

AERO-SERVO-ELASTIC ANALYSIS OF 2D AIRFOIL IN ALLEVIATING TRANSONIC FLOW-INDUCED VIBRATIONS THROUGH FLAP CONTROL

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ABSTRACT

Next-generation high-aspect-ratio wings are highly susceptible to aeroelastic instabilities like flutter and limit cycle oscillations. These risks peak in the transonic regime, where shock wave dynamics significantly reduce stability margins through strong aerodynamic nonlinearities. Current industrial certification often relies on linearized theories that fail to resolve complex, time-domain interactions between moving shocks and control surfaces. This research performs a high-fidelity aero-servo-elastic analysis of a 2D airfoil to evaluate the effectiveness of active flap control in suppressing transonic flow-induced vibrations. The framework couples the OpenFOAM high-fidelity solver for inviscid, compressible flow with a custom structural solver via the preCICE interface. A PID controller commands flap deflections based on real-time pitching moments and accelerations, utilizing Radial Basis Function (RBF) interpolation to ensure tight two-way coupling. Preliminary validation shows that the PID controller effectively suppresses initial pitch disturbances. The flap deflection converges to a steady state of 14° to maintain the target orientation, successfully stabilizing the coupled system. This study establishes a robust high-fidelity platform for validating active control laws in complex nonlinear regimes. Such capabilities are essential for the safe design of future energy-efficient, highly flexible aircraft.

INTRODUCTION

The design of next-generation transport aircraft increasingly features high aspect ratio wings to reduce induced drag and improve fuel efficiency [1, 2, 3]. However, these slender, flexible structures are more susceptible to high deflections and aeroelastic instabilities, such as flutter and limit cycle oscillations (LCO), which can result in catastrophic structural failure or fatigue damage [1, 4, 5, 6]. These risks are most pronounced in the transonic flight regime ($M_\infty \approx 0.8 - 1.2$), where the formation and periodic motion of shock waves introduce strong aerodynamic nonlinearities [7, 8, 9]. A critical phenomenon in this regime is the “transonic dip”, where the flutter speed margin is significantly reduced compared to subsonic or supersonic conditions [2, 9, 10, 11]. Traditional aeroelastic certification primarily relies on linearized potential flow theory, such as the doublet-lattice method, which cannot accurately predict shock wave dynamics or shock-induced flow separation [4, 7, 8, 12]. While Active Control Technology (ACT) using trailing-edge flaps offers a promising solution for suppressing these vibrations, its effectiveness is often compromised by the high sensitivity of transonic shocks to control surface movement [7, 13]. High-fidelity computational aeroelasticity (CAE) models that couple nonlinear fluid solvers with structural dynamics are required to resolve these complex interactions [8, 10, 14]. Current studies frequently utilize Reduced-Order Models (ROMs) or simplified aerodynamic transfer functions to reduce computational costs, but these methods may fail to capture the full nonlinear behavior of the coupled fluid-structure system in the time domain [7, 9, 15]. Consequently, there is a gap

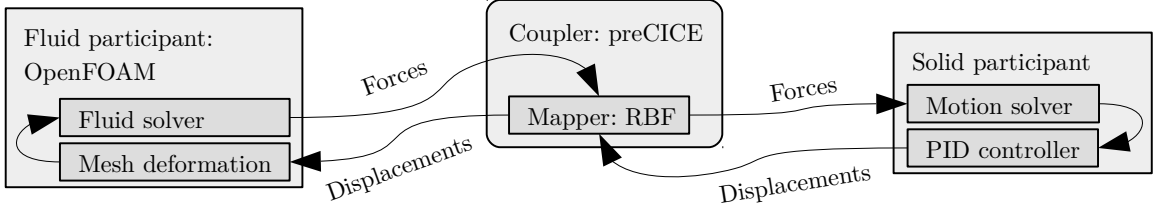


Figure 1: Layout of the framework

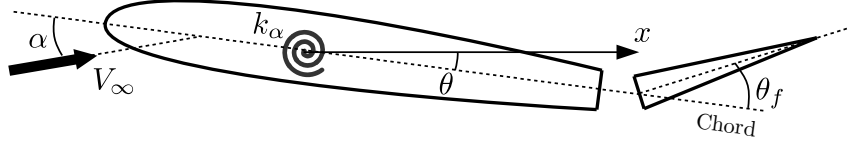


Figure 2: Problem definition of the test case

in applying high-fidelity, scale-resolving simulations to the design and validation of robust control laws for transonic vibration alleviation [3, 7].

The objective of this research is to perform a high-fidelity aero-servo-elastic analysis of a 2D airfoil to evaluate the alleviation of transonic flow-induced vibrations through active flap control. This computational study couples an inviscid, compressible flow model solved via OpenFOAM with a custom structural solver. The 2D geometry consists of a main airfoil section and a trailing-edge flap, both moving as rigid bodies restrained by optional springs and dampers. The flap is connected to the wing via an actuator driven by a Proportional-Integral-Derivative (PID) controller. By employing a fully coupled time-domain approach, this study investigates the effectiveness of PID-controlled flap deflections in suppressing unstable aeroelastic oscillations driven by transonic shock dynamics.

METHOD

The computational framework comprises two primary participants: a fluid solver and a structural solver, coupled via a dedicated coupler module (see Fig. 1). The fluid solution is obtained using OpenFOAM [16], where the Navier-Stokes equations are discretized and solved via the finite volume method. The resulting fluid forces (pressure and shear stresses) acting on the solid surfaces are transferred to the preCICE coupling interface [17]. Since the surface meshes of the fluid and structural domains need not coincide, a Radial Basis Function (RBF)-based interpolation is performed within the coupler to map quantities between non-matching grids. These mapped forces serve as input to the in-house solid participant, where the structural response is computed. Based on the instantaneous pitching moment and linear acceleration of the wing section, a PID controller embedded within the solid participant generates a flap deflection command θ_f . This command determines the rigid-body displacement vector for each surface node, which is then mapped back to the fluid domain through the same RBF-based interpolation scheme. A residual-based tight coupling scheme ensures strong two-way interaction between the participants, enforcing full convergence of both force and displacement fields within each time step before proceeding to the next.

PRELIMINARY TEST CASE

The computational framework is validated using the test case illustrated in Fig. 2, where α denotes the angle of attack, V_∞ the freestream velocity, k_α the torsional spring coefficient, θ the pitch angle, and θ_f the flap deflection angle. As a preliminary simplification, the flow is

assumed incompressible and laminar. The computational domain consists of 25k cells, with a total simulation time of 2.5 s and a time step size of $\Delta t = 0.0025$ s. Freestream conditions are set to $V_\infty = 20$ m/s and $\alpha = 2^\circ$. The torsional spring stiffness is $k_\alpha = 0.5$, and the PID controller gains are set to $k_p = 4.0$, $k_d = 0.0$, and $k_i = 20.0$, with the objective of maintaining $\theta = 0^\circ$. The main body is connected to the absolute frame at 15% chord.

The sudden initialization of the flowfield induces an initial pitching moment, causing the airfoil to pitch downward (see Fig. 3). The flap controller responds actively to this disturbance, generating a counteracting flap deflection. The time histories of both angles are shown in Fig. 4. As observed, the airfoil immediately pitches down, triggering a strong controller response with an initial flap deflection of $\theta_f \approx 11^\circ$. This suppresses the pitch-down motion, though significant oscillations persist until $t \approx 0.5$ s. Beyond this point, the target pitch angle of 0° is achieved, and the flap deflection converges to a steady value of approximately 14° .

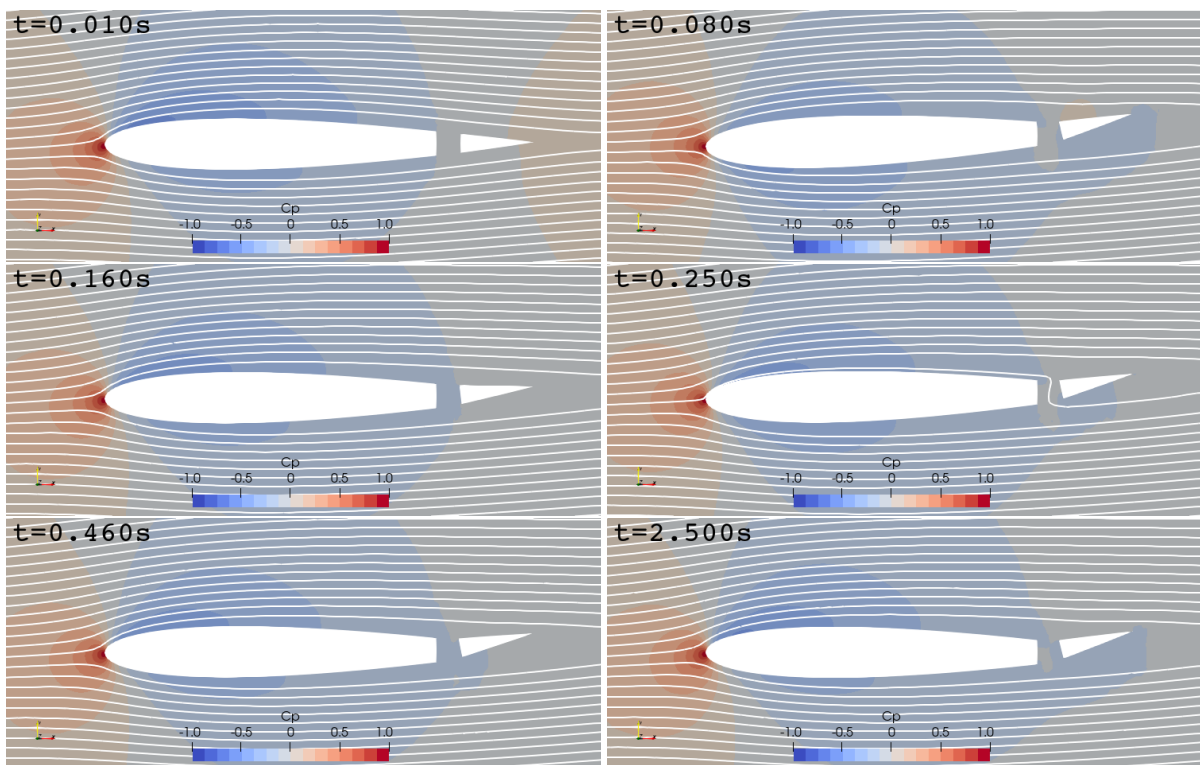


Figure 3: Computed flowfield in OpenFOAM: pressure contours and streamlines

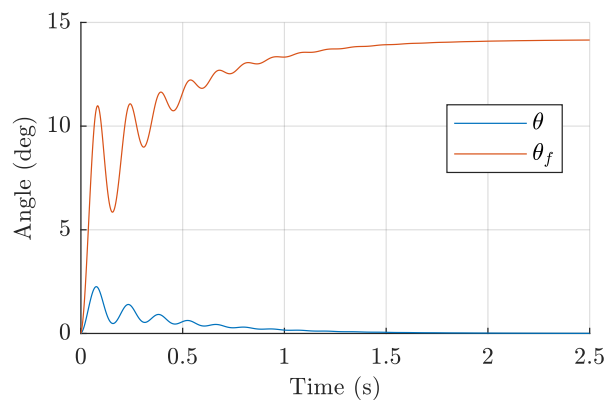


Figure 4: Time variation of pitch (θ) and flap deflection (θ_f) angles

Currently, the framework operates successfully in a coupled manner with the high-fidelity flow solver OpenFOAM. Future work will involve fine-tuning the controller parameters, extending the model to include compressible flow effects, and investigating transonic flow phenomena.

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