Research in the Department of Music Technology and Acoustics of the Hellenic Mediterranean University: An Overview and Prospects

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Abstract: - The Department of Music Technology and Acoustics of the Hellenic Mediterranean University offers a unique higher education program in Greece, addressing the growing demand for specialists in music technology, sound technology, and acoustics. It aims to educate specialized professionals in the rapidly advancing scientific fields of music technology and acoustics, mainly driven by the swift progress in electronic technology. The Department aims to address a gap in the professional market by producing highly skilled graduates, capable not only of keeping up with the latest scientific and technological developments but also of leading the way by introducing innovative approaches and methods. The Department combines art, science, and technology, focusing on sound recording, analysis, synthesis, and music production. Music technology encompasses various cutting-edge fields such as network music performance, artificial intelligence in music, and music embodiment. Acoustics refers to fundamental aspects of sound as well as its generation, transmission, and related phenomena. It includes research fields such as physical acoustics, optoacoustics, and vibroacoustics. This overview presents the research activities, methodologies, and results. A discussion of future research works and pointers to future technological evolution towards real-world music and acoustics applications is also provided.

Key-Words: - music technology, acoustics, research activities, network music, artificial intelligence, acoustic ecology, optoacoustics, musical acoustics.

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1 Introduction

The Department of Music Technology and Acoustics (MTA) of the Hellenic Mediterranean University (HMU), [1], is unique in higher education in Greece and fulfills the ever-growing demands for specialized engineers in the fields of music technology, sound technology, and acoustics. At an international level, it is among the few BSc programs with such an interdisciplinary orientation in their studies, along with the BSc program of the University of Edinburg entitled “Acoustics and Music Technology”, [2] and that of the University of Southampton, [3], entitled “Acoustics with Music”. Greece lacks specialized human resources in Music Technology and Acoustics nowadays the evolution in electronic technology drives a continuous progress and ever-growing professional prospects in the field. The Department bridges this gap by training highly skilled graduates proficient in a wide variety of related fields. These individuals are not just adept at keeping up with the latest advancements in these fields but are also at the forefront, pioneering innovative approaches and techniques. The Department has a strong research orientation and extroversion, through which students are directly exposed to the developments in the field at the national and international level, and the development and establishment of research projects and cooperation programs with Greek and foreign universities and stakeholders.

The art of music and sound is strongly interconnected with science (mathematics, physics) and technology (informatics, electronics). Music Technology, [4], [5], focuses on the study and the design of mechanisms, algorithms, tools, software applications, devices, electronic devices, and above all their synergy as used by musicians to create, perform, compose, notate, analyze, record and process music and sound. Modern cutting-edge fields (state-of-the-art) are Network Music Performance, Music Information Retrieval, Artificial Intelligence in Music, Machine Learning in Audio and Music, Computational Musicology, Electroacoustic Music, Acoustic Ecology and Soundscape Ecology, Human Movement Sciences and Technologies in Music, Gesture-Controlled Interactive Audio and Music Systems and New Musical Instruments. The science and technology of Acoustics, [6], [7], studies the properties and behavior of sound, as well as its applications. Acoustics is the science of sound, including its production, transmission, and effects, including biological, physiological, and perceptual effects. The study of acoustics revolves around the generation, propagation, and reception of mechanical waves and vibrations. The basic subfields of Acoustics, [8] are: Physical Acoustics, Bioacoustics, Engineering Acoustics, Architectural Acoustics, Environmental noise, Musical Acoustics, Psychoacoustics, Optoacoustics, Room Acoustics, Vibroacoustics, and Ultrasonics.

In this work, an overview of the research in the Department is presented. The research activities, along with the scientific methodology applied at each research subfield, are described in section 2, and representative scientific results are presented in section 3. This review of our research areas and their subfields and methodologies aims to summarize our research studies and motivate new and innovative research works and pointers for future potential enhancement of research achievements on a real-world application level, considering the strengthening of within-department and international collaborations.

2 Research Activities and Methodology

The scientific methods developed and applied in the research fields of music and sound technology and of acoustics, are here presented categorized in the form of research subfields.

2.1 Music and Sound Technology

The main research subfields of music and sound technology where the MTA significantly contributes and exhibits leading expertise are music embodiment, network music performance, artificial intelligence in music, electroacoustic music composition, and acoustic ecology and soundscape ecology. These basic subfields are further presented and analyzed along with the methods applied.

2.1.1 Music Embodiment

Traditionally, music has been studied through its symbolic representation, i.e., music notation, standing for the aesthetic value of a musical work as a composition. Later, more emphasis was given to its performative aspect, that is the expressive rendition of a musical piece by a performer, studied through the analysis of the musical signal, that is an audio recording. In recent years we have been observing a shift of interest with a growing number of publications emphasizing the role of the human body and its movement in music. The reason for this shift lies in theories of embodied cognition—more recently including embodied music cognition too, [9], —that consider knowledge as an emergent phenomenon that is acquired through the action of doing and dispute the notion that cognition involves representations, [10], [11]. Since multimodality has been identified as a central quality of musical experience and embodiment, [12], [13], empirical studies of human body movement in music most often involve capturing a plethora of multimodal data by movement-related sensors and state-of-the-art motion capture technologies, previously mostly employed in the realm of cinema for animation purposes.

Embodied music cognition is a term that incorporates all music-related human body movements, ranging from music performance to music listening. Examples of experimental work include, for instance, the study of effort in Hindustani vocal improvisation on the occasions of manual interactions with imaginary objects by singers, [14]; the analysis and rendering of multimodal data, especially so electromyography data for analyzing muscle contraction as a measure of bodily tension, performability and athleticism in comparison to the musical tension of a composition, [15]; the rhythmic and stylistic regional diversity of musician-dancer interaction in traditional Cretan dances [16]; or even the study of single drumming strokes as loading conditions to FEM-BEM mathematical models in cymbal vibroacoustic behavior, [17].

For instance, [14], reports on the first ecologically valid study of effort-related mappings between sound sculpting gestures (gestural interactions with imaginary objects) and the voice in Hindustani Dhrupad vocal improvisation. The aim was to devise formalized descriptions to infer the amount of effort that such interactions are perceived to require and classify gestures as interactions with elastic versus rigid objects. The findings were obtained through the application of an empirical sequential mixed methodology in analyzing original multimodal data of Dhrupad vocal improvisation performances.

The data was collected for the specific study, primarily in India, and includes interviews, audio-visual material, and 3D movement data captured by a passive marker-based optical motion capturing system (Naturalpoint Optitrack). Seventeen vocalists, encompassing both professionals and amateurs, with diverse genders, ages, levels of musical experience, and training durations, were enlisted for the study, only two of whom were of non-Indian origin. To ensure uniformity in gestural resemblance, all selected individuals share the same musical lineage as disciples of the esteemed vocalist Zia Fariduddin Dagar, who was also recorded as part of the study.

Participants were briefed solely on the study's connection to music and movement, with no additional details provided. Musicians received compensation for the recording of performances at an hourly rate, excluding interviews. Written informed consent forms and recording agreements release forms were signed by all participants. To enhance ecological validity, musicians were instructed to engage in improvisation without any specific guidelines. All recordings took place in domestic settings, typically in the living rooms where musicians conduct their daily musical activities, adapted to accommodate recording needs as depicted in Figure 1.

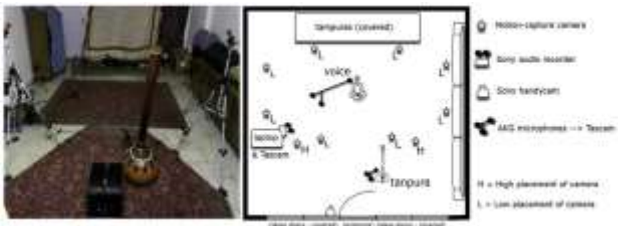

Fig. 1: Typical equipment setup, photo taken at the music school of maestro Zia Fariddudin Dagar in Palaspe, Panvel in India, [14]

The methodology considered both first-person and third-person perspectives in the analysis of musical gestures, [18] and involved the integration of qualitative ethnographic techniques (thematic analysis of interviews and video observation analysis) with quantitative methods (regression analysis for effort inference and gesture classification based on a combination of acoustic and movement features). Figure 2 illustrates the sequential mixed methodology that guided the study, featuring gesture images sourced from [19]. The findings of this research will be detailed in the Results Section 3.1.1.

The motivation for such systematic work is twofold: On the one hand, to gain a deeper understanding of various music traditions and conditions, and on the other hand, to acquire knowledge of how gesture-sound links deduced from designed experiments could lead to human-computer-interactions for music that are more physically plausible, [18], [20]. Hence, the results of such work may have implications for strategies for the development of artificial gesture-sound mappings in the design of electronic musical instruments and interactive music and music-related applications, [19], [21], [22].

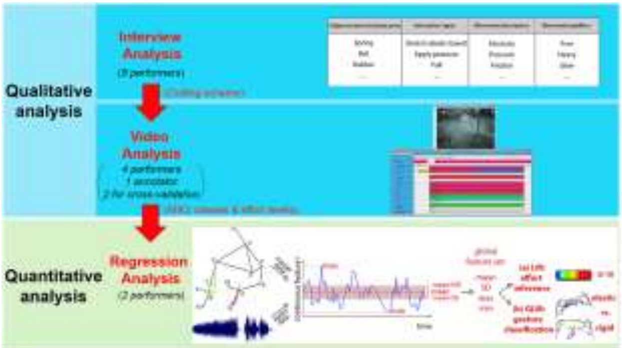

Fig. 2: Sequential mixed methodology featuring gesture images, [14]

2.1.2 Network Music Performance

Considering the performative aspect of music, the last few decades have witnessed a significant body of research efforts dedicated to enabling musicians to collaborate in virtual environments, thus circumventing the necessity for physical co-presence. The relevant research area is known as Networked Music Performance (NMP) and is particularly challenging when considering true-bidirectional audio-visual interactions of musicians over computer networks, [23]. Compared to common teleconferencing systems, NMP systems have multiple requirements, which mainly account for reducing communication latencies and increasing the quality of live audio streams. Speech-based human interaction, in teleconferencing and VoIP applications, is highly tolerant to latency, with an acceptable mouth-to-ear delay of 150-200 ms, [24]. Unfortunately, in music performance, the tolerable communication latency is lower by approximately an order of magnitude, i.e. between 25-30 ms and it is known as Ensemble Performance

Threshold (EPT), or “the level of delay at which effective real-time musical collaboration shifts from possible to impossible”, [25].

Further to latency, NMP systems are characterized by excessive requirements in network throughput. This is mainly because, unlike speech, most musical instruments have a broad acoustic spectrum, hence requiring high sampling rates (at least 44.1 kHz, as opposed to speech signals that commonly use 8 kHz). Moreover, due to the excessive requirements in reducing latency and increasing throughput, live audio signals are highly prone to sound distortions owing to data losses over the network. In Wide Area Networks (WAN), packet loss is frequently observed and caused by congested network paths or by faulty networking hardware across the path. In the case of audio, losing network packets will result in dropouts at the receiving end. Audio dropouts correspond to signal discontinuities perceived as glitches, which, in the case of NMP, can seriously hinder the collaboration of music performers.

Despite almost three decades of research efforts, the main challenges faced by the implementation of NMP systems have not been defeated. NMP is a vision rather than a technological affordance and may only be feasible under certain conditions, namely through highly reliable network infrastructures (e.g. academic networks) and short geographical distances. Nevertheless, the ongoing progress in network and audio codec technology, e.g. the Opus codec, which is currently the de facto standard for real-time audio streaming over IP, allows us to increasingly consider alternative setups in which NMP may be feasible as well as useful, [23].

Moreover, recent progress in computational intelligence and machine musicianship suggests the advancement of NMP applications equipped with predictive capabilities to anticipate and reproduce musicians’ performance remotely, thereby mitigating latency and quality constraints. At present, NMP research is highly interdisciplinary as it involves numerous aesthetic, technical, and perceptual aspects. Among other domains involving networked collaboration, the COVID-19 pandemic manifested a compelling need for the development of systems supporting online music education. In music learning and teaching, it is rather uncommon for connected peers to simultaneously perform the same piece of music. It is instead more common that a teacher or a student will perform a musical excerpt, and others will be required to imitate or discuss the performance. This practice allows for alleviating the excessive requirements in network reliability and realizing more feasible NMP setups. Researchers appear to be increasingly investing in the development of novel applications and services for online music learning, [26]. The innovation capacity as well as the improvement of user experience in such efforts can be significantly enriched by considering research accomplishments on artificial intelligence, musical acoustics, room acoustics, and music embodiment.

2.1.3 Artificial Intelligence in Music

Researchers in MTA have examined generative deep learning methods since their early developments, mainly regarding the possibilities that such methods offer for human control of the musical output. This control could either be in the form of pre-designed parameters, e.g., for generating drum rhythms by adapting to new contexts that they have not encountered during training by proper annotation of compositional conditions, [27]. Such models exhibited some interesting adaptations to time signatures that were not included during training. Or through real-time interaction, either by changing rhythm and pitch-related parameters by allowing the user to move a 2-dimensional square within some predefined limits, or by allowing musicians to improvise on a given chart and having the system to create the proper piano accompaniment, [28].

Additionally, such methods have proven useful for visualizing large datasets under different perspectives that are set by the user. Methods based on Long Short-Term Memory (LSTM) and more recent Transformer-based approaches have produced interesting results that allow users to explore large databases of jazz standard song charts (i.e., scores with chord symbols) according to a wide range of user-defined criteria. As in the case of music generation, sequence learning methods capture some high-level features that allow human interaction and “communication” of some basic concepts. For instance, given proper annotations, some high-level features can be inferred from the context, e.g., transformers were able to capture the concept of 12-bar blues when trained to identify the blues form from “raw” symbolic representation of memory (without explicit annotations about the length of a piece in bars).

Recent machine learning methods have exhibited impressive results that have been developed to demo or product-level by worldwide recognized companies and universities. Such examples include the ChatGPT family of dialogue systems and DALLE 2 for image generation, among many others. Even though such deep learning methods capture high-level concepts, there is an open question about the extent to which the result they produce can be creative, [29]. To put the question differently, can those methods create new conceptual relations that can capture unlearned but "entailing" interpretations that explain new, unseen data in new ways, or allow the generation thereof that is not only (impressively) adhering to specific (learned) norms, but also actively recombining knowledge in a way that reveals something new? This is what creative humans do naturally, even without the need for huge training datasets; imagine what low quantities of "data" were available to J.S. Bach.

A model that describes and explains human creativity is Conceptual Blending, [30]. This model has inspired the development of theoretical methods that explain musical creative processes, [31] and computational methods (based on Goguen's formulation, [32]) for music generation (among other fields) that combine rule-based and "traditional" machine learning approaches. Those methods learn specific components of harmonic knowledge from data and can recombine those components effectively, creating new harmonic spaces that integrate learned parts in new arrangements that are justified through the preservation of well-established musical principles, described through rule-based formulations.

This generative combined approach has led to the development of the CHAMELEON melodic harmonization assistant, which has been evaluated by composers of different levels, as an assistive tool for making melodic harmonizations, [33]. Except for that, a similar approach has been examined for the cross-harmonization of jazz standards, [34], where the melody of one song is harmonized with the harmonic space of another song. Similar approaches have been examined for melody and drums rhythm, generation. In the latter two approaches, the "creative part" involved blending high-level features of melodies and drum rhythms. The "generative" component, i.e. rendering those features to music, was carried out by genetic algorithms that targeted the high-level features mentioned above in their fitness functions.

What sets such research apart from current trends in machine learning generative methods is the fact that the creative component is separated from the generative component. This approach in some sense identifies the necessary creative processes on a "System 2" level, while it takes advantage of the "System 1" inherent properties of machine learning methods. More details for this discussion can be found in a popular article, [35].

2.1.4 Electroacoustic Music Composition - Musical Instruments

MTA is represented by academic members in the Hellenic Association of Electroacoustic Music Composers (HELMCA), [36] and members of the International Confederation of Electroacoustic Music (CIME/ICEM), [37]. Electroacoustic Music (EAM) is the artistic field that is in a constant search for innovation, both during research and in the application, of electroacoustic technology for the aesthetic creation of sound forms and the musical organization of sound, [38], [39], [40], [41]. Its close relationship with the evolution of musical technology, as well as contemporary aesthetic searches, makes it a constantly renewed field of research and artistic creation, [42]. The field of EAM is a convergence of the techniques and technologies of sound composition, processing, and projection as well as aesthetic criteria and analytical methodologies for the study and creation of sound forms, [43].

From a historical perspective the first field of applications in music technology is the invention of new (in their time) musical instruments. Present studies of design and invention integrate different materials and technologies for sound production, manipulation, and the diffusion of their sound. These research studies present musical instruments that can be electronic, electroacoustic, hybrid, digital, for one or more musicians, «intelligent», extended, networked, automated, robotic, and interactive, [44], [45]. Their design demands knowledge and skills from various fields of science, music, and technology, [44], [45], [46]. From the beginning of the 20th century until today many new musical instruments have been invented, but a few of them have been survived and still in use today, like Theremin, Onde Martenot, Analogue Modular Synthesizers, and others. Over the past two decades, there has been an ever-increasing interest in the research, design, and use of new electronic musical instruments, and members of MTA work in this field.

2.1.5 Acoustic Ecology and Soundscape Ecology

An artistic and in parallel scientific subfield of research in MTA is acoustic ecology and soundscape ecology, [47], [48]. Acoustic ecology, also known as soundscape studies, is a field that explores the interaction between humans and their surroundings through sound, [49]. Soundscape ecology investigates the acoustic connections between various living organisms, including humans, and their environment, whether they reside in marine or terrestrial ecosystems.

The soundscape terminology was established by R. Murray Schafer, as the sonic environment, technically any portion of the sonic environment regarded as a field of study. The term refers to actual environments or abstract constructions such as musical compositions and tape montages, particularly when considered as an environment, [50]. Schafer's terminology helps to express the idea that the sound of a particular locality (its keynotes, sound signals, and sound marks) can - like local architecture, customs, and dress - express a community's identity to the extent that settlements can be recognized and characterized by their soundscapes, [49].

Acoustic ecology can set the base for a dynamic monitoring instrument for the evaluation of the environment by observing the acoustic signature of species and landscapes, [51]. Acoustic indices are increasingly being used when analyzing soundscapes to gain information on biodiversity and describe the environment. There has been considerable interest and research to develop and compute acoustic indices that represent the characteristics of the soundscape, [52], [53], [54].

Ongoing research, in the frame of a PhD thesis, focuses on the soundscape of the White Mountain in Crete using analytical methods of acoustic ecology, soundscape ecology, and ecoacoustics. The way soundscape analysis can provide a feasible approach for the environmental monitoring of the acoustically unknown areas in the area, is investigated. Additionally, the observation of the soundscape as a monitoring system of an ecosystem function and sustainability and the analysis of the acoustic activity are introduced as methods which can efficiently recognize the changes in the ecological integrity and can be a valuable tool for environmental management.

Furthermore, several research studies on specific soundscapes of Crete and Greece have been conducted in MTA in the framework of Bachelor Theses. A mixed methodology of recording and analysis has been developed and applied to those projects. The study, recording, and preservation of the sound diversity (analogous to biodiversity) of protected natural areas aim not only to the advantage of scientific knowledge but also to the awareness of an ecological balance of the world through sound. This aim is served through soundscape musical composition that brings this ideal balance to the focus of attention, [55].

2.2 Acoustics

The main research subfields of acoustics where the MTA is significantly contributing and exhibiting leading expertise are physical acoustics, optoacoustics, ultrasonics, vibroacoustics, and musical acoustics. These basic subfields are further presented and analyzed along with the methods applied.

2.2.1 Physical Acoustics, Optoacoustics, Ultrasonics

Researchers of MTA in collaboration with the Institute for Plasma Physics and Lasers (IPPL) of the Centre of Research and Innovation of HMU are experts in laser-matter interaction and have developed whole-field dynamic laser interferometry methods, [56], capable of studying the dynamic behavior of the irradiated matter and the generation and propagation of ultrasonic waves. These interferometric methods have very high spatial and temporal resolution, while nanosecond and femtosecond laser pulses are used. A white-light interferometry method has also been implemented to monitor permanent damages and to evaluate the ablation depth of the laser-irradiated samples. Moreover, pump-probe transient reflectivity optical setups, [57], have been developed capable of studying the generation of nano-acoustic strains in thin metallic films (such as Au, Ag, Ti, Ta) deposited on substrates (such as Si, ZnO, glass) using optoacoustic transduction on the laser irradiated samples.

Researchers of MTA are experts in numerical modeling and simulations of coupled multiphysics problems using basic numerical methods like the Finite Element Method (FEM), the Finite Difference Method (FDM), and the Boundary Element Method (BEM). Numerical methods can simulate complicated processes, i.e., when the material properties are anisotropic, viscoelastic, or temperature-dependent, as well as complicated geometries of dynamic structures. The numerical methods have many advantages compared to the analytical methods since the solution domain is divided into many smaller domains that are allowed to have different values of physical properties and/or varying loading conditions. FEM is ideal for solving complicated multiparametric problems like laser-matter optoacoustic interactions. The researchers of the Department have carried out multiphysics FEM simulations to investigate the interactions of pulsed lasers (ns, ps, or fs duration) with thin solid films and study their dynamic thermomechanical behavior, [56] and their transduction efficiency. The FEM model is capable to compute the phase changes of matter, to concerning the material properties, as well as to provide detailed insights into physical quantities such as displacements, temperatures, velocities, stresses, and plastic strains at every spatiotemporal solution time step. These simulations can monitor the generation and propagation of surface acoustic waves (SAWs), [56] and longitudinal waves, [57] and are validated by experimental interferometric measurements and pump-probe techniques developed by researchers of the Department.

To study the dynamic behavior of the irradiated samples via FEM numerical simulations a CAD geometry of the structure to be irradiated is first created, then a fine mesh geometry is generated, and transient Multiphysics coupled thermal-structural analysis takes place. The heat conductivity and mechanical wave propagation equations are solved, while the laser source is considered as a heat source loading term for the simulations. Elastoplastic material properties as well as temperature-dependent material (thermal and mechanical) properties are considered for the simulations. The modeled structure can be any type of material such as metal, polymer, semiconductor, composite, or metamaterial. The appropriate boundary conditions should be also provided for the developed model. An important aspect of the developed models is that the Lagrangian mesh may be locally adaptive depending on the simulation needs.

The recent development of compact and cost-effective nanosecond, picosecond, and femtosecond laser systems, capable of inducing breakdown in ambient air or other gases and solids, has facilitated the widespread integration of laser-plasma sound sources across scientific and industrial domains. Typical LPSS applications include, among others, Laser-Induced Breakdown Spectroscopy (LIBS), [58], non-destructive testing and diagnostics [59], signal transmission for underwater or air-water communication, and military applications, [60]. The Department has made significant contributions and exhibits leading expertise in the study, characterization, and exploitation of laser-plasma sound sources in ambient air. Laser-plasma sound sources (LPSSs) in ambient air are generated by optoacoustic transduction of fast (nanosecond) or ultrafast (picosecond - femtosecond) laser pulses with sufficient energy focused on a gas gaseous, liquid, or solid target. In ambient air, laser-induced breakdown (LIB) with consequent generation of an LPSS requires optical intensities above the threshold of approximately 2×10^{11} W/cm^2. Laser breakdown triggers a fast thermalization process in the air which results from the interaction of hot free electrons with heavy particles (ions, atoms, and molecules) within the ionization volume. The thermalized air bubble undergoes rapid expansion and elastic contraction, hence generating rapid pressure fluctuations that lead to the emission of an acoustic pulse. After the emission and propagation of the pulse away from the source, the medium returns to its initial state. The acoustic pulse has a characteristic time-domain profile of an N-pulse with a duration that can span from a few microseconds to tens of microseconds, depending on the characteristics of the incident laser radiation. Concurrently, the excited volume emits light due to luminescent processes and localized thermal excitation. Previous research carried out by MTA in collaboration with the IPPL of the HMU and the Electrical and Computer Engineering (ECE) Department of the University of Patras (UP) has revealed a correlation between the optical and acoustic signals generated by laser-induced breakdown in air, enabling the prediction of the acoustic emission of the LPSSs from the respective light emission.

In terms of frequency content, the generated acoustic N-pulse exhibits a low-end response with a first-order high-pass profile (see also Results section). For nanosecond laser pulses, this spectral range extends from subsonic frequencies (< 20 Hz) to the upper audible frequency range (~ 20 kHz) or the near ultrasounds (< 50 kHz). Femtosecond laser pulses typically yield a wider frequency range that extends well into the mid-ultrasound range (> 500 kHz), at a cost of reduced acoustic energy within the audible range. At the high-frequency end of the spectrum, the acoustic N-pulses exhibit a well-defined response that diminishes with increasing frequency. The peak pressure levels achieved by LPSS can exhibit significant variation, ranging from barely perceivable (a few decibels) to exceptionally loud (130 dB or higher). This variability predominantly depends on the total optical energy deposited into the targeted medium, such as ambient air. MTA and the aforementioned partners have carried out extensive research on the correlation between laser radiation characteristics, namely laser pulse energy, duration, wavelength, and focusing conditions, and acoustic pulse characteristics, particularly acoustic pulse pressure, energy, and duration, [61].

Additionally, the geometry of laser-plasma sound sources ranges from a completely spherical (point-like) configuration to an elongated one (cylindrical or line-like). This variability is contingent upon the characteristics of the incident laser radiation and results in acoustic emissions spanning the entire range from fully omnidirectional to highly directional. Specifically, tightly focused short laser pulses, typically in the nanosecond range, create point-like plasma sources characterized by dimensions of the order of a millimeter emitting spherical sound waves. Conversely, the loose focusing of ultra-short laser pulses, in the picosecond or femtosecond range, gives rise to the formation of line-like sources, commonly known as laser-plasma filaments. These filaments typically possess sub-millimeter thickness and lengths that can vary from a few millimeters to hundreds of meters, contingent on the laser pulse energy and focusing conditions. Laser-plasma filaments produce cylindrical acoustic waves known for their distinct directional and propagation characteristics. Recently, MTA and IPPL and collaborating partners have introduced a computational model that allows for the estimation of the acoustic directivity of the resulting plasma source in the far field, considering its specific geometry, [61]. Also, the team has shown that energy deposition by non-linear interaction of femtosecond laser pulses with ambient air can be effectively modeled by use of Particle-In-Cell (PIC) codes, [59]. Moreover, a research group including members of the MTA has proposed the exploitation of optoacoustic transduction for the reproduction of audio signals via massless, spatially unbound, movable, and potentially remote LPSSs, [62], [63].

2.2.2 Vibroacoustics, Musical Acoustics

MTA is among the pioneers in the study of musical instruments using laser-based interferometric techniques. Experimental modal testing allows the identification of modal parameters of vibrating musical instruments such as natural frequencies, mode shapes, and modal damping for the substructures of the musical instruments. Modal analysis is a combination of a method for the calculation of the frequency response function (FRF) of the vibrating instrument and the visualization of the resonant modes. This analysis has been the topic of numerous studies in the past years, [64], [65].

A widely used modal analysis technique is based on the impulse response measurements utilizing an impact hammer and an accelerometer, [66]. Using the signals of the applied force and a kinematic quantity (e.g. acceleration) the FRF can be calculated by various estimators, which are ratios of the auto and cross spectra of the input and output signals. These measurements can provide the FRF, which contains information about the frequencies where the resonances occur and can lead to vibration characteristics of the system such as damping etc. On the other hand, they do not provide any information concerning the vibration mode itself, e.g., how the system vibrates and the amplitude distribution. For this, holographic methods are applied, which are also used in the field of musical acoustics, [66], [67], [68], [69].

An interferometric technique, namely Electronic Speckle Pattern Interferometry (ESPI), [66], is used in the Department for the visualization of vibration modes. It is a technique that uses laser light together with detection video recording and processing to visualize static and dynamic displacements of the measuring objects. A brief description of ESPI follows. A laser beam is split in two. The first, illuminates the vibrating object, the reflected beam is combined with the second beam, and the resulting hologram is captured by a CCD camera. The resulting images contain spatial information of the vibrating surface, along with amplitude information of the perpendicular to the surface vibration. The combination of the impulse response measurement with the ESPI results provides a detailed description of the vibrating instrument.

Finite element analysis is ideal for predicting how musical instruments respond to any kind of force loads, vibrations, and variations in environmental conditions (temperature, relative humidity, etc.), [70], while in musical acoustics, the BEM formulation is commonly used to calculate the sound radiated by simulated musical instruments, [71]. Researchers in the Department have simulated the vibroacoustic behavior of string musical instruments such as the violin and the bouzouki, [66], as well as the vibroacoustic behavior of percussion musical instruments, [17], [72]. The vibroacoustic behavior of the string musical instruments has also been validated by experimental measurements using ESPI, impact hammer, and psychoacoustic tests, [66], thus a collaboration of researchers performing simulations and experiments has been accomplished in the Department. In the study of the vibroacoustic behavior of cymbals via FEM-BEM simulations, motion experiments have also been performed providing accurate data for the drumstick cymbal interaction, [17]. Results of this study may be further used as reverse engineering inputs, to machine learning models for the estimation of geometrical and mechanical parameters of cymbals from audio signals, enhancing the collaboration between the faculty members of the Department.

Regarding the methodology for studying the vibrational and acoustic behavior of musical instruments via numerical simulations a CAD geometry of the musical instrument is initially created, based on the real geometric characteristics or via 3D scanning, then a fine mesh geometry is generated and various numerical analyses: such as modal, frequency response function, harmonic, [73], in the frequency domain as well as time domain FEM-BEM vibroacoustic analysis, [17], can later be performed depending on the needs of the research. For all these different simulations proper material properties, loading, and boundary conditions are provided to the developed model.

3 Results

The research in the scientific areas and the subfields described above, has led to novel results and cutting-edge applications. Representative research results and key findings are presented here.

3.1 Music and Sound Technology

3.1.1 Music Embodiment

Regarding the aforementioned study (see section 2.1.1) which explores the embodied aspects of Hindustani/Dhrupad vocal music, the findings indicate that while Dhrupad singers exhibit some variability in how they use their hands during singing, there remains a level of consistency in how they associate effort with different melodies and types of gestural interactions with imaginary objects. However, various cross-modal associations are identified among the vocalists, which depend on the specific melodic mode (raga), the mechanics of vocal production, the structure of the improvisation (alap), and analogies between different domains.

For instance, in the case of Dhrupad vocalist Afzal Hussain, the effort level exerted by the vocalist's body is associated with:

1. The pitch range within each octave, specifically the highest note reached during the ascending portion of the melodic glide (whether in the upper or lower part of the octave).
2. The melodic intention to ascend or move toward the tonic note in the subsequent melodic progression.
3. The size or interval of the ascending portion of the melodic movement.
4. The asymmetry between ascending and descending melodic glides, where ascending corresponds to an intensification in effort, and descending corresponds to an abatement in effort.

There is an observed trend for interactions with elastic objects (stretching or pushing-compressing) to be more effortful than interactions with rigid objects (pulling gestures: medium levels; throwing: low; two types of grips: effortless).

Additionally, in terms of gesture classification, results have highlighted specific cross-modal association trends between gesture classes (interactions with elastic versus rigid imaginary objects), effort levels (ranging between 0-10, 10 being the highest), melodic intention (ascent vs. descent) and octave pitch range (low, high part of octave); the latter being closely related to more stable vs. unstable melodic movements for each melodic mode (raga Jaunpuri).

The findings obtained from all participants also demonstrate the feasibility of creating concise models for estimating effort and classifying gestures using a limited set of statistically significant acoustic and movement features derived from the original data. Two variations of these models were developed: (a) one tailored to best suit each performer and (b) one designed to capture shared behaviors across different performers. Variations between these models can be attributed to either unique gestural styles, suggesting the need for an individualized approach for each performer, or a weakness of the selected low-level features in capturing the fundamental aspects of the responses. The latter could be due to the restricted dataset size and the challenge of quantifying subjective aspects that involve some level of interpretation.

In essence, these findings underscore a substantial connection between effort and melodic characteristics, although the relationship with performers' hand gestures appears to be less straightforward, more personalized, and potentially less consistent. For example, the subsequent analytical representation of effort levels relies on a general linear model derived from the original data, which exhibits a higher degree of overlap across performers in terms of the number and type of features. It holds that, [14]:

$$effort = -2.13 * f1 + 2.3 * f2 - 1.34 * f3 + 0.93 * f4 + 0.65 * f5$$

where:
f1 = starting minimum pitch on a relative logarithmic scale (about the tonic).
F2 = maximum pitch on an absolute logarithmic scale (pitch height).
F3 = mean value of velocity calculated on the mean position of the two hands.
F4 = SD of velocity calculated on the mean position of the two hands.
F5 = mean hand distance according to handedness, only used for one of the singers.

Figure 3 provides a schematic representation of parameter mapping, highlighting the potential integration of the linear model into evolving Electronic Musical Instruments. It visually represents the changes in acoustic and movement features based on different levels of user effort.

These findings could inform the optimization of Electronic Musical Instruments by incorporating effort as an intermediary mapping layer. This naturally prompts discussions about the possibility of utilizing physiological data as a more intuitive measure of effort in wearable technologies.

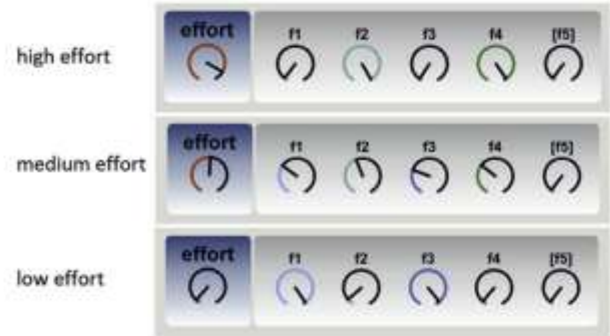

Fig. 3: Schematic overview of potential parameter mapping in new Electronic Musical Instruments, [14]

3.1.2 Networked Music Performance

MTA has contributed to the research domain of NMP by presenting one of the early systems for real-time music collaboration, called DIAMOUSES. As realized through dedicated experiments, DIAMOUSES can support a wide range of music performance scenarios including music rehearsals, music lessons, and jamming sessions, [23]. DIAMOUSES is presented as one of the first systems investigating remote musical interactions at the 'Networked Music Performance' article on the Wikipedia and has produced some of the first graphical user interfaces for NMP, [23], such as the one shown in Figure 4.

In the years that followed, MTA contributed to the MusiNet project, which used the Opus low-latency audio codec to ease communication throughout commonly available network infrastructures. Part of this research was devoted to investigating the perspective of NMP collaborations in traditional music, thus promoting NMP as an enabling technology for remote ethnic groups to widely disseminate their musical culture. An attempt of a Cretan music performance conducted through the network is depicted in Figure 5.

In the post Covid-19 era, NMP research endeavors in MTA were devoted to the development of the MusiCoLab platform for online music education. MusiCoLab provides a suite of collaborative, web-based applications supporting online music teaching and learning by facilitating musical artifacts such as music scores (shown in Figure 6) and backing tracks (shown in Figure 7) as collaborative objects that may be manipulated and transformed during synchronous and asynchronous music learning. A distinct focus of MusiCoLab is to make use of current achievements in artificial intelligence for automatic music content analysis to enhance engagement in music learning, [74].

Fig. 4: Graphical User Interface of the DIAMOUSES project during a networked music rehearsal

Fig. 5: Traditional music performance conducted through the network using the MusiNet infrastructure for NMP. Preparation of musicians to before the experiment (Left). One of the musicians collaborating through the network (Right)

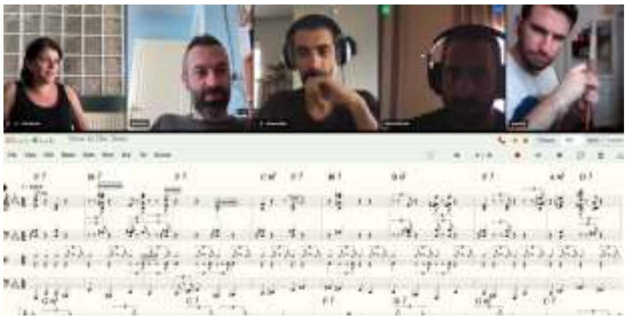

Fig. 6: Collaborative transformations of music notation artifacts in MusiCoLab

Fig. 7: Collaborative music learning using a backing track in MusiCoLab

3.1.3 Artificial Intelligence in Music

The most interesting results regarding AI in music have been produced by the development of the core method that performs conceptual blending in musical cadences, [75].

This method is the basis for building compound harmonic spaces that allow melodic harmonization. Building those compound spaces is closely related to what human composers do: we get a new concept (e.g. the tritone substitution) by recombining things that are already known (perfect and phrygian cadence) and use it in a way that reveals something new about our world (i.e. that both-direction resolutions are possible). Figure 8 shows the voice relations that are involved in generating this result, with bold lines/connections indicating strong relations and thin lines weak but considerable relations. This new concept can be employed in various contexts provided by the melody. With this method, the generative and the creative processes are distinct: the generative part is creating the concrete chords for a given melody; the "creative" part has initially figured out the new component that provides alternative interpretations of what we already know (about how chord transitions work within the initial spaces).

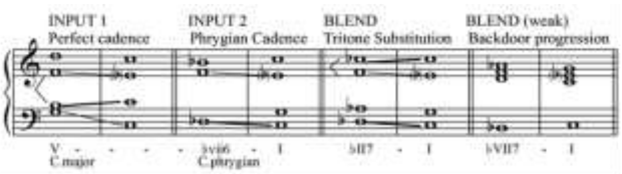

Fig. 8: Conceptual Blending of the Perfect and the Phrygian cadences creates the tritone substitution and the backdoor progression chord sequences

Fig. 9: Melody with segments in the C and F# tonalities harmonized with the blended C and F# Bach chorale major spaces

This method has produced results in various directions, [76], regarding the creative exploration of harmonic spaces, including blending of harmonic idioms that are "incompatible" (meaning that they have few common or similar chords) and blending of harmonic spaces that result from transposed versions of the same harmonic space (e.g. the harmonic space of the Bach Chorales in C and F# major tonalities). Especially in the latter case, the method proved useful for producing harmonic solutions for harmonizing melodies with implied harmonic characteristics that are inconsistent with a given harmonic space. The example in Figure 9 shows such an example, where segments of the melody are composed in different tonalities. Blending the harmonic space of the Bach Chorales in C and F# major tonalities provides a solution to this unconventional melody (regarding the style of Bach Chorales) that recombines what is already known (i.e. the space of Bach Chorales) and reveals something new (i.e. that such remote tonalities can be bridged by manipulating specific components of the existing space).

Fig. 10: Two example cross-harmonizations with "Solar" as Song A and (a) Giant Steps and (b) Time Remembered as Song B. Melody mismatches are indicated. In (a), melody mismatches are very often, in contrast to (b)

The application of the method that was adjusted for generating cross-harmonizations of jazz standards (i.e. melody of one song reharmonized based on the harmony of another), indicated that there are still details in the generative part (i.e. the part that applies chords to the given melody) that need to be corrected. Figure 10 (taken from [34]) shows that in some cross-harmonizations, some produced chords harmonize melodic segments that include notes that are “incompatible” with the chord; identifying those incompatibilities, however, would require the formulation of extensive sets of rules for each chord. It is a future challenge to examine how deep learning models would help toward implicit learning of such rules from data.

3.2 Acoustics

3.2.1 Physical Acoustics, Optoacoustics, Ultrasonics

Representative results of pump-probe experimental measurements along with FE results are shown in Figure 11 from a research collaborative work of the MTA researchers with IPPL, that studies the photoacoustic transduction on Ta and Ti thin films, [57]. Figure 11a presents comparative transient reflectivity signals from Ta and Ti thin films coated on Si <100> substrates. The reason behind the larger modulation depth on the Ta sample, compared to the Ti sample, is the result of enhanced photoacoustic transduction. Figure 11b shows the time evolution of the strain penetrating the substrate at 4 nm depth from the interface with the metal, as calculated by the FE model for both Ta/Si and Ti/Si samples. Due to the larger Young’s modulus of Ta higher strains are developed. Both experimental and simulation results demonstrate that Ta exhibits superior photoacoustic properties.

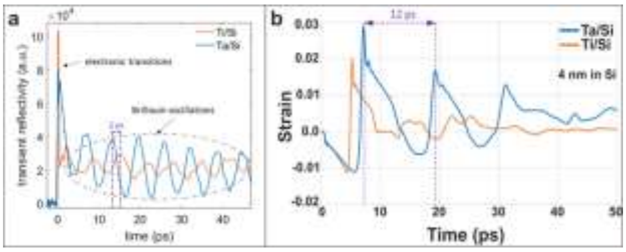

Fig. 11: a) Measured transient reflectivity signals for the 25 nm Ta and Ti films on Si substrates showing the electron excitation and Brillouin oscillations characteristic feature, b) Calculated strain distribution in 25 nm metal/Si systems as a function of time, for a depth of 4 nm in the Si substrate.

Regarding the research on simulated optoacoustic interactions, Figure 12a shows representative results of the vertical component of displacement for three different distances from the center of an irradiated Si target via a 6 ns laser pulse. Moreover, Figure 12b shows characteristic contour plot results of vertical displacement for three different temporal moments. The laser intensity is in the thermoelastic regime, and it is evident that an SAW is generated and propagates through the sample. The speed of ultrasonic waves can be calculated by dividing the distance between two nodes by the time required for the wave to propagate from one node to the other. Thus, the propagation speed is calculated to be ~5000 m/s. This value has low deviations from the value of 5200 m/s, which is found when using the analytical equation found in [77], for SAW. A thermal structural FEM simulation was performed, to obtain this result, considering temperature-dependent thermal and mechanical properties, while the laser source of Gaussian distribution is considered as the heat source loading term.

Regarding research on LPSS, new results from the study of the acoustic directivity of LPSSs generated by strongly focused nanosecond pulses are here presented. Figure 13a shows a schematic diagram of the LPSS measurement process. The LPSSs are formed by laser pulses with a 6 ns duration of 532 nm wavelength and 120 mJ energy, focused by a 75 mm lens. For the acoustic measurements, a high-dynamic range and broadband microphone are used (G.R.A.S 46BE) connected to a high-sampling rate audio interface (RME Fireface 802). Recording is done by Audacity software. Figure 13b shows the acoustic directivity of the generated laser-plasma sound sources measured at 12 cm from the source. The polar diagram of Figure 13b is calculated by taking the total acoustic energy of the measured N-pulses on the azimuthal angles 0, 30, 60, and 90 degrees. The emission towards the directions from 120 to 180 degrees is extrapolated considering cylindrical symmetry. The source exhibits a mild directionality as the acoustic emission on the laser propagation axis is approximately 5 dB lower than on the axis perpendicular to the laser path. This is expected since, as it is well known, even with strong focusing the plasma source exhibits a slightly elongated geometry that mainly occurs due to plasma back-propagation, [78].

However, the directional characteristics of the source become weaker with increasing observation distance. Figure 14a shows the acoustic directivity of the LPSS generated under the same conditions, this time measured at 60 cm. Figure 14b shows the respective acoustic frequency spectra where, for reasons of completeness, three measurements on the xz plane at elevation angles 30, 60, and 90 degrees are also plotted. From the two diagrams, it becomes evident that the plasma source exhibits an almost perfect omnidirectional emission at 60 cm distance, with a maximum deviation of less than 1 dB between different angles. The measurements on the xz plane validate the assumption of cylindrical symmetry used to extrapolate the data.

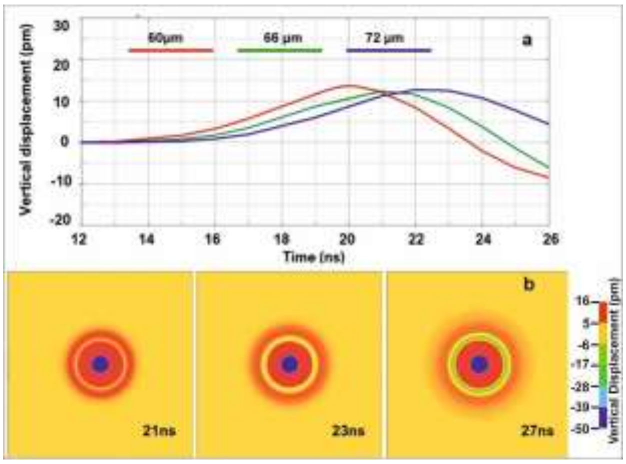

Fig. 12: a) The evolution of vertical displacement for three different distances from the center of an irradiated Si target in the thermoelastic regime. b) Contour plots of vertical displacement for three temporal moments

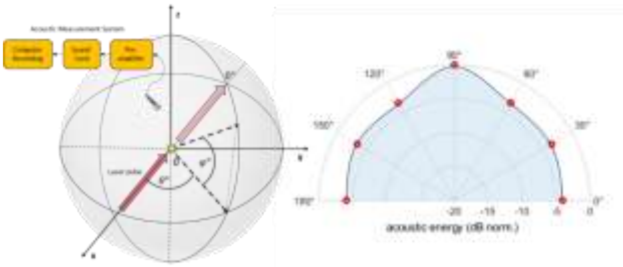

Fig. 13: a) Schematic diagram of the process for measuring the acoustic directivity of LPSSs, b) acoustic directivity of LPSSs generated by strongly focused nanosecond laser pulses with 6 ns duration, 532 nm wavelength and 120 mJ energy measured on the xy plane at 12 cm distance

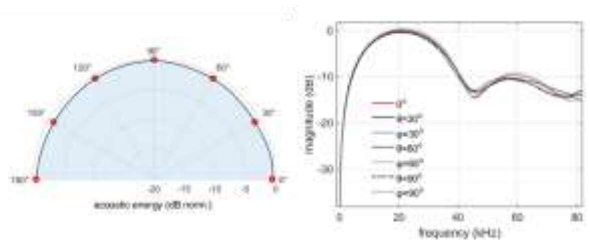

Fig. 14: a) Acoustic directivity of LPSSs generated by strongly focused nanosecond laser pulses with 6 ns duration, 532 nm wavelength, and 120 mJ energy measured on the xy plane at 60 cm distance and b) respective acoustic frequency spectra with additional xz plane measurements

3.2.2 Vibroacoustics, Musical Acoustics

Figure 15 shows the combination of impulse response measurements along with ESPI results on a carbon fiber bouzouki. The red dot highlights the matching between a resonance frequency in the FRF plot provided by impulse response measurements, and the related vibration mode, as given by ESPI, [65].

Figure 16 shows representative numerical results of a drumstick-cymbal interaction via time-domain FEM-BEM simulations, [17]. Figure 16a shows the pressure distribution of the cymbal 3 ms after being hit by the drumstick, while Figure 16b demonstrates the computed normalized pressure at a point located in the air. For this vibroacoustic simulation, the drumstick body is considered a rigid body, while the cymbal is considered a deformable body. A marker-based motion capture (mocap) system is used for capturing the real loading conditions to be used in the FEM-BEM simulations during the drum-stick-cymbal interaction. The recorded velocity and the spatial coordinates of the drumstick and the cymbal are adopted by the FEM-BEM model. FE is used to model the 8-inch splash B20 bronze alloy cymbal, while BE is used to model the surrounding air. The point where the normalized sound pressure, arising from the impact, is computed corresponds to an assumed microphone position in the acoustic field.

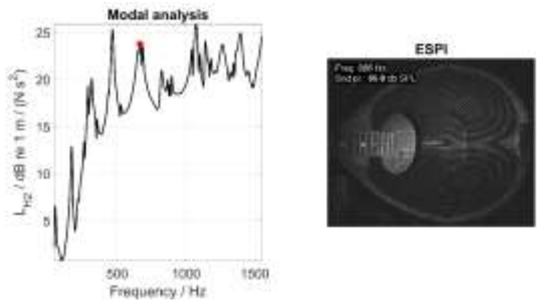

Fig. 15: Combination of a frequency response function and an ESPI image for the visualization of the vibration mode, which is excited at the resonance highlighted with the red dot

Representative results of ESPI experimental measurements along with FE results are shown in Figure 17, as part of a collaborative research effort by MTA researchers investigating the vibroacoustic characteristics of cymbals, [72]. Different CAD approaches are used to model the complex geometry of a curved splash cymbal. The CAD model indicates the critical points of curvature changes and allows for a good approximation by two three-point arcs, able to interpolate the cymbals' curved geometry. A uniform thickness is assumed for the developed geometry. Figure 17 shows the experimental and numerical modal results that present better agreement. The FEM cymbal model has a thickness of 1.3 mm.

The experimental techniques that have been previously described in combination with numerical calculations can fully describe the vibrational and acoustical behavior of musical instruments. The application of the methods' combination during the manufacturing process of musical instruments may lead to assemblies of optimized vibration characteristics.

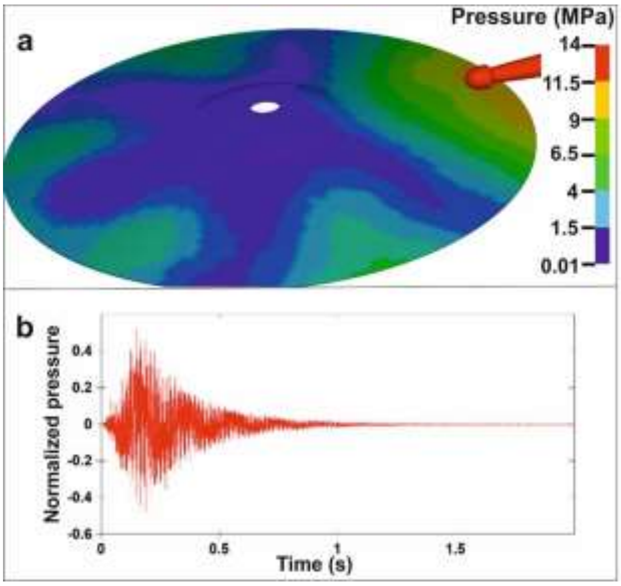

Fig. 16: a) Pressure distribution of the splash cymbal 3 ms after the initiation of the drum-stick-cymbal interaction, b) Time domain FEM-BEM results of sound pressure for the splash cymbal

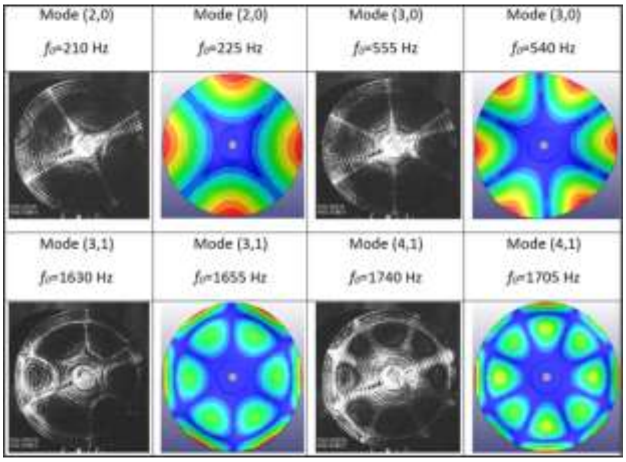

Fig. 17: Four vibration modes and the related resonant frequencies using ESPI and FEM

Regarding local Cretan Music, researchers of the department conducted a vibrational analysis of the Cretan lyra top plate, using ESPI, impulse response analysis, and FE analysis. The vibration amplitude distributions obtained by time average ESPI for each eigenfrequency were in good agreement with the predicted ones from the FE analysis. A vibrational study for the full Cretan lyra assembly was also performed, [63]. Time-average ESPI experimental vibration analysis of the main normal modes of two Cretan lyras of different periods, was performed. The first one was a pear-shaped Cretan lyra of 17th century and the second was a contemporary one. The results showed that the variations in observed normal frequencies were primarily attributed to distinct geometric characteristics and shapes. In general, the 17th-century pear-shaped lyra was smaller in all characteristic dimensions compared to its contemporary counterpart. Consequently, its resonance frequencies were higher for the corresponding characteristic normal mode.

4 Conclusion, Discussion, and Research Prospects

Research in MTA maintains a highly multidisciplinary character that produces results in a wide range of fields spanning from the area of optoacoustics to human embodiment and artificial intelligence. The unique and broad specializations of the research and personnel, in combination with high-end equipment that is available for studying the physical properties of sound and music, have opened new perspectives towards novel research in music technology and acoustics. The scientific novelty and cutting-edge know-how accumulated by the members and groups provide strong potential for the transition towards impactful scientific applications. Such a transition is expected to be further amplified by broader collaborations and the incorporation of mature application-level scientific components, such as artificial intelligence, in a wider range of research activities within MTA.

Particularly, the research in MTA on percussion sound classification by use of artificial intelligence is quickly evolving towards product-level maturity. The very limited relevant literature, [79], [80] shows that the field is not explored and is highly prospective in this direction, with future work focusing on the formation of a large sound database via a programmable motorized drummer machine. Frequency response function modal analysis of percussion instruments, such as cymbals, and idiophones, and corresponding measurements of the instrument's sound spectrum will be performed. The large sound database will be used to train machine learning models to identify different geometrical characteristics and material properties of the instruments from their acoustic response. The efficient drummer machine will enable the fast formation of large databases of objective measurements, effectively eliminating the subjective human factor. This sound database will constitute a reference for the validation of vibroacoustic numerical models estimating percussion instruments' sound synthesis.

Furthermore, the MTA team working on LPSS is currently developing a novel method for the precise characterization of phononic crystals and acoustic metamaterials, [81], that is anticipated to significantly boost the design and adoption of acoustic meta-structures in real-world applications. LPSS exploitation in acoustic perception measurements, biomedical engineering e.g., ultrasound focusing for noninvasive treatment, and study of sound-mater interaction by laser-driven excitation of acoustic meta-structures is planned for the near future. This optimal acoustic excitation tool will be used complementarily to the motorized excitation system for the evaluation of idiophones, e.g., percussive instruments, with unprecedented advantages, especially in real-time acoustic monitoring of the manufacturing process.

Also, future work includes fusing pre-trained models of images of vibrational modal patterns of given 3D models, [82] and materials with music instrument simulation tools, [83] into a complete tool for the estimation of the impact of different materials and structures in the sound of musical instruments. Accurate implementation of such models would allow instrument manufacturers to make justified decisions during the instrument design phase, but also to explore new materials, shapes, and structures. Such a computational tool, together with the ESPI method developed in MTA for the experimental determination of vibrational modes of acoustic musical instruments, will constitute a complete solution for optimization and innovation in musical instrument design.

Moreover, many possibilities emerge from the idea of leveraging pre-trained machine learning models in specific modalities and fusing them through fine-tuning processes that require few examples for training. One such example is the development of a model that relates upper-body gestures of Hindustani vocalists collected from video and motion capture systems with raga-specific melodic information of the singing voice. Such models could prove useful for the accurate large-scale automatic annotation of special gestures in audio-visual datasets with Hindustani music, allowing, for instance, users to search for audiovisual segments within large databases incorporating specific gestures (possibly performed by the user as a system-input query). These research approaches can be implemented both in situ and remotely, taking advantage of the networked music performance, as presented. Additionally, room and soundscape acoustics may be also considered to enable studies of human-environment music and sound acoustics interactions.

The unique multidisciplinary approach to the physics of sound, audio technology, and artistic aspects of music exercised in MTA, together with the growing collaboration between the various groups of the Department, is expected not only to broaden scientific interest in music technology and acoustics but also lead to unique product-level results.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Vasilis Dimitriou, Maximos Kaliakatsos-Papakostas, and Evaggelos Kaselouris carried out the conceptualization.

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Stella Paschalidou, Chrisoula Alexandraki, Makis Bakarezos, Vasilis Dimitriou, Maximos Kaliakatsos-Papakostas, Evaggelos Kaselouris, Nektarios A Papadogiannis, Katerina Tzedaki, and Nikolas Valsamakis were responsible for writing, review and editing.

Spyros Brezas was responsible for the management and coordination responsibility for the research activity planning and execution and is the corresponding author (denoted by *).

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