論文の内容の要旨

論文題目　The Behavior of an Encapsulated Microbubble in the Ultrasound Field

(超音波音場における膜被包性マイクロバブルの挙動)

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Dynamics of an encapsulated microbubble in ultrasound field is practically relevant to the ultrasound contrast agents and targeted drug delivery in medical application. The properties of the encapsulating membrane and the applied ultrasonic pressure concern the stability of the contrast-enhanced agents or drug-carrier vesicles. In this work, the surface stability problem of the encapsulated bubble subjected to ultrasonic pressure waves is numerically addressed.

To predict the nonlinear process, the continuity equation and Navier-Stokes equations are directly solved by means of a boundary-fitted finite-volume method on an orthogonal curvilinear coordinate system. The membrane mechanics is treated referring to the shell theory and coupled into the dynamic balance at bubble surface. The strain-stress relationship is enclosed by the hyperelastic constitutive laws. The Skalak law and the neo-Hookean law are adopted to represent the strain-hardening and strain-softening materials respectively.

The simulation code first reproduces the shape oscillation of a gas bubble as shown in an existing experimental study. Before the simulation of encapsulated bubble cases, the stability problem of an encapsulated bubble in ultrasound field is analyzed theoretically. The derived dynamic equations for the shape oscillation predict the instability condition of $\omega_0=n\omega_k$, that is, the zeroth-order natural frequency and the higher-order natural frequency have an integral multiple relationship. In addition, the analysis of the eigenvalue problem is able to evaluate the higher-order natural frequency.

Next seven encapsulated bubble with initial radii from 1μm to 7μm are investigated numerically. The effects of the encapsulating membrane on the bubble surface stability are analyzed referring to the resonance structure. The resonance curve is derived by linearizing the modified Rayleigh-Plesset equation. According to the resonance curve, the membrane raises the bubble's natural frequency for small bubbles; whereas this effect is attenuated as the bubble's initial size grows. The numerical results are generated to show that when the natural frequency deviates from the driving frequency, the bubble exhibits a stable oscillation. In the vicinity of resonance, large-amplitude pulsation enhances the compressive stress developing inside the membrane, thereby inducing higher-order shape modes in the encapsulated bubble. In contrast, for the gas bubble with comparable pulsation amplitude, the deformation does not occur due to the effect of surface tension. Furthermore, the shape oscillations of the encapsulated bubble have subharmonic characteristics, which imply a potential application for medical imaging since subharmonic oscillation is unique to contrast-enhanced microbubble. As the bubble radius further increases, the difference of oscillatory amplitude between gas bubble and encapsulated bubble is narrowing. When the natural frequency approaches to half of the driving frequency, both gas bubble and encapsulated bubble will experience subharmonic radial oscillations. In addition, the radii of the Skalak bubbles for which the shape instability will appear are consistent with the theoretical analysis.