Nonlinear fluid-structure interaction dynamics of an elastically mounted flapping airfoil in an inviscid fluid

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Fluid-structure interaction (FSI) often leads to instability such as aero-elastic flutter which is undesirable in engineering applications. However, this could be desirable to natural flyers or swimming animals as they can exploit the coupling of the surrounding unsteady flow with their flexible wings/fins to enhance their propulsion capability. Hence, understanding of the FSI dynamics of the natural flyers/swimmers is crucial for the design of nature inspired Micro Aerial Vehicles (MAVs) or Autonomous Underwater Vehicles (AUVs). As a first step towards developing this understanding, an elastically mounted airfoil has been considered in the present study. The model captures the span-wise flexibility of the cross section of a wing. In this paper, the nonlinear FSI dynamics of an elastically mounted symmetric airfoil with a periodic actuating force in inviscid flow condition has been studied from a dynamical systems viewpoint. In the absence of the actuating force, the system undergoes a Hopf bifurcation as the free-stream velocity is increased resulting in a stable limit-cycle oscillation from a fixed point response. On the other hand, more complex system dynamics is observed in the presence of a periodic actuating force as the amplitude of the forcing is increased at a post-critical reduced velocity. The frequency of the actuating force is kept between the uncoupled pitch and plunge natural frequencies of the structure. The bifurcation analysis considering the amplitude of the actuating force as the control parameter reveals a rich dynamical route to chaos.

The nonlinear structural model has been coupled with an inviscid flow solver using a weak coupling strategy. The structural model is a symmetric airfoil supported by a translational and a rotational spring along the plunge (bending) and pitch (torsion) degrees of freedom respectively with cubic nonlinearity to model large deformation as shown in in Fig. 1. The flow part is solved by unsteady vortex lattice method (UVLM). Since, the flow solver is governed by linear potential theory, the structural nonlinearity is solely responsible for the interesting nonlinear behaviour of the system dynamics. The structural governing equations are solved using fourth order explicit Runge-Kutta integration scheme. The flow solver is validated with the available literature and the time step of the coupled simulations is chosen by a time convergence test of the FSI solver.

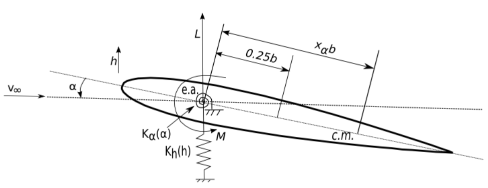

Figure 1: Schematic of the structural model

A bifurcation analysis is performed considering the nondimensional amplitude of the actuating force to be the bifurcation parameter. As the control parameter is increased, the response dynamics switches from a periodic to chaotic phase. The transition in the dynamics is also reflected in the aerodynamic loads. The response of the elastically mounted airfoil as well as the aerodynamic load time histories are analyzed by using techniques of nonlinear time series analyses such as frequency spectra, Poincaŕe sections, phase space reconstruction, Lyapunov exponent etc. The Poincaŕe section has been obtained in a stroboscopic manner by sampling the trajectories with the forcing frequency. The phase space is reconstructed by the time delay embedding theorem [1] with predetermined optimum time delay and minimum embedding dimension of the phase space [2, 3]. A broadband frequency spectra, scattered points in the Poincaŕe section, a strange attractor in the reconstructed phase space and the positive Lyapunov exponent characterizes the chaotic transition in the FSI dynamics.

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