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Symphony of Molecules: Can Sound Frequency Tune the Structure of Liquid Water for Functional Use?

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Abstract

Liquid water is a highly correlated molecular system whose structure and dynamics are governed by a continuously evolving hydrogen-bond network. Beyond thermal and electromagnetic perturbations, mechanical excitation in the form of sound waves has emerged as a potential means of interacting with collective molecular degrees of freedom in liquids. This study examines whether sound frequency can transiently tune the structural and dynamical response of liquid water in a controlled and physically consistent manner. The objective is to investigate frequency-dependent sound–water interactions by interpreting observed effects as non-equilibrium, history-dependent responses rather than permanent structural modification or long-term memory. Drawing upon established experimental observations and theoretical insights into collective hydrogen-bond dynamics, the paper outlines plausible mechanisms through which acoustic excitation may couple to extended molecular motion. Emphasis is placed on physical constraints such as reversibility, dissipation, and relaxation toward equilibrium. The analysis highlights key implications for understanding sound-induced modulation of liquid behavior while maintaining strict adherence to thermodynamic principles, thereby providing a conservative and scientifically credible foundation for exploring functional acoustic effects in liquid water.

Keywords: Sound–matter interaction; Liquid water; Frequency-dependent response; Hydrogen-bond dynamics; Collective molecular behavior

1. Introduction

Liquid water is a deceptively simple substance whose microscopic behavior gives rise to a wide range of complex and often anomalous macroscopic properties. Despite being composed of small, neutral molecules, water exhibits strong intermolecular correlations due to its hydrogen-bond network, resulting in collective structural and dynamical behavior that

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distinguishes it from ordinary molecular liquids. These characteristics are responsible for water's unusual thermodynamic, mechanical, and transport properties and continue to motivate extensive experimental and theoretical investigation.

At the molecular level, water is not a static arrangement of molecules but a continuously evolving system in which hydrogen bonds are constantly breaking and reforming.
Importantly, these rearrangements are not purely local or random; rather, they often involve coordinated motion among multiple molecules. Such collective dynamics operate over a broad range of length and time scales and play a central role in determining how water responds to external perturbations. Understanding these correlated motions is therefore essential for any attempt to influence or control water's behavior in a physically meaningful way.

While thermal and electromagnetic interactions with water have been widely studied, mechanical perturbations—particularly in the form of sound and vibrational excitation—have received comparatively less systematic attention in the context of molecular-scale dynamics. Sound waves introduce organized, frequency-dependent pressure and density fluctuations that propagate through the liquid. In a strongly hydrogen-bonded system such as water, these fluctuations may couple not only to
individual molecular motions but also to collective degrees of freedom associated with the hydrogen-bond network.

The motivation for studying sound-frequency effects in liquid water arises from this possibility of selective coupling. If certain sound frequencies overlap with intrinsic relaxation or collective modes of the liquid, they may transiently influence structural correlations or dynamical pathways without inducing permanent change. Such frequency-dependent interactions, if present, would represent non-equilibrium responses governed by relaxation and dissipation rather than violations of thermodynamic principles.

The relevance of collective dynamics is therefore central to this study. Treating water as a correlated many-body system provides a physically consistent framework for exploring how externally applied sound fields may modulate its behavior on short timescales. This perspective avoids speculative interpretations and instead focuses on measurable, reversible effects that are compatible with established liquid-state physics.

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The scope of the present work is to examine, within a conservative and scientifically grounded framework, whether sound frequency can transiently tune the structural or dynamical response of liquid water. The study does not propose long-term memory or permanent structural modification. Instead, it seeks to clarify plausible mechanisms, define physical constraints, and outline conditions under which frequency-dependent sound–water interactions may be meaningfully investigated. By doing so, the work aims to provide a rigorous foundation for future experimental and theoretical studies of functional acoustic effects in liquid systems.

2. Physical Background of Sound–Water Interaction

The interaction of sound with matter is fundamentally a problem of how mechanical energy propagates through and couples to the internal degrees of freedom of a medium. In liquids, sound waves manifest as longitudinal pressure fluctuations that induce periodic variations in density, local stress, and molecular velocity fields. Unlike electromagnetic radiation, which primarily interacts with electronic or intramolecular vibrational states, sound couples directly to translational and collective motions, making it particularly relevant for probing liquid-state dynamics.

From a theoretical perspective, the response of a liquid to acoustic excitation is governed by resonance and relaxation processes. Resonance occurs when the frequency of an external driving force overlaps with intrinsic dynamical modes of the system, allowing efficient energy transfer. In liquids, these modes are typically broad and overdamped rather than sharply defined, reflecting the dissipative nature of molecular motion. As a result, resonance in liquids is better understood as frequency-selective enhancement of response rather than as narrow, long-lived oscillations.

Relaxation processes play a central role in determining how liquids respond to sound. When a pressure perturbation is applied, the system is displaced from equilibrium and subsequently relaxes through molecular rearrangement and energy dissipation. The characteristic relaxation timescales depend on viscosity, intermolecular interactions, and collective molecular organization. In water, relaxation involves not only individual molecular diffusion but also cooperative rearrangements of the hydrogen-bond network, which introduce additional timescales beyond those found in simple liquids.

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Sound-induced effects in liquids are therefore inherently non-equilibrium in nature. The applied acoustic field continuously drives the system away from equilibrium, while dissipative processes act to restore equilibrium once the excitation is removed. Any frequency-dependent response must be understood within this balance between external driving and internal relaxation. Importantly, such responses are transient and reversible, consistent with thermodynamic constraints.

The interaction between sound and water can be analyzed across multiple length and time scales. At the macroscopic scale, classical hydrodynamics accurately describes sound propagation in terms of pressure waves and bulk material properties such as compressibility and viscosity. At the mesoscopic scale, sound couples to density fluctuations and collective modes involving clusters of molecules. At the microscopic scale, pressure oscillations can transiently influence intermolecular distances and orientations, subtly modulating hydrogen-bond stability and rearrangement pathways.

Low-frequency sound is of particular interest because its characteristic timescales can overlap with collective relaxation processes in water. In this regime, the applied acoustic field does not simply average out at the molecular level but may interact with extended dynamical correlations within the liquid. This does not imply permanent structural change; rather, it suggests the possibility of frequency-dependent modulation of relaxation behavior while the system remains in a driven, non-equilibrium state.

Within this theoretical framework, sound–water interaction is best viewed as a problem of frequency-dependent coupling between external mechanical excitation and intrinsic collective dynamics. Any observable effects must be constrained by dissipation, finite relaxation times, and eventual return to equilibrium. This perspective provides a physically consistent foundation for exploring whether sound frequency can transiently tune the dynamical response of liquid water without invoking speculative or unsupported mechanisms.

3. Molecular and Collective Dynamics in Liquid Water

The molecular behavior of liquid water is dominated by its hydrogen-bond network, which links individual water molecules into a continuously fluctuating, three-dimensional structure. Each molecule can participate in multiple hydrogen bonds, leading to a highly interconnected

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system whose properties cannot be fully understood by considering isolated molecules alone. Instead, water must be treated as a correlated many-body system in which intermolecular interactions play a central role.

Hydrogen bonds in water are inherently transient, breaking and reforming on ultrafast timescales. However, these processes are not independent or random. Experimental studies have shown that hydrogen-bond rearrangements often involve cooperative molecular motion, where changes in one bond are accompanied by correlated adjustments in neighboring molecules. Such cooperativity gives rise to collective dynamics that extend beyond the first solvation shell and influence the liquid's macroscopic response.

Insights into these collective behaviors have been obtained through a range of experimental techniques, including neutron and X-ray scattering, ultrafast infrared spectroscopy, and terahertz spectroscopy. These methods reveal the presence of low-frequency modes associated with density fluctuations, orientational relaxation, and network-level rearrangements of hydrogen bonds. Importantly, these modes reflect motions of molecular clusters rather than single molecules, highlighting the collective nature of water's dynamics.

Complementary information has been provided by molecular dynamics simulations, which allow direct visualization of hydrogen-bond networks and their temporal evolution. Simulations consistently show that structural rearrangements in water propagate through correlated pathways, involving multiple molecules moving in a coordinated fashion. Such studies also demonstrate that collective relaxation processes occur over a wide range of timescales, from picoseconds to much longer diffusive regimes, depending on the nature of the perturbation.

The relevance of collective dynamics becomes particularly important when considering external mechanical excitation, such as sound waves. Acoustic perturbations introduce spatially and temporally organized pressure fluctuations that can interact with extended molecular correlations in the liquid. Because collective modes involve coherent motion of molecular groups, they provide a more effective channel for coupling with acoustic fields than purely local, high-frequency intramolecular vibrations.

From this perspective, acoustic tuning of liquid water is not expected to act on individual hydrogen bonds in isolation, but rather on the collective response of the hydrogen-bond

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network. If the frequency of the applied sound overlaps with characteristic collective relaxation timescales, it may transiently bias network rearrangements or modify correlation lifetimes while the system remains in a driven, non-equilibrium state.

Understanding molecular and collective dynamics is therefore essential for evaluating how sound frequency may influence liquid water. By framing water as a dynamically correlated system, this approach provides a physically consistent basis for exploring frequency-dependent acoustic effects without invoking permanent structural changes or anomalous behavior. The collective nature of hydrogen-bond dynamics forms the key link between microscopic molecular motion and macroscopic acoustic response.

4. Frequency-Dependent Effects of Sound on Liquid Structure

Sound waves introduce organized mechanical perturbations into liquids in the form of oscillatory pressure and density variations. The influence of such perturbations on liquid water depends not only on their presence but critically on their frequency, amplitude, and duration. These parameters determine how effectively acoustic energy couples to molecular and collective degrees of freedom and whether the resulting response remains localized, dissipative, or extended across the hydrogen-bond network.

Frequency plays a central role because liquid water supports a broad spectrum of intrinsic relaxation and collective modes rather than sharply defined resonances. When the frequency of an applied acoustic field overlaps with characteristic relaxation timescales of density fluctuations or hydrogen-bond rearrangements, the liquid may exhibit an enhanced dynamical response. In this context, frequency dependence does not imply long-lived oscillatory behavior, but rather a selective modulation of relaxation pathways while the system is externally driven.

The amplitude of the acoustic excitation determines the strength of the perturbation. At low amplitudes, sound–water interactions remain within the linear response regime, where molecular displacements are small and fully reversible. In this regime, transient modulation of intermolecular distances and orientations may occur without inducing cavitation, heating, or chemical change. Higher amplitudes, however, can introduce nonlinear effects, making it difficult to isolate intrinsic molecular responses from
secondary phenomena. Therefore, physically meaningful frequency-dependent tuning is expected primarily under moderate, carefully controlled excitation conditions.

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The duration of acoustic exposure further influences the observed response. Short-duration excitation probes the immediate, time-dependent response of the hydrogen-bond network, while longer exposure may allow cumulative non-equilibrium effects to develop. Importantly, even under sustained excitation, any sound-induced modification of structure or dynamics must remain transient and decay once the driving force is removed, reflecting the dissipative nature of liquid water.

Prior experimental studies in liquids have reported that acoustic fields can influence relaxation behavior, fluctuation spectra, and transport properties under specific conditions. In water, low-frequency vibrational and acoustic studies suggest sensitivity of collective hydrogen-bond dynamics to mechanical perturbations, although reported effects are often subtle and strongly dependent on experimental parameters. These observations support the view that sound interacts with collective molecular motion rather than directly imposing static structural order.

From a physical standpoint, frequency-dependent effects of sound on liquid structure are best understood as non-equilibrium dynamical responses. Acoustic excitation continuously drives the system away from equilibrium, while intrinsic relaxation processes act to restore it. Any observed structural or dynamical modulation therefore reflects a balance between external driving and internal dissipation, rather than the formation of stable or long-lived ordered states.

In the context of the present study, sound-frequency-dependent effects are interpreted conservatively as transient modifications of collective dynamics within the hydrogen-bond network. This framing avoids speculative claims and instead focuses on measurable, reversible responses that are consistent with established principles of liquid-state physics. Such an approach provides a robust foundation for exploring whether controlled acoustic excitation can be used to tune liquid behavior for functional purposes without violating thermodynamic constraints.

5. Hypothesis and Physical Constraints

The central hypothesis of this study is that sound frequency can transiently tune the collective structural and dynamical response of liquid water by coupling to intrinsic relaxation and collective modes of its hydrogen-bond network. This tuning is proposed to occur only while the system is externally driven or within a limited relaxation window

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following excitation, and it does not imply permanent structural modification or long-term information storage in the liquid.

Within this framework, sound-frequency tuning is understood as a non-equilibrium, history-dependent response, where prior acoustic excitation influences subsequent molecular dynamics for a finite duration. The hypothesis assumes that specific sound frequencies may interact more efficiently with collective modes of water, leading to temporary modulation of correlation lifetimes, relaxation pathways, or density fluctuations. Such effects, if present, arise from enhanced coupling between external mechanical perturbations and cooperative molecular motion rather than from changes to the static equilibrium structure.

Strict physical constraints govern this hypothesis. First, reversibility is a fundamental requirement. Any sound-induced modification of structure or dynamics must decay as the system relaxes back toward equilibrium once the acoustic excitation is removed. Liquid water at ambient conditions cannot sustain long-lived ordered states without continuous energy input, and therefore any tuning effect must be inherently temporary.

Second, dissipation plays a central role. Acoustic energy introduced into the liquid is ultimately dissipated through viscous losses, molecular rearrangements, and thermalization. As a result, sound-frequency tuning must be accompanied by entropy production and cannot lead to energy-free or self-sustaining structural changes. The finite lifetime of any observed effect is therefore determined by intrinsic relaxation processes within the hydrogen-bond network.

Third, the hypothesis must remain fully consistent with thermodynamic principles, particularly the second law of thermodynamics. The proposed tuning does not violate equilibrium statistical mechanics, as it operates only under driven, non-equilibrium conditions and vanishes once the driving force ceases. No decrease in entropy or spontaneous emergence of long-range order is implied.

Additional constraints concern experimental interpretation. Any apparent tuning effect must be clearly distinguishable from secondary phenomena such as bulk heating, cavitation, changes in dissolved gas content, or boundary-induced resonances. Only effects that demonstrate clear frequency dependence, reproducibility, and predictable relaxation behavior

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can be meaningfully attributed to sound-frequency interaction with collective molecular dynamics.

By explicitly defining these constraints, the present hypothesis remains scientifically conservative while still allowing for experimentally testable questions. It provides a rigorous basis for exploring whether controlled acoustic excitation can transiently modulate the behavior of liquid water in a manner that is physically meaningful, reproducible, and consistent with established liquid-state physics.

6. Critical Perspective and Experimental Limitations

Investigating sound-induced effects in liquid water requires exceptional experimental caution, as the system is highly sensitive to external conditions and prone to artefacts that can obscure or mimic genuine molecular-level responses. A critical perspective is therefore essential to ensure that any observed frequency-dependent behavior is interpreted within a physically meaningful and reproducible framework.

One of the most significant experimental challenges is heating. Acoustic excitation, even at moderate intensities, can lead to localized or bulk temperature changes due to viscous dissipation. Since hydrogen-bond dynamics, relaxation times, and density fluctuations in water are strongly temperature dependent, even small uncontrolled temperature variations can produce apparent changes in structure or dynamics. Without precise thermal monitoring and control, such effects may be incorrectly attributed to sound-frequency tuning rather than simple thermal response.

Another major source of artefacts arises from cavitation and nonlinear acoustic effects. At sufficiently high acoustic amplitudes, transient cavitation can occur, generating microbubbles, shock waves, and localized pressure extremes. These phenomena can dramatically alter the physical state of the liquid and introduce irreversible changes that are unrelated to subtle collective molecular dynamics. Experiments aiming to study frequency-dependent tuning must therefore operate well below cavitation thresholds and verify that the acoustic field remains within the linear response regime.

Dissolved gases and nanobubbles present additional complications. Sound fields can nucleate, redistribute, or oscillate gas bubbles within water, particularly at low frequencies. These bubbles can influence acoustic propagation, optical measurements, and scattering

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signals, leading to responses that reflect gas dynamics rather than intrinsic properties of the liquid. Careful degassing procedures and characterization of gas content are necessary to separate genuine water dynamics from bubble-related effects.

Boundary conditions and container effects also play a critical role. Resonances associated with experimental vessels, transducers, or interfaces can produce frequency-dependent responses that are not intrinsic to bulk water. Standing waves, reflections, and coupling between the container and the liquid may introduce artefacts that depend strongly on geometry and material properties. Robust experimental design therefore requires variation of container dimensions and materials to confirm that observed effects are independent of boundaries.

Measurement sensitivity and reproducibility constitute further limitations. Many proposed sound-induced effects in water are expected to be subtle and short-lived, making them vulnerable to noise and statistical uncertainty. Reliable identification of frequency-dependent behavior demands time-resolved measurements, repeated trials, and quantitative analysis rather than qualitative observation. Single-run experiments or poorly controlled parameter sweeps are insufficient to support meaningful conclusions.

Finally, interpretative restraint is essential. Even when reproducible changes are observed, they must be framed conservatively as transient, non-equilibrium responses rather than as evidence of permanent structural tuning or anomalous behavior.
Over-interpretation not only undermines scientific credibility but also obscures legitimate physical insights into collective dynamics.

In summary, rigorous experimental control, careful separation of primary and secondary effects, and conservative interpretation are indispensable when studying sound–water interactions. Recognizing these limitations is not a weakness of the present approach but a necessary condition for establishing scientifically credible evidence of frequency-dependent acoustic effects in liquid water.

7. Future Directions and Functional Implications

Further progress in understanding sound–water interactions requires carefully designed experimental and theoretical studies that can isolate genuine collective molecular responses from secondary effects. Future experimental work should prioritize controlled,

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frequency-resolved investigations, where sound frequency, amplitude, and exposure duration are systematically varied while all other parameters are held constant. Such studies would allow identification of frequency ranges where the liquid exhibits enhanced sensitivity, providing evidence for selective coupling to intrinsic relaxation or collective modes.

Time-resolved experimental approaches represent a particularly promising direction. Pump–probe-type measurements, in which acoustic excitation is applied for a defined period followed by delayed structural or dynamical probing, could reveal whether prior sound exposure influences relaxation behavior on short timescales. Techniques such as ultrafast infrared spectroscopy, terahertz spectroscopy, neutron scattering, or dynamic light scattering may be employed to track transient changes in correlation lifetimes, density fluctuations, or hydrogen-bond rearrangement dynamics. Demonstrating reproducible decay toward equilibrium would be essential for confirming non-equilibrium tuning rather than permanent modification.

Complementary insight can be obtained from molecular dynamics simulations incorporating externally applied oscillatory pressure or density fields. Simulations allow direct access to molecular-level information that is difficult to extract experimentally, including time-dependent hydrogen-bond statistics, collective displacement patterns, and energy dissipation pathways. By comparing simulation results across different driving frequencies and amplitudes, it may be possible to identify which collective modes are most susceptible to acoustic excitation and to estimate realistic timescales for transient tuning effects.

From a functional perspective, any practical relevance of sound-frequency interaction with water must remain grounded in conservative physical interpretation. Rather than invoking permanent structural alteration, functional implications should be considered in terms of temporary modulation of liquid behavior under controlled conditions. For example, transient changes in relaxation dynamics or transport properties may be relevant in confined systems, interfacial water, or processes where liquids are continuously driven, such as in microfluidics or acoustic manipulation techniques.

Biological and material contexts may also offer controlled environments in which sound–water interactions could play a role, provided that interpretations remain cautious. In such systems, water often exists in non-bulk or constrained states where collective dynamics differ from those of bulk liquid. Exploring how sound interacts with these modified dynamical

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regimes may help clarify whether frequency-dependent effects are amplified or suppressed under confinement.

Overall, future research should emphasize reproducibility, parameter control, and integration of experiment with simulation. By avoiding over-extrapolation and maintaining strict adherence to thermodynamic and statistical-mechanical principles, these studies can determine whether sound-frequency-dependent tuning of liquid water represents a measurable and functionally relevant manifestation of non-equilibrium collective dynamics.

8. Conclusion

This study has examined the possibility that sound frequency may transiently influence the structural and dynamical behavior of liquid water, framing the problem within established principles of liquid-state physics and non-equilibrium thermodynamics. By treating water as a correlated molecular system governed by a continuously evolving hydrogen-bond network, the analysis emphasizes collective dynamics rather than isolated molecular interactions as the relevant scale for sound–water coupling.

The central idea explored is that externally applied acoustic fields, when appropriately tuned in frequency, amplitude, and duration, may interact with intrinsic relaxation and collective modes of water. Such interactions are interpreted conservatively as temporary, frequency-dependent modulation of dynamical behavior, occurring only under driven or near-driven conditions. No claims of permanent structural alteration, long-term memory, or violation of thermodynamic constraints are implied. Instead, all proposed effects are required to be reversible, dissipative, and to decay as the system relaxes back toward equilibrium.

Throughout the discussion, particular emphasis has been placed on distinguishing genuine molecular-level responses from experimental artefacts. Factors such as heating, cavitation, dissolved gases, and boundary effects can easily produce apparent frequency-dependent behavior if not rigorously controlled. Recognizing these limitations is essential for maintaining scientific credibility and for ensuring that any observed effects are correctly attributed to collective molecular dynamics rather than secondary phenomena.

The scientific value of studying frequency-dependent sound effects in water lies not in asserting anomalous properties, but in deepening understanding of how external mechanical

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driving interacts with correlated liquid systems. Carefully designed experiments and simulations can provide insight into non-equilibrium relaxation processes, collective motion, and the limits of controllability in complex liquids. Such knowledge is broadly relevant across physics, chemistry, and interdisciplinary fields where liquids are subjected to mechanical or vibrational excitation.

In conclusion, while permanent tuning of water structure is not supported by established physics, the investigation of transient, frequency-dependent acoustic effects represents a scientifically meaningful and experimentally testable direction. By maintaining a conservative interpretative framework and rigorous methodological standards, this line of research can contribute to a more nuanced understanding of collective dynamics in liquid water and inform future studies of sound–matter interaction in complex fluids.

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