forumacusticum 2023

MULTISCALE MECHANICAL STUDY OF MARINE SEASHELLS AND POSSIBLE CONSEQUENCES IN THE DESIGN OF BIOINSPIRED MATERIALS

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ABSTRACT

Determining the mechanical properties at the macroscopic scale of biomaterials with complex shape is challenging due to the fine structure of these materials. Furthermore, biomaterials usually have composite and hierarchical microstructures. This paper presents a combination of experimental and numerical studies on the shells of two different species belonging to the *Turritellidae* family, aiming to investigate the link between the dynamic behavior of the shells and their mechanical properties. The proposed procedure involves the use of micro–Computed Tomography scans for the accurate determination of geometry, Atomic Force Microscopy and Nanoindentation to evaluate local mechanical properties, surface morphology and heterogeneity, and Resonant Ultrasound Spectroscopy coupled with Finite Element Analysis simulations to determine global modal behavior. The results demonstrate that, even when the complex microstructure of the shell is not considered, its effective mechanical properties can still be determined by correlating the computed and measured experimental vibrational behavior. The study also revealed that the unique shape of *Turritella*'s shell (a three-dimensional helicoconic structure) plays a role in its vibration-damping behavior. Moreover, the proposed research method can be extended to other complex natural structures to determine their structure-dependent dynamic properties, which will ultimately help in the design of bioinspired materials and structures with advanced vibration control.

Keywords: *bioinspired materials, dynamic properties, impact-resistant structures.*

INTRODUCTION

Throughout long evolution, biological entities have refined various mechanical, optical, and thermal characteristics that contribute to their overall fitness by addressing specific requirements. In terms of mechanical properties, extensive research has been conducted to uncover the exceptional quasistatic properties exhibited by numerous natural systems [1]. However, the dynamic mechanical properties of these systems have yet to be thoroughly investigated, with only a few remarkable examples documented to date [2,3]. Nature has ingeniously crafted marine shells to serve as a dual-purpose solution: shielding mollusks from predators and providing a safe habitat. Extensive research efforts have been dedicated to investigating the mechanical properties of their microstructure across different scales.

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This exploration has yielded valuable insights for developing biomimetic materials with enhanced impact resistance [4]. While the microstructure of shells is crucial for absorbing impacts, their overall configuration governs their modal characteristics and ability to dampen vibrations. These aspects are intrinsically linked to the primary function of the shell. In this study [5], our attention is directed towards the examination of two shells from the *Turritellidae* family, specifically, the *Turritella_terebra* [1] and the *Turritellinella tricarinata*[2]. These shells exhibit a distinctive conispiral form, accompanied by secondary spirals on their surface, as depicted in Fig. 1. To comprehensively understand their complex structure, we employ a combined approach that integrates numerical simulations and experimental techniques at both micro and macro scales. Through this methodology, we explore the overall mechanical characteristics of the shells, analyze their modal response, and evaluate their vibration properties.

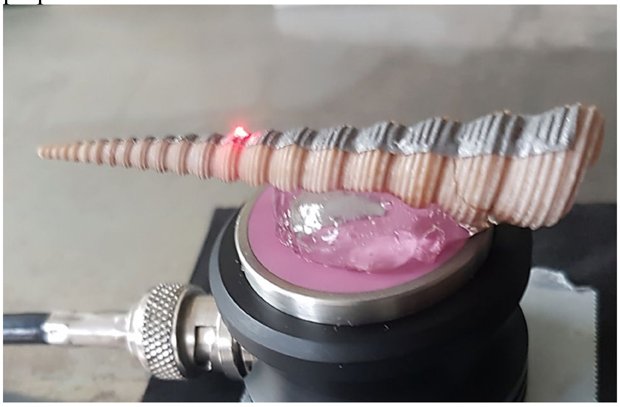

Figure 1. *Turritella terebra* shell mounted on a piezoelectric transducer during ultrasonic excitation experiments.

METHODS & RESULTS

We employed various imaging techniques and experimental methods to investigate the shells. The Micro-Computed Tomography (μ-CT) scan was conducted, utilizing specialized software to analyze and interpret the captured images. This process facilitated the precise characterization of the shell's geometry, which was subsequently imported into the finite element software for further analysis.

Additionally, the microstructure of the shells was directly observed using an electron microscope, providing valuable insights into its internal composition and arrangement. Atomic Force Microscopy (AFM) was employed to assess the nanoscale mechanical properties, enabling the spatial mapping of Young's modulus. Simultaneously, AFM also facilitated the topographic characterization of the polished surface of the samples. Instrumented nanoindentation experiments provided supplementary data, reinforcing the results of the abovementioned techniques.

The vibrational properties of the overall structure of the samples were characterized through Resonant Ultrasound Spectroscopy (RUS). This technique, by also making use of numerical Finite Element Analysis (FEA), allowed us to extract the mechanical properties of the samples from the experimental results. Additionally, it enabled us to investigate the vibration attenuation capabilities of the samples.

In Fig. 1, the experimental setup for the ultrasound measurements is illustrated, while Fig. 2 presents the recorded resonance frequency spectra along 60 points of the longitudinal axis of the shell. To retrieve the global mechanical properties, such as Young's modulus and Poisson's ratio, FEA using COMSOL Multiphysics was performed on the shell geometry. The simulated eigenfrequencies were matched with the experimental data, thus allowing the determination of the mechanical properties, which in this case turned out to be $E=53\pm2$ GPa and $\upsilon=0.35\pm0.06$.

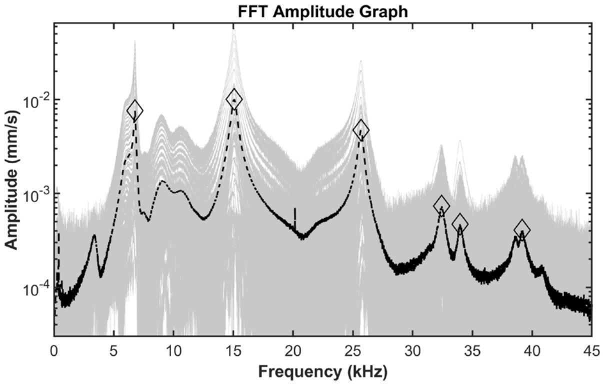

Figure 2. Gray solid lines are the particle velocity spectra recorded along the longitudinal axis of the shell while the black dashed line represents their average. Diamond symbols represent the resonance frequencies.

Then, we proceeded to calculate and compare the dynamic response of the structure of the shell with that of a simplified, purely conical shell (Fig. 3). Our findings revealed that, in addition to exhibiting the same vibration modes as the ideal conical shell, the real shell displayed a significantly richer spectral behavior. This heightened

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[1] Linnaeus 1758

[2] Brocchi 1814

spectral complexity was attributed to the peculiar structural features, particularly the conispiral configuration. Moreover, this intricate structure suggested enhanced attenuation capabilities against impacts. Indeed, the highest modal density exhibited above about 100 kHz by the shell offers more equivalent spring-damper subsystems to spread impact energies.

It is widely known that natural systems displaying efficient impact attenuation often possess hierarchical, interfacial, porous, and composite architecture. Therefore, these effects can be examined to advance the design of bioinspired phononic structures with efficient impact resistance or vibration-damping properties.

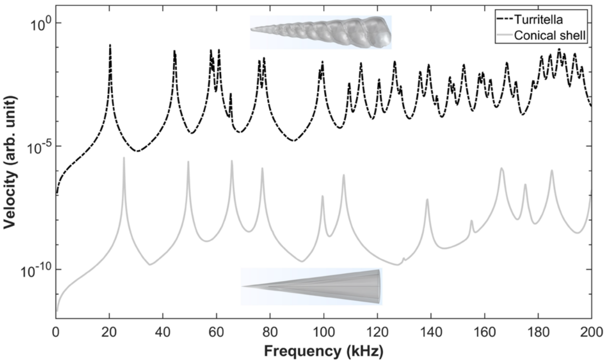

Figure 3. Calculated velocity spectrum for a *Turritellinella tricarinata* sample (dash line, black) and for an ideal, conical shell (solid line, grey) with the same mass and length as the Turritella. The data of *Turritellinella* were shifted to avoid overlap. The isotropic loss factor, in both cases, is equal to **5×10⁻³**.

The shell's geometric structure exhibits a hierarchical configuration, where the spiral shape surface, in turn, features even smaller spirals. The geometric properties of the second order of hierarchy are presented in Fig. 4. Notably, the pitch, representing the distance between two adjacent small whorls on the shell surface, decreases towards the apex of the shell. Similarly, the thickness of the spirals shows a slight decreasing trend towards the apex. These observations indicate that the shell possesses graded properties that are known to induce interesting effects in wave propagation [6]. While it is likely that the primary purpose of this structure, reminiscent of a drill, is to aid the organism in burrowing through mud [7], it is also intriguing to explore the potential secondary functionality of this hierarchical structure in influencing the vibrational behavior of the shell.

Consequently, we calculated the frequency response function of the shell up to 400 kHz, considering both the presence and absence of the second order of hierarchy. The obtained spectra, up to 200 kHz, are shown in Fig. 5. Within the investigated frequency range, the second-order spirals do not significantly affect the results, regardless of whether they are retained or removed from the structure. The shape and number of peaks in the frequency response function exhibit minimal differences, with only a slight frequency shift. This observation is reasonable, as the finer structures at smaller length scales are expected to manifest their effects at higher frequencies. It should be noted that extending this analysis to higher frequencies complicates the interpretation of the results and becomes computationally demanding due to the requirement of smaller element sizes for the mesh. Therefore, alternative methods are needed. In this regard, studies have demonstrated that corrugated surfaces, such as planar or planar-like structures with periodically varying thickness, offer a viable means of controlling wave propagation. These surfaces create Bragg scattering band gaps, leading to destructive interference, and prohibiting wave propagation in specific frequency ranges.

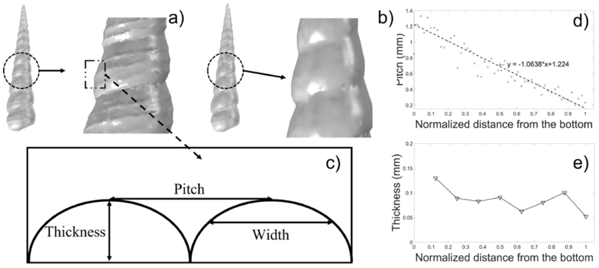

Figure 4. Hierarchical properties of the shell. **a)** The second-order hierarchy of spirals is visible on the first one. **b)** Only the first-order hierarchy is preserved. **c)** A pitch p, a thickness t and a width w are defined for the smaller spirals shown in panel a). **d)**: the pitch of the smaller spirals is decreasing towards the apex of the shell. **e)** The thickness of the smaller spirals also slightly decreases towards the apex of the shell. The width of the spirals is rather constant around a value equal to about $w \approx 0.25$ mm.

Controlling wave propagation using corrugated surfaces has been previously explored in the context of beams [8] and plate structures [9]. These studies have revealed the potential of this approach for various technological applications [10]. The geometrical description of these previously investigated structures is closely linked to the varying thickness characteristic observed in shells, indicating the need for a comprehensive investigation. Our research group is currently engaged in a thorough exploration of this topic, considering diverse factors that can be utilized to adjust the wave dispersion characteristics of shells possessing thickness profiles featuring hierarchical configurations.

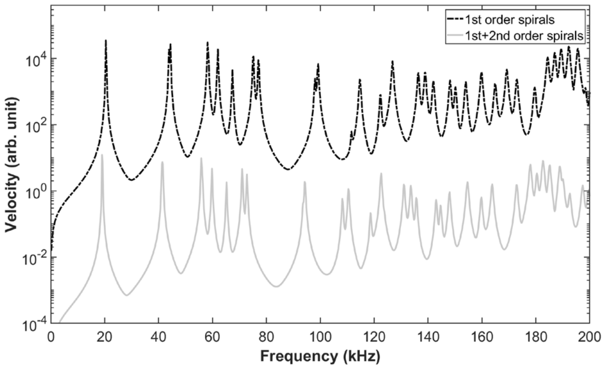

Figure 5. Frequency response velocity spectra of the shell calculated for the first-order only (dash line, black) and for first and second-order of hierarchy (solid line, grey) up to 200 kHz. The data of the first-order of hierarchy were shifted for clarity.

CONCLUSION

The method proposed in this study can be systematically applied to characterize other biological structures with notable vibration behavior, particularly those possessing hierarchical features. By doing so, we can gain deeper insights into their evolutionary development and utilize this knowledge to inspire the design of bioinspired structures: we are currently investigating several examples in this regard. These investigations will contribute to expanding our understanding of biological systems and provide valuable inspiration for the development of novel bioinspired designs.

ACKNOWLEDGMENTS

YL, ML, FSS, GG, VFDP, ASG, NMP, FB, and MT acknowledge the European Commission under the FET Open ‘‘Boheme’’ Grant No. 863179. The authors also thank the Science Museum of Trento (MUSE) for providing the *Turritella terebra* samples. YL acknowledges the financial support for the doctoral study provided by the China Scholarship Council (CSC).

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