Application of Koopman operator theory to the data-driven control of nonlinear bubble dynamics

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Abstract

Encapsulated microbubbles (EMBs) are used in biomedicine for both diagnostic and therapeutic purposes that include ultrasound imaging and targeted drug delivery. A data-driven method to control the oscillations of EMBs using the applied acoustic field is presented based on Koopman operator theory, which is a method for transforming a nonlinear dynamical system on a state space into a linear system on an infinite-dimensional function space. This method preserves the underlying nonlinear dynamics of the system, and the function spaces can be approximated through data-driven methodologies, which enables the application of classical linear control strategies to the nonlinear system. Here, we apply a Koopman linear quadratic regulator (KLQR) to control the nonlinear oscillations of a spherical EMB through the applied acoustic field. The control of EMBs presents novel challenges due to the presence of a slow manifold that arises in the phase plane spanned by the bubble radius and radial velocity. This slow manifold confounds control in its vicinity and requires special care in formulating the KLQR controller through the judicious selection of Koopman eigenfunctions to capture the relevant dynamics. Results are presented that demonstrate the effectiveness of the modified KLQR controller in driving the EMB to follow arbitrarily-prescribed radial oscillations and stabilize at nonequilibrium radii.