Resonance-Controlled Surface Forces in Confined Aqueous Films

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Surface forces between solids immersed in water are typically measured under static conditions, without vibrations, even though most real interfaces, from engineered devices to biological tissues, function in environments where vibrations are constantly present. In this work, we use a multimodal surface forces apparatus to determine how nanometer-scale vibrations modify both long-range electrostatic interactions and short-range hydration forces between mica surfaces separated by water or dilute electrolyte solutions. By varying vibration frequency and amplitude, we detect a mechanical resonance in the low-kilohertz range at which a pronounced long-range repulsive force emerges. This effect is consistent with a vibroacoustic lift force produced by inertial hydrodynamics within the confined liquid film. The resulting dynamic "levitation" increases the average distance between the surfaces, in quantitative agreement with a continuum description of the squeezed film, showing that even extremely small vibrations can greatly enhance repulsion beyond classical expectations.

At very small separations, the same resonant vibrations also reorganize the hydration structure. Away from resonance, the interaction is dominated by a conventional short-range hydration force associated with a water layer about one molecule thick. At resonance, however, this confined water film expands into a more solid-like layer several molecules thick, whose thickness and effective decay length can be tuned by changing the vibration amplitude. This interfacial structure can also be reversibly formed and removed simply by turning the vibrations on and off. These findings show that surface forces are not fixed material characteristics, but rather interactions that can be dynamically tailored through nanovibrations. This insight has important consequences for colloidal stability, adhesion, lubrication, nanomechanical systems, and biointerfaces, where naturally occurring or intentionally applied vibrations could be used to enhance, suppress, or switch interfacial forces at solid–liquid boundaries.

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surface forces, nanovibrations, acoustic levitation, hydration forces, electrostatic forces

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