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Non-linear extensions to shell models of ultrasound contrast agents: theory and experiment

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The standard UCA models, characterized by the area dilatation modulus and viscosity of the encapsulating membrane, are extended in order to account for deviations from linear material behaviour and for non-spherical pulsations. The former effect is captured by introducing a parameter that measures the degree of membrane softness, whereas the latter is modelled by introducing a bending elasticity. Lipid shells exhibit the phenomenon of 'thresholding behavior' where excursions in the relative area dilatation are measured only beyond a critical sound amplitude. Treating the lipid shell as strain softening reproduces this non-linear behaviour which can be further optimized by controlling the shell softness parameter. Such a tuning can be used to estimate the degree of softness for the contrast agent BR-14. Stability analysis allowing for shape distortions provides an estimate for the bending elasticity that reproduces the experimentally observed threshold for growth of surface modes. Phase diagrams are constructed for BR-14, based on high-speed optical observations and stability analysis. Both experiment and numerical analysis exhibit a smaller variation between the stability threshold of subsequent shape modes in the case of UCA's, as compared to free bubbles. Numerical simulations reproduce the experimentally observed saturation of growing shape modes for pre-stressed UCA's.