Coupled CFD, Structure and Control Tool for Simulation of Flapping Wing Analysis

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Extended Abstract

Unmanned air vehicles (UAVs) are becoming ubiquitous, and the technologies that drive their development are pushing the envelope of viable mission profiles for these systems. Finding solutions to achieve effective and efficient flight performance in unpredictable flow regimes such as urban areas and cluttered indoor environments is essential to future of UAVs. As the demand for these small vehicles grow due to the missions they enable, there is a need to rethink the design to achieve the desired performance. In nature, larger flying animals tend to rely on their wings to glide or soar, and these wings provided some of the inspiration for early aircraft design. However, smaller flying animals rely more heavily on wing flapping to create the lift and control forces needed for flight, and this is an area that holds promise for small UAVs.

Scientists and engineers have employed a mix of biological and computational studies to understand the wing mechanisms and kinematics of species ranging from fruit flies to hummingbirds to bats. The accumulation of these efforts has led to an understanding of the flow physics for different wing geometries, configurations, and kinematics for both hover and forward flight, as described by Ramamurti and Sandberg [1,2] and Viswanath et al. [3]. The decreasing size of the UAVs makes them susceptible to the fluctuating magnitude and direction of gusts. Flapping wings hold promise for controlling transient dynamics of smaller vehicles in complex environments. Improved modeling of wing surface stretching and other deformations is needed to determine the extent to which flexible wing surfaces contribute to the agility of flying animals and to provide guidance in materials selection and wing shape and kinematics design for flying vehicles. Another challenge facing flapping flight design is in understanding vehicle control authority for given wing configuration and kinematics limitations. Therefore, it is important to understand the effects of external flow changes on the on the wing surface deformation and on the vehicle dynamics.

We have previously conducted computational studies of flapping wings and flapping wing platforms, and compared results of these studies with experimental data from both biological and man-made wing counterparts, see Ramamurti et al. [4,5]. However, while these comparisons proved useful for aiding the process of designing bio-inspired UAV platforms, the accuracy of the simulated wing kinematics suffered from lack of a proper wing deformation model. In this paper, we discuss the development and validation of two additions to our proven computational fluid dynamics (CFD) solver. First, a fluid-structure interaction (FSI) solver is validated against two benchmark test cases. Second, a set of closed-loop vehicle control algorithms are coupled to the CFD solver and used to predict the performance of a prototype flapping wing UAV.

Most natural flyers such as bats use an articulated skeleton covered with elastic membrane for morphing their wings during flight. In this paper, we consider bio-inspired wings comprised of carbon fiber structures and elastic Mylar membrane between them. A coupled CFD-structural (ASICSD) solver was developed for this purpose. In order to validate the coupled solver, the problem is broken into two, one for the coupled fluid and beam case and the second for the coupled fluid and membrane case. For the former, the benchmark case described by Turek and Hron [6] of the flow around a cylinder with an elastic beam behind the cylinder was simulated. The flow around the cylinder is in the laminar regime ranging from Reynolds number, Re = 20 to 200. The displacement at the end of the beam is compared to that reported in [6]. The coupled solver required extremely small timesteps due to the stiffness of the structure and the explicit time stepping limitation of the ASICSD solver. Hence, a coupled structural solver based on eigen modes of the beam was developed. Details of the coupled solver will be given in the final version of the paper. This coupled code was validated for a cantilevered beam with a point load at the end of the beam. Next, the solver was used to simulate the benchmark case shown in Figure 1. Several eigen modes were included in the coupled solver and for the first test case of Re = 20 all of the modes reached a steady state solution as shown in Fig. 2. The converged displacement is 8.787×10^{-4} compared to the values of 8.28×10^{-4} reported in [6]. For the unsteady case of Re = 200, the displacement time history is shown in Fig. 3. The mean displacement is 1.572×10^{-3} with the range of $\pm 34.21 \times 10^{-3}$. This is in good agreement with results reported for various coupled solvers. Figure 4 shows the instantaneous pressure and velocity distribution for the case of Re = 200.

For the latter, the validation case for a membrane model of Rojratsirkul et al. [7] was simulated. The membrane airfoil geometry consists of thin latex sheet stretched between a leading edge and a trailing edge mount. Experimental observations show that the membrane deformation is nearly two-dimensional for a range of angels of attack tested. Hence, a coupled membrane structural model was developed for this. Details of the structural solver will be in the full version of the paper. Initial steady state solutions at $\alpha = 4°$ and $8°$ were obtained for a Re = 2500 and compared to the numerical results reported by Gordnier [8] and are in good agreement. Figure 5 shows the comparison of the displacement of the membrane. In the final version of the paper, the simplified membrane model coupled with the CFD solver will be compared with the generalized FSI solver, and higher Re cases will be simulated and included.

In order to test coupled vehicle controller with the CFD, both open and closed loop test were performed for a notional flapping wing UAV. The configuration is described by Geder et. al [9]. Initial coupled simulations of pitch attitude control maneuver were performed using a simple proportional derivative control algorithm based on wing stroke angle bias and showed that with closed loop control the vehicle can regain the commanded attitude in 3 flapping cycles of the wing. In the final version of the paper, simulations of the coupled roll-yaw maneuver will be included.

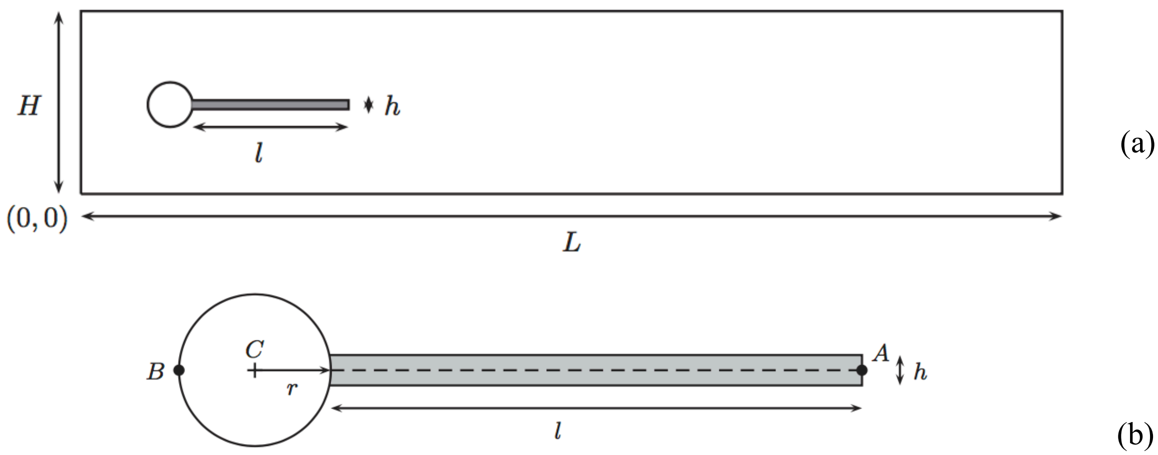

Fig. 1. Turek-Hron benchmark configuration, (a) computational domain and (b) structural details.

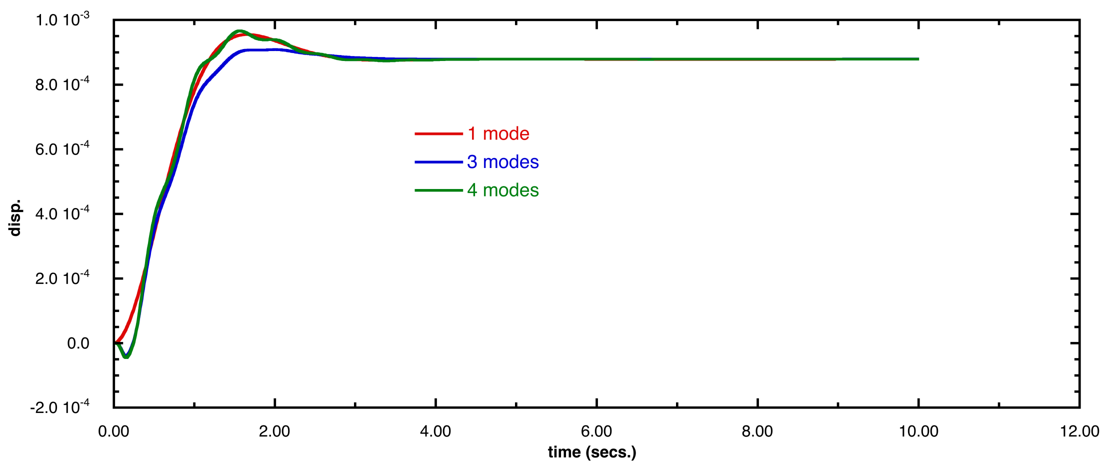

Fig. 2. Displacement time history for the Turek-Hron benchmark case, Re = 20.

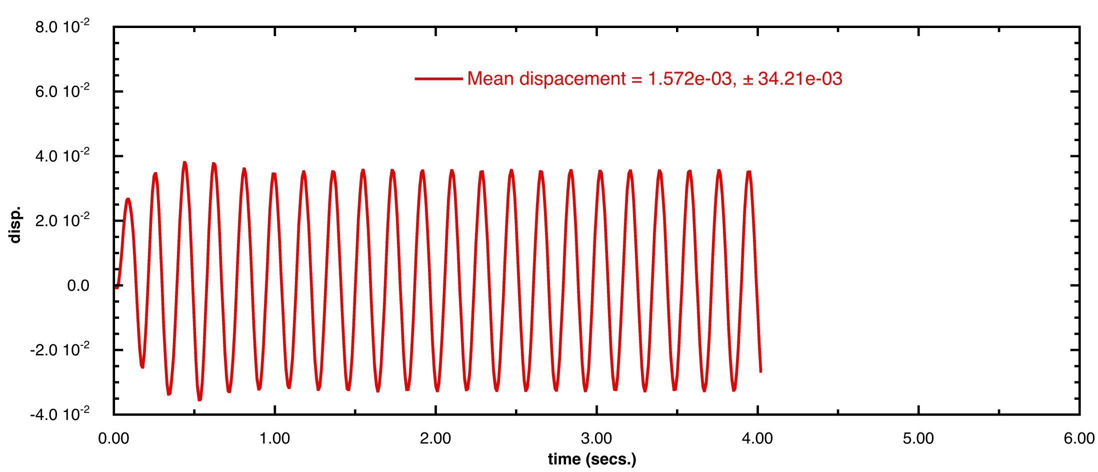

Fig. 3. Displacement time history for the Turek-Hron benchmark case, Re = 200.

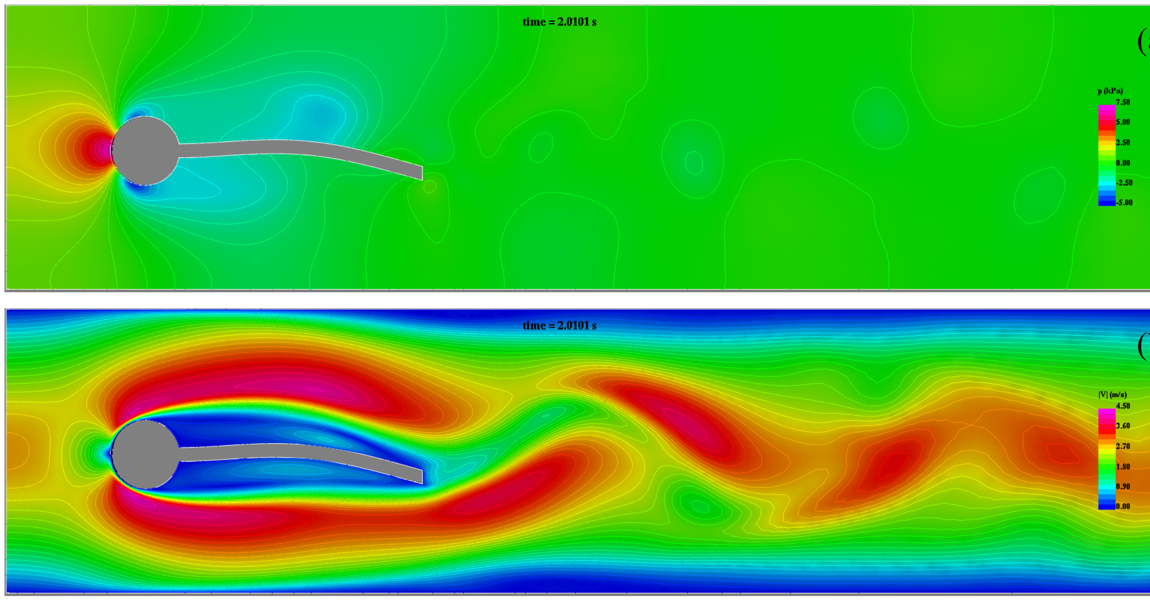

Fig. 4. Flow results for Turek-Hron benchmark case, Re = 200, (a) pressure distribution and (b) magnitude of velocity.

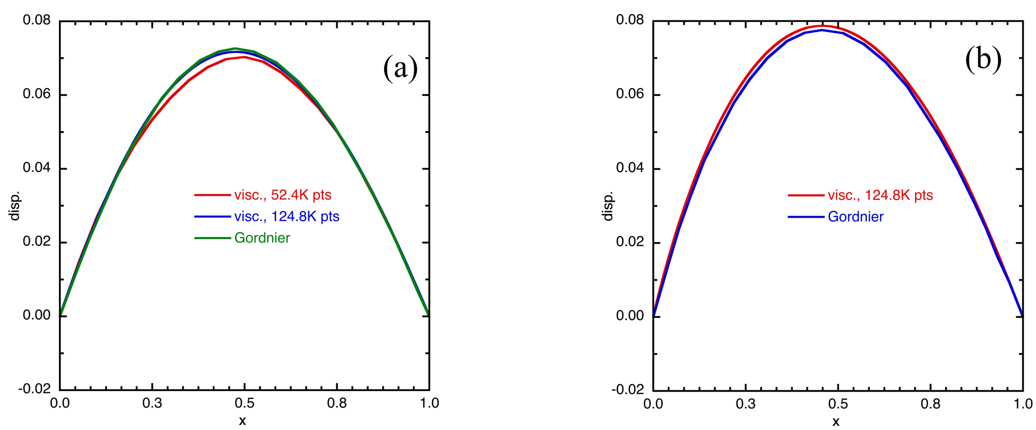

Fig. 5. Comparison of deflection of the membrane, Re = 2500, (a) $\alpha = 4°$ and (b) $\alpha = 8°$.

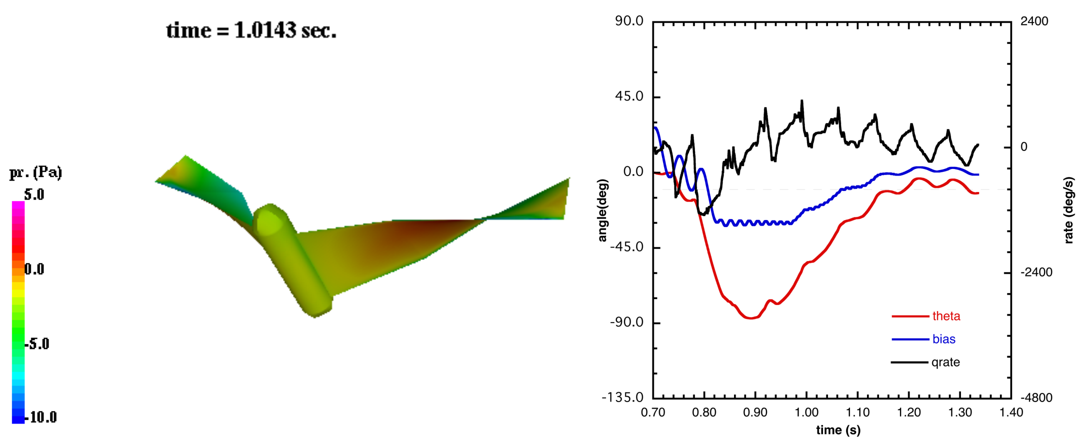

Fig. 6. Closed loop pitch response with wing stroke angle bias control.

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