FDM is the most widely used process. It utilizes a thermoplastic filament heated to its melting point by a light source [39–41]. In DLS, mixed ultraviolet light and oxygen are used to continuously grow 3D parts from a small vat of liquid resin. The material cures during the printing process, resulting in a rigid polyurethane object. The claimed printing time is 25–100 times faster than traditional printers [41].

The materials used in 3D printing are thermoplastic filaments, such as polylactic acid (PLA), polymer powders (usually polyamide), polymer filaments (Polyethylene Terephthalate, PET), photopolymer powders, metal powders and others [42]. A significant challenge in the manufacture of 3D-printed musical instruments lies in the complexity of fabricating such intricate designs. This process demands advanced manufacturing skills and specific tools, typically available only in specialized workshops operated by highly trained craftsmen [43]. In the musical instrument industry, the quality of 3D-printed parts is determined by the mechanical and acoustic standards, set by the manufacturer [5]. While it is feasible to quantitatively measure sound in terms of frequencies, amplitudes, harmonic content, and more, the qualitative assessment of these sounds poses challenges. Subjectivity comes into play when involving human players and listeners, making it challenging to provide an objective evaluation [5,44].

Despite the difficulties, research on additively manufactured musical instruments has advanced, with a predominant emphasis on wind instruments and, to a lesser extent, string and percussion instruments. Research predominantly focuses on wind instruments due to the costliness associated with their traditional manufacturing methods. The rationale behind this emphasis lies in the fact that the material of a wind instrument has a comparatively lesser impact on the produced sound when contrasted with strings or percussion instruments, as indicated in former studies [5,43–46].

Guitars [5,47,48], violins [5,42,48], flutes [44,46,48], claves [49], drums [5], whistles [5], and mouthpieces for wind instruments [35] have all been successfully 3D-printed, with their sound effectively compared to traditionally crafted counterparts. Research in this field extends beyond classical instruments to encompass traditional and even lost musical instruments, either replicated based on descriptions or existing parts. Notably, traditional instruments like the Hawaiian ukulele [43], Greek anakari [45], Japanese shakuhachi [43], and many others were successfully reproduced through 3D printing, producing sounds remarkably like conventionally constructed counterparts. Additionally, efforts were made to revive lost instruments, such as the cornet [37], and to create entirely new ones, like slide pipes [43] (whistle-like instruments), which were 3D-printed and featured in various concerts.

In addition to 3D-printed polymers, the potential application of 3D-printed bio-inspired composites has also attracted interest from scientists. Nacre and chitin, among other materials, stand out as promising candidates for bio-inspired composites due to various noteworthy properties they exhibit. De Maio et al. [50] conducted a study on 3D-printed nacre, incorporating hollow platelets to achieve good sound absorption, lightweight properties, and mechanical performance. The composite demonstrates a combination of properties, which resemble cellular materials, and the ability to dissipate energy. By extending their previous work, De Maio et al. [51], studied the influence of parameters such as geometry, on the attenuation properties of nacre. The wave attenuation properties were also the topic of the study of Lu et al. [52]. Consequently, nacre can be described as a non-brittle ceramic, due to its high strength and high roughness [53]. This enables the use of nacre 3D-printed bio-composites to the crafting of idiophones or parts of other musical instruments.

3D printing technology has profound impacts on the musical industry. It enables the customization of musical instruments, fostering innovation in design and even giving rise to entirely new instruments. Moreover, the potential for mass production using 3D printing has the capacity to enhance accessibility and affordability of musical instruments. Additionally, this technology is instrumental in rapid prototyping and the faithful replication of vintage or rare instruments, contributing to the preservation of musical heritage [5,43,45,54].

2.3. Metamaterials in Musical Instrument Manufacturing

Metamaterials, designed to exhibit unique acoustic properties, not found in nature, often display distinctive transmission spectra influenced by their specific geometric and material configurations. Analysis of the recorded acoustic signal provides information about acoustic band gaps, resonance frequencies, and other key features contributing to the metamaterial’s ability to manipulate and control sound propagation. In the literature a comprehensive definition of acoustic metamaterials hinges on the concept of utilizing purposefully designed internal structures, as opposed to inherent material properties, for the manipulation and control of acoustic fields and waves within fluids [6]. Mechanical metamaterials constitute another subset of architected materials, characterized by unparalleled mechanical properties or functionalities. Comparable to acoustic metamaterials, these distinctive attributes arise from the synergistic interaction between the deliberate design of their 2D or 3D (micro)architectures and the materials they are composed of [6].

The incorporation of metamaterials in musical instruments offers the potential to significantly alter the instrument's sound. Modifying existing instrument geometries introduces additional band gaps in their spectrum, and the strategic utilization of multiple such band gaps allows for the intentional shaping of a designed sound. In the literature, metamaterial structures have been made by attaching a ring of masses on a drum membrane [55], leading to a cloaking behavior of vibrations from within the ring into the area outside the ring and vice versa. In a similar study [56], tubes and bars attached to a plain PLA plate resonated at discrete frequencies. The vibrations in the bars were damped due to internal damping, leading to bandgaps in the radiation spectrum of the entire plate occurring at these discrete bar frequencies. To generate metamaterial structures on the top plate of a guitar [57], the soundboard underwent modifications by incorporating a pattern of elliptical holes on the underside. Two types of holes were implemented based on their orientation. When the long side was parallel to the longitudinal axis of the soundboard's wood, they were designated as longitudinal holes, while alignment with the radial axis led to the designation of radial holes. The results indicated that these metamaterials effectively tuned the instrument's response without compromising its structural integrity.

3. Vibro-Acoustic Analysis and Assessment of Musical Instruments Made of Composites and Alternative Materials

The experimental and numerical methods used for vibration and acoustic analysis retrieved from the literature will be presented, as well as studies for vibro-acoustic analysis of composite musical instruments, 3D-printed musical instruments and metamaterials used in musical instruments.

3.1. Experimental and Numerical Methods for Musical Instrument Vibroacoustic Studies

For the study of the vibrational behavior of composite and alternative materials for musical instruments, several methods are applied. The bending and torsional characteristics were measured by the three-point bending test [14,58,59] and the tensile force oscillation method [14,59]. The frequency response function (FRF) is the most common measured quantity, which is derived by an input and an output signal. The excitation signal is usually an impulse hammer hit [12,15,29,60,61]. Alternatively, a shaker can be used [61], a coil to apply a force by changes in the current [16,62], a piezo element [58], a ball utilizing a pendulum [28] and a speaker [60]. The response of the vibrating system can be detected by a laser scanning vibrometer [60,61,63], an accelerometer [23,60] and a piezo element [16]. In case the analysis includes acoustical characteristics such as radiativity [29], the sound is recorded by a microphone [12,29]. Apart from vibration FRF analysis, which is usually based on a kinematic quantity (displacement, velocity, acceleration), modal analysis can be performed using non-contact methods. The vibration modes can be visualized by Electronic Speckle Pattern Interferometry (ESPI) [23]. Furthermore, the operating deflection shapes can also be revealed by a microphone array, in terms of near field acoustic holography [61]. The spatial arrangement of the microphones in [55] enabled the capture of variations in pressure and particle velocity, providing detailed information about a drumhead's vibrational modes. For the matching between simulated and measured values, several descriptors can be used, such as the eigenfrequencies absolute error and modal assurance criterion [63].

The fundamental numerical methods extensively employed in the literature to investigate the vibrational and acoustic behavior of musical instruments include the finite element method (FEM) [64–66], the finite difference method (FDM) [67,68], and the boundary element method (BEM) [69,70]. Numerical methods offer notable advantages over analytical approaches, as they involve subdividing the solution domain into smaller subdomains. Each subdomain can possess distinct values of physical properties and experience varying loading conditions. Through FEM modal analysis numerical simulations [16,65,71,72], the impact of various variables such as thickness, curvature, material properties, density, and elastic constants on the instrument's vibration modes can be effectively demonstrated. These computational studies provide valuable insights for experimental modal testing. Additionally, FRF FEM analysis [65,71,72] can illustrate the characteristic peak resonances corresponding to different frequencies. In the domain of musical acoustics, the BEM formulation is commonly utilized to compute the radiated sound produced by the simulated musical instruments [69,70,73].

3.1.1. Vibro-Acoustic Assessments of Musical Instruments with Composites

The type of matrix and reinforcement significantly impact the material's mechanical and acoustic properties. The arrangement and thickness of composite layers influence their bending and vibrational characteristics, which, in turn, affect the acoustic response [74]. The damping capacity of the material plays a role in absorbing and dissipating vibrational energy. The manufacturing method used to produce the composite, such as lay-up technique, curing conditions, and molding processes, can affect material uniformity and, consequently, vibro-acoustic properties. Moreover, the overall design and geometry of the composite structure can influence its dynamic response and acoustic performance.

The exploration of composite materials in the manufacturing of musical instruments constitutes an intriguing research domain within musical acoustics, steadily gaining prominence over time. In an in-depth examination focused on violins, Schelleng [75] delineated prerequisites essential for replicating the vibrational characteristics of a wooden plate using a plate made from a different material. Building upon these criteria, Haines, and Chang [76] delved into the prospect of substituting wood with a composite plate, particularly in the crafting of top plates for guitars and violins.

The violin stands as one of the most extensively studied musical instruments. Duerinck et al. [60] dedicated their research to establish a measurement protocol for potential modal analysis evaluations of wooden violins. In their investigation, both a carbon and a wooden violin were subjected to testing. The measurements primarily focused on coherence, the occurrence frequency of signature modes, their damping characteristics, and the associated risk factors linked to each measurement method. In the latter case, the FRF was computed for various inputs and outputs. The violins were excited using an impact hammer, an electromagnetic shaker, a piezoelectric element, and a loudspeaker, while the response was captured through the utilization of an accelerometer and a laser scanning vibrometer. Moreover, Duerinck et al. [12] performed listener experiments for the evaluation of violins made of composites. Soundboards made of various composites were attached to a violin body, in a way that the only difference among the violins was the soundboard. Part of the study was the measurement of the acoustic radiation of the violins in a hemianechoic room with an impact hammer excitation. The variation in the radiation is shown in Figure 6. The study concluded that diverse sounds and timbres of violins made from fiber-reinforced polymers can be produced.

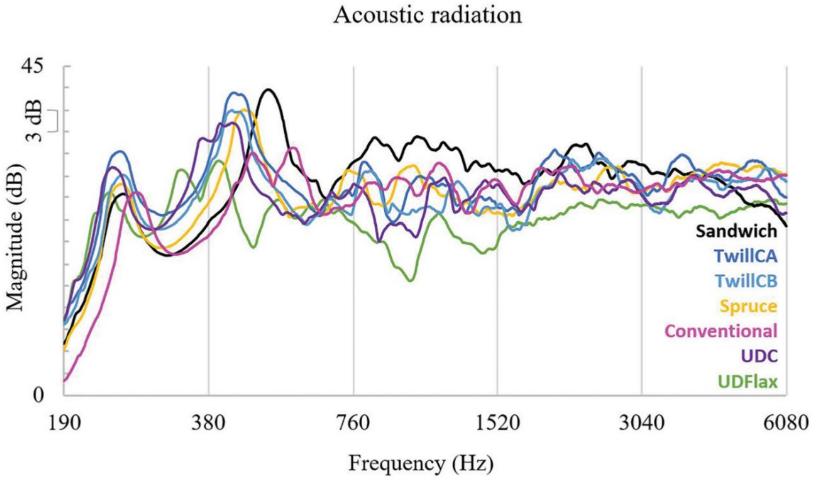
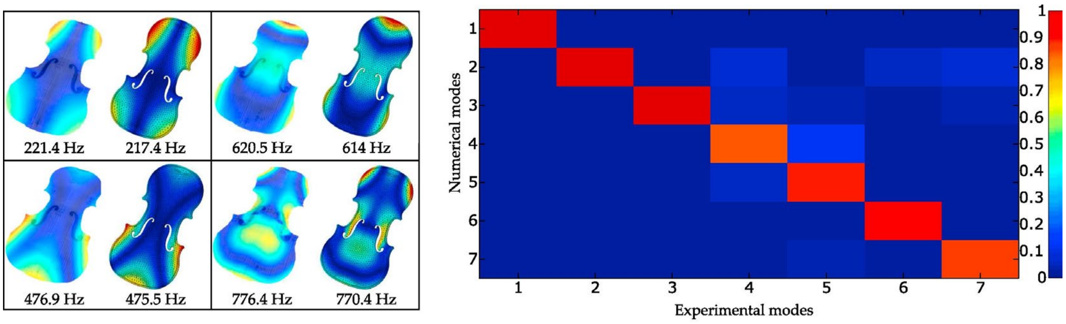


Figure 6. Acoustic radiation among a conventional violin and violins having the same body and different soundboard. Reprinted with permission from [12]. Copyright 2020, Acoustical Society of America.

Zambrano et al. [13] discussed about the performance of violins made from carbon fiber composites and wooden ones, using finite element modal analysis for their comparison. The models underwent validation through comparisons with experimental studies conducted by other researchers, leading to the conclusion that, for instruments sharing identical geometry, a superiority of wood over CFRP was evident. Dominy and Killingback [77] presented the development of a carbon fiber violin. During the manufacturing process, they performed modal analysis in the frequency domain using laser vibrometer measurements. Furthermore, the investigations conducted by Lu [71] and Kaselouris et al. [72] using FEM simulations delved into the feasibility of replacing the conventional wood material in top plates with composite materials. The outcomes of both studies revealed a noteworthy distinction in the vibrational characteristics between composite soundboards and their traditional wooden counterparts. Viala et al. [63] employed a bio-based composite material for the violin top plate in their study, wherein they conducted an analysis to determine its elastic and damping properties through the application of an inverse method. This involved a synergistic approach that combined modal finite element analysis and experimental modal measurements. The soundboard was excited by a speaker and the velocity of the vibration was detected by a scanning laser 3D vibrometer. The 3D velocity fields were used to estimate the modal basis. To validate their methodology, the authors compared the vibration modes by assessing the congruence between the results obtained from both measurements and simulations. They also used the modal assurance criterion (MAC) for the comparison of numerical and experimental modes of vibration. Representative results of their validation comparisons are shown in Figure 7.



(a) (b)

Figure 7. (**a**) Representative experimental (left) and numerical (right) modal deformed shapes, (**b**) MAC matrix between numerical and experimental modal basis after minimization procedure. Reprinted from [63] with permission from Elsevier. Copyright 2018 Elsevier.

Ono et al. [14] produced fiber-reinforced composites for the manufacturing of sound boards. They measured the vibrational properties such as Young's and the shear modulus, and the flexural internal friction. They also extracted the frequency response characteristics using forced excitation. In addition, the sound power level of the emitted sound was determined. In continuation to their previous work [14], Ono and Isomura [15], used their composite materials for the manufacturing of a guitar sound board. Due to the initial deviation in terms of Young's modulus from Sitka spruce, they made an alternative composite by reinforcing the radial direction with carbon fibers. The comparison of the radiated sound power and the vibration characteristics among Sitka spruce and the used composites were presented. The differences in the radiated sound from guitars with soundboards made of composite material, due to carbon fiber reinforcement either only to the longitudinal direction or to both longitudinal and radial directions, was the topic of another study by Ono and Okuda [59]. The frequency transfer function was calculated using the force of an impact hammer, which excited the bridge, and the emitted sound using a condenser microphone. Roest [78] conducted a detailed investigation into the manufacturing of a composite guitar, focusing on achieving an acoustic response comparable to wood. His methodology involved the development of a composite, ultimately resulting in a carbon fiber reinforced polyurethane foam. Throughout the study, he quantified the damping properties of various materials employing laser scanning vibrometry. A similar study was also performed by Probert [79] for a guitar having a body made of composites and a wooden fingerboard. Modal analysis using finite element modelling and experimental methods was performed. For the latter, the instrument was excited by a loudspeaker and the output of a laser scanning vibrometer provided the frequency response.

Furthermore, traditional musical instruments have also been extensively studied. Brezas et al. [23] presented an integrated method for the evaluation of musical instruments. The method was applied to quantify the vibrational characteristics of a carbon fiber Bouzouki. The combination of FEM simulations, modal measurements incorporating an impact hammer and an accelerometer, holography through ESPI and psychoacoustic tests was proposed for the vibrational description of the instrument. The visualization of a resonance frequency, as located on a frequency response graph by means of ESPI is shown in Figure 8.

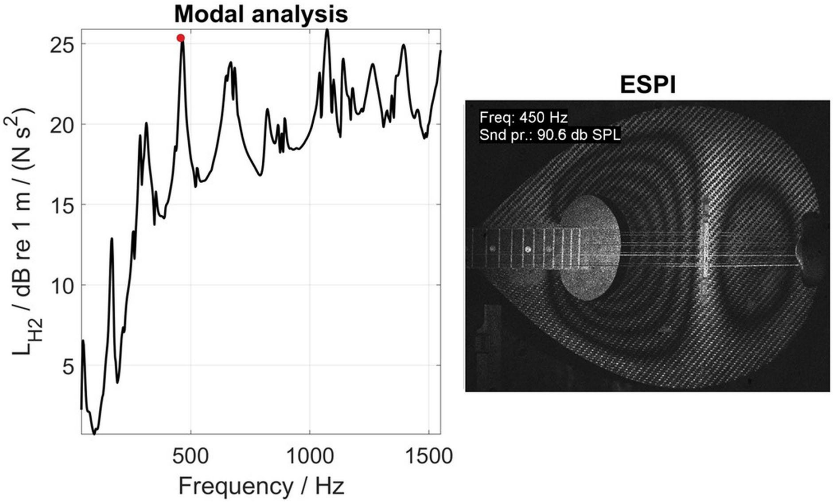


Figure 8. Matching of a resonance frequency (red dot) on a frequency response graph (**left**) with the corresponding vibration mode as revealed through ESPI measurements (**right**) for a carbon fiber bouzouki. Reproduced under a Creative Commons Attribution 4.0 International License [23]. Copyright 2023, MDPI.

Acet et al. [34] introduced three variations of a Turkish traditional string instrument made of composites using carbon and glass fiber. The radiated sound of the composite instruments was compared to the sound of a wooden instrument. Despite, having different sound colors the authors concluded that composite materials could serve as viable alternatives in instrument manufacturing.

The manufacturing of the shell of an Indian drum made of composite materials was proposed by Damodaran et al. [29]. The drum shell was manufactured as a sandwich configuration. The outer wall was a carbon fiber/epoxy face sheet, and the core was made of balsa. The performed flexural vibration measurements led to the calculation of the Young's modulus based on the resonance frequency, and the internal friction based on the vibration damping. For the extraction of the mode shapes, the frequency response function of the drum with the composite shell was calculated by an input provided by an impact hammer and an output as recorded by a microphone. To replace the traditional wooden top plates by composite ones, Phillips et al. [28] investigated the properties of a flax-reinforced (bio-composite) sandwich panel. Modal analysis was used to calculate the Young's and shear modulus, internal friction, and static mechanical properties. The specimen under investigation was excited by a steel ball. After the top plate characterization, a ukulele was manufactured and qualitatively compared to a high-quality wooden ukulele. The comparison results showed that the flax-reinforced sandwich structure can successfully act as a top plate. The impact on the resonant frequencies of a drum shell made of composite CFRE by using structural reinforcements at the edges of the composite drum shell was studied by Ibáñez-Arnal et al. [16]. The study combined finite element and modal analysis. For the latter research, a resonance detection method based on the external excitation of the shell by sine wave was utilized and piezo sensor was used to record the response. Figure 9 demonstrates representative modes of vibration extracted from the simulations.

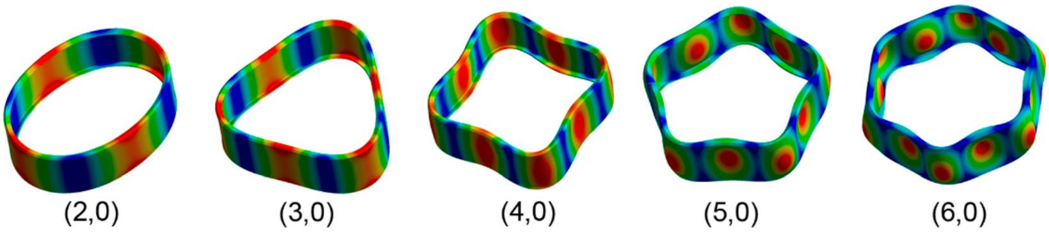


Figure 9. Vibrational modes (m, 0) of drum shell obtained from FEM modal simulations. Reproduced under a Creative Commons Attribution 4.0 International License [16]. Copyright 2019, MDPI.

A good agreement between FEM and experimental results is also shown in Figure 10 for the same number of CFRE layers and the same length of the structural reinforcement.

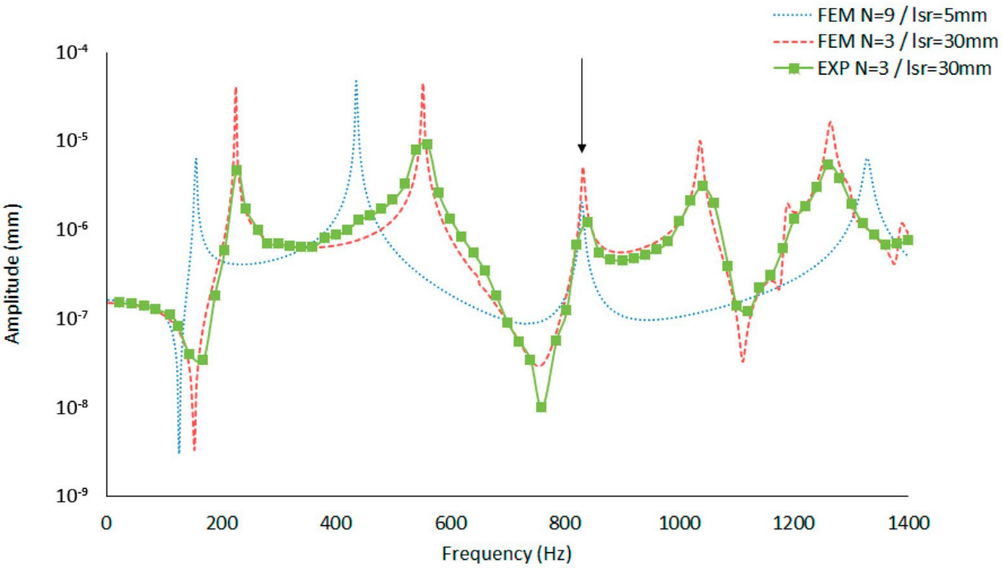


Figure 10. CFRE drum shell amplitude vs. frequency obtained by modal FEM and experimental analysis (lsr stands for the length of the structural reinforcement and N the number of layers). Reproduced under a Creative Commons Attribution 4.0 International License [16]. Copyright 2019, MDPI.

3.1.2. Vibro-Acoustic Assessments of 3D-Printed Musical Instruments

The elastic properties of a 3D-printed component or structure play a crucial role in determining its vibro-acoustic behavior [42]. These properties depend not only on the material itself but also on the structure's internal filling. Other material properties such as density, internal damping, and homogeneity can significantly impact the vibro-acoustic behavior. The geometric shape, size, and overall design of the structure can influence how vibrations are transmitted. The level of precision in the 3D printing process, including layer resolution and material deposition consistency, can affect the structural integrity and vibrational characteristics. Parameters such as printing speed, layer thickness, and infill density during the 3D printing process influence the internal structure and, consequently, the vibro-acoustic properties. Zhong et al. [80] proposed a technique for estimating the elastic properties of 3D-printed materials, via fused-filament-fabrication (FFF), using modal-impact-sound analysis. They performed FEM-BEM simulations that considered the material anisotropy and estimated the material elastic properties by minimizing the residuals between the simulated and recorded modal impact sound features. The impact sounds were recorded by a microphone. Figure 11 demonstrates the modal sound synthesis process. Michon et al. [36] performed impulse measurements and FEM simulations to study the vibro-acoustic performance of simplified string instrument bodies/resonators.

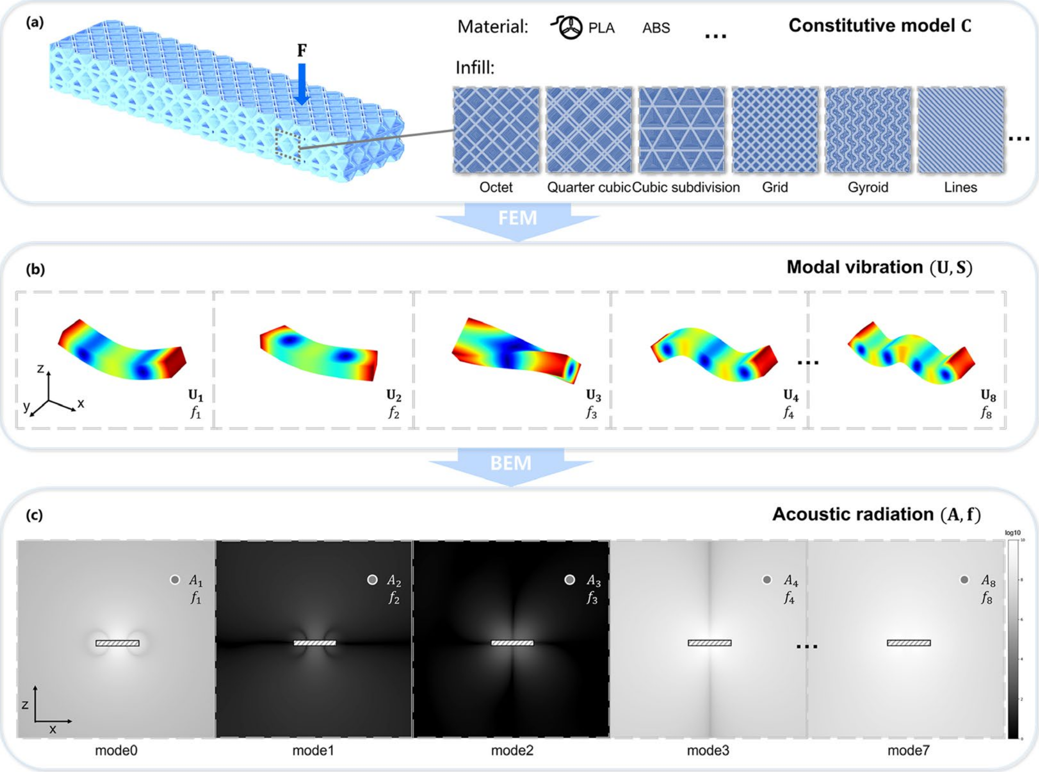


Figure 11. Modal sound synthesis process. (**a**) The constitutive model is established for modal vibration macroscopically describing the mechanical performance of different filament materials and infill patterns. (**b**) Sequential mode frequencies and shapes are computed, where eigenvector U indicates mode shape, and eigenvalue $S = 4\pi^2 f^2$ indicates mode vibration frequencies. (**c**) Acoustic radiation is generated by the pairs of surface vibrations, and certain modes are amplified depending on the impact force position, where A is the sound amplitude at a spatial location, and f is the frequency. Reprinted from [80] with permission from Elsevier. Copyright 2023 Elsevier.

Numerous researchers have explored and developed 3D-printed musical instruments based on the acoustic properties of thermoset materials and their internal structures. In a study conducted by Evans and McComb [49], the acoustical behavior of 15 PLA (filament) claves was investigated, with variations in dimensions and designs, including filled, pipe, and void claves. Claves, characterized by their simple cylindrical geometry and suitability for hand-played percussion instruments, are convenient for testing. The researchers adopted a two-pronged approach, comparing experimental recording results with both mathematical analysis predictions and FEM simulations. Their findings indicated that frequencies of PLA claves could be accurately predicted in cases with a filled design but not in cases with a pipe design. Although PLA claves approximated the typical size of traditional claves, they could not easily replicate the acoustic characteristics, particularly the pitch, of classical wooden claves. Alfarisi et al. [81] designed and developed a hand-cranked music box base made from PLA and manufactured via 3D printing. Experimental recordings demonstrated that the sound spectrum closely resembled the original at frequencies within the range where human hearing is most sensitive (500–4000 Hz).

Furthermore, FEM results demonstrated that the loudest and best sound quality can be achieved using a 60° angle slope for the music box base structure. Mulholland et al. [82] designed and printed a keyboard instrument, specifically a 3D-printed grand piano action and a self-tuning controller, with the intention of advancing the modern piano. However, further refinement was needed for its optimal functionality.

Frischling et al. [42] designed and developed a high-quality violin with the capability of being 3D printed and assembled at a low cost. Throughout the project, multiple iterations of the violin were created to achieve a 3D-printed version, closely resembling a wooden one. Violins made of PLA or carbon fiber were printed using both vector and mesh models. Upon model testing, it was verified that a 3D-printed violin performs similarly to a wooden violin, with frequencies between the instruments aligning. The total cost to print and build the instrument was found almost 10 times cheaper than a wooden student violin. ODD Guitars [83], founded by Olaf Diegel, Professor of Additive Manufacturing and an experienced design engineer in 3D printing and advanced manufacturing technologies, has been at the forefront of exploring additively manufactured musical instruments, particularly focusing on 3D-printed guitars. Kantaros and Diegel [5] collaborated on a study investigating the production of additively manufactured musical instruments, with a primary emphasis on 3D-printed guitars. ODD Guitars designed multiple guitars using different materials and geometries, aiming to discover the optimal combination for an electric guitar. The instruments were manufactured using Powder Bed Fusion (PBF) technology, specifically PA2200/nylon material. In the process, FEM analysis was employed to simulate the acoustic behavior of the additively manufactured guitars. The analysis revealed a deflection in the body under 100 kg of tension in the first design iteration. Subsequently, a second design iteration was tested, resulting in reduced deflection (Figure 12).

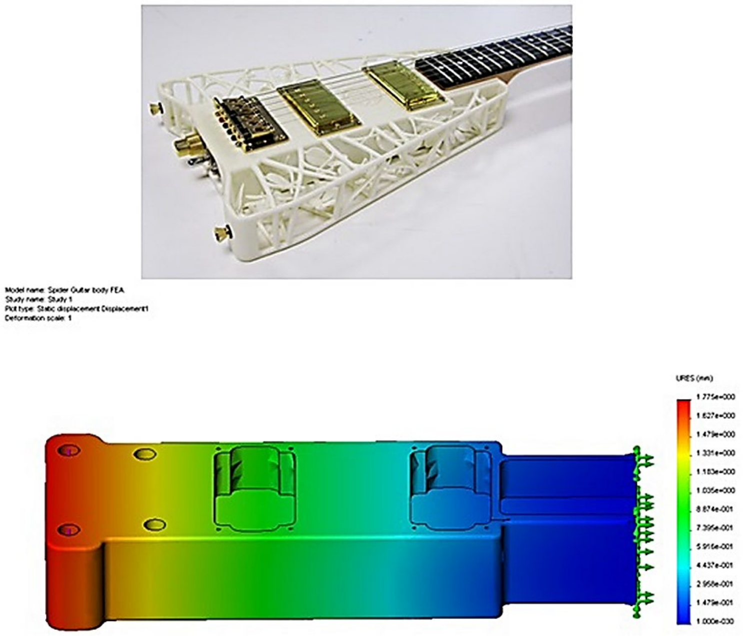


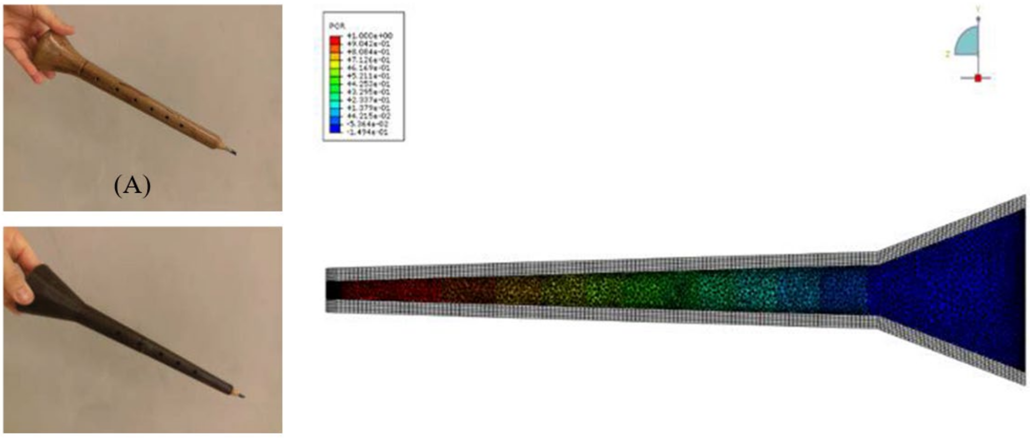
Figure 12. Finite element analysis showing deflection of 2nd iteration ODD Guitar body. Used with permission of [Emerald Publishing Limited], from [5]; permission conveyed through Copyright Clearance Center, Inc.

After several trials with guitars featuring different designs, they underwent a redesign to address the issue of deflection. The revised design incorporated a wooden core inside the additively manufactured nylon body, as shown in Figure 13, effectively eliminating the deflection problem. ODD Guitars employed additive manufacturing technologies not only for printing electric guitars, but also for acoustic guitars, drums, keyboards, saxophones, whistles, and more. The role of additive manufacturing is rapidly expanding in musical instrument research, enabling the production of instruments in a timely and cost-effective manner.

Figure 13. Final design of an ODD Guitar body using an internal wooden core. Used with permission of [Emerald Publishing Limited], from [5]; permission conveyed through Copyright Clearance Center, Inc.

Many research studies on 3D-printed musical instruments focus on wind instruments, leading to numerous works dedicated to developing wind instruments and/or individual components of them. In the study of Zoran [44], a flute was designed and printed using two different 3D printing technologies: FDM and Object PolyJet technology. The prototypes were based on a standard concert flute. To address mechanical challenges, the models underwent variations and changes, evolving through different design iterations in the pursuit of an optimal solution. However, FDM technology proved to be not mature enough to produce sufficient flute keys and proper air pipes. Additionally, Object PolyJet technology exhibited instability over extended periods. After manufacturing, the acoustical behavior of the 3D-printed flutes was tested and found to be like classical metal flutes. Kolomiets et al. [46] investigated the behavior of a 3D-printed titanium flute. A polymer analogue was used to design the titanium flute, transforming its outer surface into lattice patterns. Titanium possesses valuable properties that allow the creation of surfaces with desirable characteristics. After selecting the optimal lattice pattern, a titanium flute was printed, exhibiting strength, high biocompatibility, and a long lifetime. Following manufacturing, the titanium flute was compared to the initial polymer analogue and a traditionally manufactured titanium flute. Studio recording tests revealed that the sound of the 3D-printed titanium flute is significantly richer than the polymer analogue. This improvement was attributed to the material's lower absorption of sound waves. Cottrell and Howell [41] developed usable clarinet mouthpieces by recreating them from surviving technical drawings, like those found in the Boosey & Hawkes Archive, using 3D printing.

The research in the field extends to include traditional and even lost musical instruments, either replicated based on descriptions or existing parts. Savan and Simian [37,43] focused on reconstructing the cornett, a Renaissance wind instrument that fell out of fashion centuries ago, becoming a museum artifact. Experiments successfully aimed at 3D printing replicas of the cornett, primarily utilizing SLS technology with some minor inclusions of SLA and FDM. In [43], in addition to the cornett, they also designed and successfully developed the shakuhachi, a traditional Japanese bamboo flute, and the ukulele, a small four-string guitar, a traditional Hawaiian musical instrument. The same study addressed the design of Fagottini and Tenoroons, the smaller members of the Renaissance bassoon/curtal family. Due to the rarity of playable small bassoons, the 3D-printed Fagottini and Tenoroons were successfully compared to their traditional counterparts and were used in normal concerts. Kokkinos et al. [45] studied experimentally and numerically the acoustical behavior of Kefalonian traditional instruments made from various materials and several anakari instruments were designed and manufactured traditionally from two wood types and from PLA by 3D printing. The 3D-printed instruments were compared to their traditional counterparts, and acoustic measurements and simulations, presented in Figure 14, demonstrated that the PLA 3D-printed anakari had significant differences in the produced sound compared to its replica made of eucalyptus, due to variations in the mechanical properties of the materials chosen.



(B) (C)

Figure 14. (**A**) An anakari made from eucalyptus wood, (**B**) a 3D-printed PLA anakari and (**C**) natural frequencies in anakari. Reproduced under a Creative Commons Attribution 4.0 International License [45].

3D printing empowers the creation of wonderfully peculiar existing instruments or entirely new musical wonders, like the innovative slide pipes [43]. These whistle-like instruments produce diverse notes by manipulating their resonance length through a push/pull slide and were successfully brought to life through 3D printing, captivating audiences in various concerts. Figure 15 demonstrates musicians performing with slide pipes.

Figure 15. Musicians performing using slide pipes. Reprinted from [43] by permission of SAGE Publications. Copyright 2023 SAGE Publications.

3D printing is on the brink of revolutionizing the musical industry by simplifying the design and creation of relatively affordable musical instruments or components. It opens the possibility of easily creating prototypes or previously nonexistent musical instruments and reproducing lost or discontinued musical treasures. Nevertheless, while 3D printing offers notable advantages, limitations such as the availability of materials and the durability of printed components, in relation to the chosen additive printing technology and design, continue to place this technique at a relative disadvantage compared to subtractive manufacturing methods [84]. PLA and PET may not be as durable as some traditional instrument materials, especially for high-stress applications, while UV-sensitive photopolymer powder may be prone to degradation over time when exposed to sunlight [85].

The repairability of 3D-printed instruments compared to traditional instruments may depend on various factors, including the type of instrument, the materials used, and the specific design. Three-dimensional printing allows for precise digital replication of damaged components, facilitating accurate repairs. The inherent flexibility of 3D printing enables tailored designs, simplifying repairs by recreating specific components. Despite the variety, not all 3D-printed materials may possess the necessary mechanical properties for musical instruments, affecting the repair's success. Some 3D-printed instruments feature complex designs, increasing the demands for repairs compared to traditional instruments with simpler structures and conventional materials. As 3D printing technology advances and becomes more integrated into instrument making, repair techniques and expertise are likely to evolve as well. The potential for refurbishing or repurposing 3D-printed instruments at the end of their life cycle holds promise for sustainable practices. Due to the layer-by-layer additive nature of 3D printing, these instruments can theoretically be disassembled with relative ease. Materials such as PLA are biodegradable and derived from renewable resources, aligning with environmental concerns. However, challenges may arise in the separation of materials in complex designs or those using multiple types of filaments. While there is an increasing emphasis on sustainability in 3D printing, there appears to be a gap in the literature regarding standardized processes for disassembly, material separation, and the efficient recycling of 3D-printed musical instruments. Addressing these gaps could contribute significantly to the environmental feasibility of 3D-printed instruments in the long run.

Moreover, the economic aspect of introducing 3D printing materials and technologies in manufacturing, particularly for musical instruments, is crucial. New filaments and powders are developed to support the rapidly evolving 3D printing technology. As an emerging technology, it is characterized by high costs in terms of consumables, machine parts, and services. The complete industrialization of the 3D printing method is expected to significantly decrease these costs in a relatively short time. This reduction will be facilitated by the standardization of the process and improvements in the capabilities of the machines. Consequently, the mass production of 3D-printed products, coupled with their limitless repeatability, high productivity, and minimal demand for human resources, will quickly lead to the production of low-cost musical instruments. The competitiveness of these instruments compared to conventionally manufactured ones will enable the production of large-volume lightweight instruments such as cellos, violas, pianos, etc. This will contribute to strengthening the green economy by minimizing traditional production waste and scraps. Social groups, including conservatoire students and amateur performers, will have the economic means to afford these musical instruments. This, in turn, will enhance the economic viability of these new production lines.

Despite their disadvantages, 3D printing technologies can revolutionize instrument design, opening doors for new acoustic experiments and musical possibilities. The significance of 3D printing in the musical instruments industry has prompted extensive research, continually pushing the boundaries to explore the possibilities of materials, printers, and the imaginative scope of designers.

3.1.3. Vibro-Acoustic Assessments of Musical Instruments with Metamaterials

Bader et al. [55] presented the characterization and evaluation of an acoustic metamaterial structure consisting of neodymium magnets applied on a mylar drum membrane with a 40 cm diameter. The structure included a ring-shaped area of 10 cm in diameter, isolated by the magnets. The area delimited by the magnets acted as a cloaking mechanism, isolating vibrations within and outside this pre-defined space for certain frequencies. Thus, the waves originating externally or internally to the ring did not traverse the boundary, leading to the formation of an acoustic band gap. Spatially resolved characterization of the metamaterial behavior was achieved both by laser interferometry, which enabled the detection of vibrations on the membrane, and using a microphone array, which enabled the reconstruction of the produced sound field. The drumhead was manually excited by an impulse hammer both inside and outside the separated area. Characteristic results from the evaluation of the pressure amplitude on the membrane via the microphone array for three different excitation positions are shown in Figure 16.

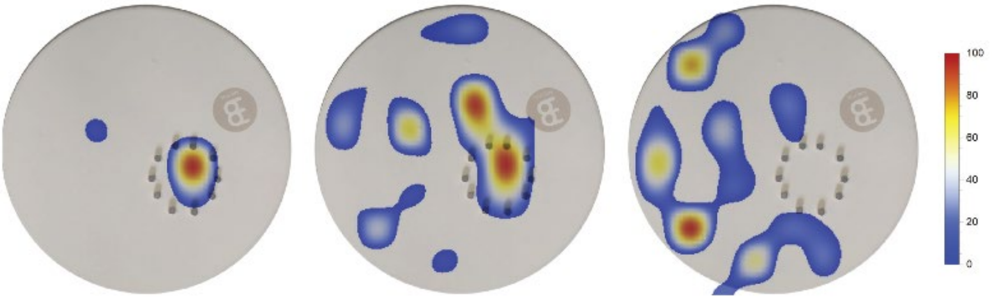


Figure 16. Density distribution of maximum pressure amplitude values of modes on the drum up to 1 kHz for three hammer strike positions (color bar in percentage of maximum density). **Left**: strike in the ring, **middle**: strike at ring rim, **right**: strike outside the ring at the opposite side of the ring. While most maximum values for the strike in the ring are in the ring, few are within the ring when the drum is struck outside the ring. A medium case is found when striking at the ring rim. (Reprinted with permission from [55]. Copyright 2020, Acoustical Society of America.

In [56], the same group demonstrated sound field mapping via the use of a microphone array for the characterization of the vibrational behavior of 3D-printed PLA plates. The plates were modified by attaching various features such as cylinders, rods, and tubes on the surfaces, acting as spectral filters and leading to the formation of band gaps.

Moreover, Espinoza et al. [86,87] presented a process for the characterization of a mechanical metamaterial structure composed of an array of circular holes (8 mm diameter) arranged in a 6 × 4 configuration within a silicone Elite Double 22 fast elastomer matrix. They studied the effect of attaching the metamaterial on the sound box of an acoustic guitar. The characterization process entailed the experimental determination of the metamaterial's frequency response to a vibration excitation. A spectrum analyzer was used to generate sine sweep signals from 300 Hz to 1 kHz, while the signal was amplified by an audio amplifier, which drove a mechanical vibrator serving as the mechanical excitation source. The response of the metamaterial was captured using an accelerometer connected to a signal conditioner. The collected data were directed to the spectrum analyzer that extracted the power spectrum. The process was repeated for different compression levels of the metamaterial, induced by a mechanical press. The influence of the metamaterial on the soundbox of an acoustic guitar was studied by attaching the metamaterial on the sound box using a coupling gel. The experiment was carried out by plucking a string tuned to a specific frequency. The acoustic behavior of the guitar was recorded using a pencil condenser microphone (Samson C02, 12 mm diaphragm, Samson, Hicksville, NY, USA) and an audio interface. The application of the method for the evaluation of the acoustic properties of wooden plates used for the manufacturing of guitar tops was demonstrated in [88]. Holes with different geometrical patterns were drilled in the wooden plates, acting as metamaterial surfaces which can effectively control the intrinsic variability of such wooden tops in terms of their acoustic response. As in acoustic instruments such as the guitar, in this case excitation of the top is airborne and is performed via the use of a loudspeaker, delivering sine sweep signals. Detection was again achieved using an accelerometer. The analysis of the measured signals focused on the detection of the (2, 0) and (0, 2) modes of the surface and was visually performed by observation of the Chladni patterns.

Lercari et al. [57] investigated the implications of incorporating metamaterials into the soundboards of classical guitars. Through simulations, they assessed how these materials influence modal behavior, sound pressure levels, and the instrument's capacity to withstand string-induced stress. Their findings indicated that the integration of metamaterials can fine-tune the instrument's response without compromising its structural integrity, affirming that employing wooden mechanical metamaterials in classical guitar soundboards is both feasible and advantageous. Figure 17 demonstrates the wooden mechanical metamaterial created by carving specific patterns of perforations into guitar top plates. Figure 18a illustrates the outcomes for the solid top and the two metamaterial variants. Noticeable distinctions are observed in the Helmholtz resonance, occurring at approximately the same frequency due to the minimal volume variation in the air cavity (less than 2%). Additionally, differences are evident in the 400 Hz range, with a more pronounced contrast at 650 Hz, albeit with a lower absolute pressure level, suggesting potential reduced audibility. To emphasize these distinctions, Figure 18b depicts the variations in pressure level.

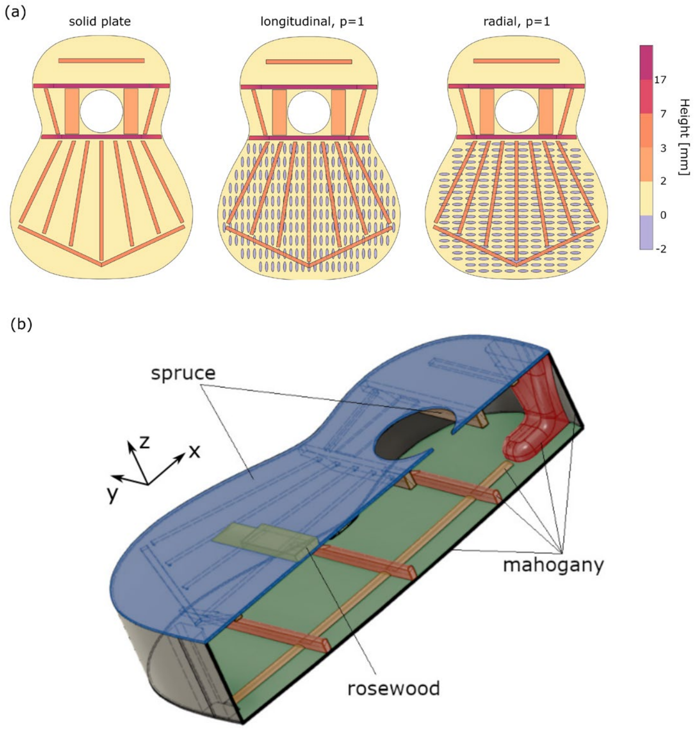


Figure 17. (**a**) Diagrams of the soundboards in three different configurations: solid, with longitudinal holes, and with radial holes. With $p = 1$, the major semiaxis of the elliptical holes is 10 mm long, while the minor semiaxis is 2.5 mm long. The figure shows the bracing and the hole patterns, and each surface is colored according to its height with respect to the lower surface of the plate. (**b**) Three-dimensional cut view of the model of the instrument's body, showing all the individual components. Reproduced under a Creative Commons Attribution 4.0 International License [57]. Copyright 2022, MDPI.

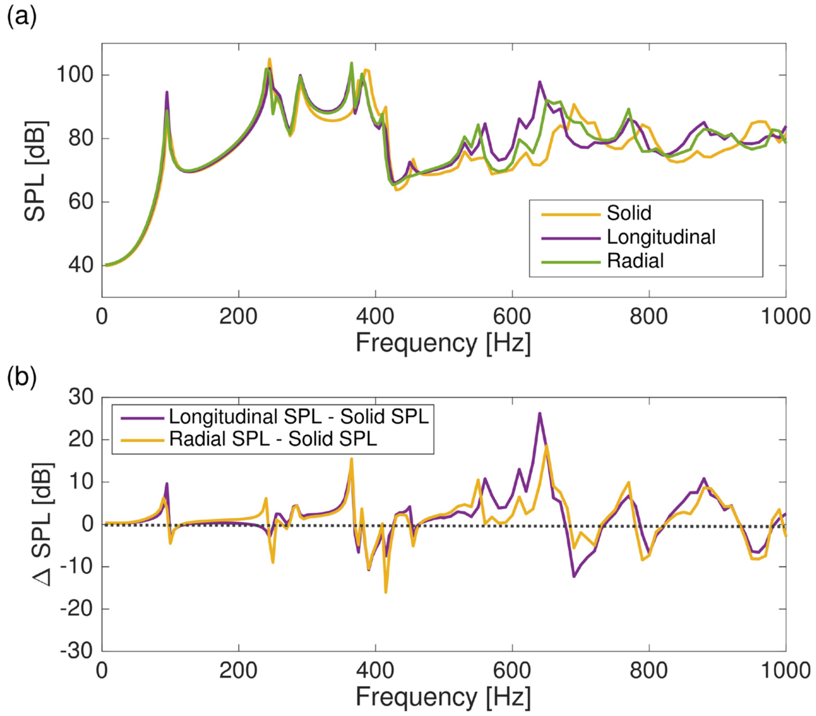


Figure 18. The sound pressure levels of the entire instrument body are compared between the solid top and two metamaterial configurations. This analysis involved applying a harmonic load perpendicular to the surface on a circular area with a 2 mm radius situated on the soundboard beneath the bridge, at the midpoint of the lower bout. (**a**) Absolute value of the SPL; (**b**) relative difference between the guitar with a solid top and the guitar with a metamaterial top plate. Reproduced under a Creative Commons Attribution 4.0 International License [57]. Copyright 2022, MDPI.

Instruments incorporating metamaterials showcase several advantages over their traditional counterparts. One notable advantage lies in the precise control metamaterials offer over acoustic properties. Unlike traditional materials, metamaterials allow for tailored manipulation of sound frequencies, enabling musicians to achieve desired tonal characteristics with a high degree of precision. Another significant benefit is the ability to finely tune weight and density. Metamaterial structures provide a unique opportunity to create instruments that are both lightweight and structurally robust. This not only enhances the overall playability of the instrument but also contributes to improved portability for musicians. Beyond functionality, the use of metamaterials allows for innovative and customizable designs. Instrument makers can explore modern aesthetics, pushing the boundaries of traditional craftsmanship.

A novel method for the experimental evaluation of acoustic metamaterials via the use of Laser Plasma Sound Sources (LPSSs) was proposed in [89]. LPSSs are generated through optoacoustic transduction, achieved by focusing fast (nanosecond) or ultrafast (picosecond to femtosecond) laser pulses with sufficient energy onto a gaseous, liquid, or solid target. In ambient air, the generation of LPSS via laser-induced breakdown (LIB) requires optical intensities surpassing the threshold of approximately 2×10^{11} W/cm^2. The LIB process leads to rapid thermalization in the air due to the interaction of hot free electrons with heavy particles (ions, atoms, and molecules) within the ionization volume. The resulting thermalized air bubble undergoes rapid expansion and contraction, leading to the generation of pressure fluctuations and the emission of an acoustic pulse. The acoustic pulse exhibits an N-pulse time-domain profile, with a duration ranging from a few microseconds to tens of microseconds, depending on the incident laser radiation characteristics [90]. Simultaneously, the excited volume emits light due to luminescent processes and localized thermal excitation. Kaleris et al. [91] have uncovered a correlation between the optical and acoustic signals produced by laser-induced breakdown, enabling the prediction of the LPSS acoustic spectra from the respective light emission. Concerning frequency content, the generated acoustic N-pulse displays a low-end response with a first-order high-pass profile. For nanosecond laser pulses, this low spectral range spans from subsonic frequencies (<20 Hz) to the upper audible frequency range (~20 kHz) or near ultrasounds (<50 kHz). Femtosecond laser pulses yield a broader frequency range, extending well into the mid-ultrasound range (>100 kHz) at the expense of reduced acoustic energy within the audible range. The peak pressure levels achieved by LPSS can vary significantly, ranging from barely perceivable (a few decibels) to exceptionally loud (130 dB or higher), depending primarily on the total optical energy deposited into the targeted medium, such as ambient air.

Due to their favorable acoustic characteristics, particularly the rapid impulse-like pressure profile, broad acoustic spectrum, controllable emission directivity and high repeatability, LPSSs constitute a near-ideal tool for the evaluation of acoustic metamaterials that can be used in musical instruments. Importantly, due to their massless and spatially unbound nature, LPSSs can be directed inside acoustic cavities or acoustic meta-structures without affecting their acoustic behavior. An indicative setup for the measurement of the acoustic response of a vibrating plate to a localized percussive excitation in or out of the structure is shown in Figure 19.

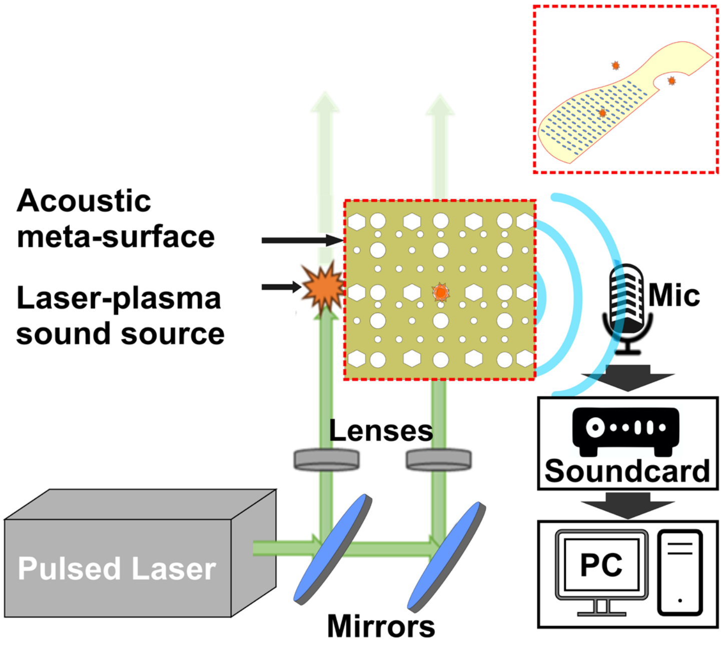


Figure 19. Experimental setup for LPSS evaluation of acoustic meta-surfaces suitable for acoustic enhancement of musical instruments with both internal and external excitation.

LPSS is the excitation source, while a microphone and/or a microphone array captures the produced sound field. Signal processing methods for direct signal removal and noise suppression are easily applicable to the measurements, especially due to the pulsed nature of the excitation. The acoustic meta-surface can be of any material type and geometry with sound transmission, resonance and/or filtering properties, such as the one shown in the red dashed-line box of Figure 19 representing the acoustic metamaterial soundboard of the guitar of Figure 17. Ongoing research on the use of LPSSs for the evaluation of AMMs suitable for acoustic enhancement of musical instruments is expected to deliver novel results and boost the research in the field.

4. Concluding Remarks

The need for innovation of the musical instrument manufacturing industry has driven researchers and manufacturers to explore alternative materials offering enhanced performance, sustainability, and versatility. In this article, we presented the utilization of composite materials, 3D-printed materials, and metamaterials as viable alternatives to conventional wood in the production of musical instruments. Fiber composites are gaining recognition as a viable alternative material, while stringed instruments constitute the highest potential application of such composites. The vibrational behavior of composite materials, influenced by factors such as matrix reinforcement types, layer arrangements, and manufacturing techniques, plays a pivotal role in shaping the overall acoustic response. In studies focused on instruments like violins, guitars, and drums, researchers have endeavored to understand the intricate interplay between material properties, design choices, and acoustic characteristics. The computational simulations and experiments of modal analysis, FRF analysis and acoustic measurements has enabled a deeper understanding of how composite materials can serve as viable alternatives to traditional wooden counterparts, ushering in new possibilities for instrument design and manufacturing.

The integration of 3D printing in musical instrument manufacturing delivers significant advantages for the historical instrument research and the creation of new instruments. Notably, it enables the swift and accurate reconstruction of historical instruments, providing empirical data that would be challenging to obtain through conventional means. This technology also empowers instrument makers and musicians by offering a simple and cost-effective method to bring creative visions to life. Three-dimensional printing facilitates the development of entirely novel musical instruments as well as modifications to existing ones, while studies ranging from claves and violins to guitars and wind instruments showcase the versatility and affordability of 3D-printed musical instruments. Particularly in wind instruments, the creation of unique sounds through shaped cavities is achieved. The inherent speed and diversity of 3D printing encourage customization, allowing for small design adjustments that result in instruments with distinct and varied sounds. While challenges such as precision of printing processes, durability and material choices persist, ongoing research, exemplified by endeavors like ODD Guitars' exploration of 3D-printed guitars, illustrates the transformative potential of additive manufacturing in reshaping the musical instrument industry. The ability to blend traditional craftsmanship with cutting-edge technology opens avenues for novel designs, cost-effective prototypes, and the recreation of lost or discontinued instruments.

The incorporation of metamaterials into the domain of musical instruments signifies a groundbreaking evolution, providing a novel approach to customizing and refining acoustic properties. Whether through the creation of acoustic band gaps, spectral filters, or novel spatial arrangements, researchers have harnessed the unique properties of metamaterials to exert precise control over vibrational behavior. Studies on drums, 3D-printed plates, and classical guitars demonstrate the far-reaching implications of incorporating metamaterials in musical instrument soundboards. By influencing modal behavior and sound pressure levels, metamaterials offer a promising avenue for fine-tuning instrument responses without compromising structural integrity. The use of these materials to enhance and/or customize the acoustic characteristics and dynamic behavior of instruments demonstrates the evolving synergy of advanced materials science and musical instrument manufacturing.

The use of composites, along with the 3D printing materials and the metamaterials in musical instrument manufacturing, highlights a dynamic intersection of conventional processes, scientific inquiry, and technological innovations. Further research in the field may offer musicians and musical instrument manufacturers unprecedented possibilities and advancements for creativity.

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