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Laminar separation flutter of a NACA0012 airfoil as a global instability

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Summary The onset of pitch-oscillations of a NACA0012 airfoil mounted on a torsion-spring is investigated by the means of a global stability analysis. Experimental studies from literature have shown this configuration undergoing on a flutter behaviour for a close range of Reynolds. This phenomenon is attributed to the laminar character of the boundary layer and to its detachment, transition and subsequent reattachment on the airfoil surface. In this regard, we carried out a linear stability analysis of the mean flow field, issued from a RANS simulation, using a Spalart–Allmaras model. A careful choice of the inlet conditions revealed to be necessary to capture a laminar separation and, as the incidence increases, a laminar separation bubble (LSB).

INTRODUCTION

The first investigation of the aeroelastic behaviour of a NACA0012 airfoil was conducted by Poirel *et al.* (2008), with an experimental set up on a Reynolds number range of $4.5 \times 10^4 < Re < 1.35 \times 10^5$. The airfoil was free to rotate in the pitch degree of freedom, presenting a self-sustained behaviour around a mean angle of attack of zero degrees and an amplitude around $5.5°$. The primary driver for this behaviour was associated to the laminar boundary layer separation on the second half of the airfoil surface, with a subsequent flow transition to a turbulent state an reattachment, forming a Laminar Separation Bubble (LSB).

Subsequent works have reproduced the same phenomenon, performing large-eddy simulations of forced pitch oscillations (Poirel & Yuan 2010) or numerical time-marching fluid-structure-interaction simulations using turbulence modelling for the Navier–Stokes equations (Poirel *et al.* 2011), to name a few. In continuation of these works, Poirel & Mendes (2014) performed experiments in the same transitional Reynolds range, but with both pitch and heave degrees of freedom, obtaining both small and large amplitude oscillations.

More recently, an aeroelastic linear stability using a mean flow from 3D DNS simulations was investigated by Negi (2019), showing a static eigenvalue that indicates a divergent behaviour of the airfoil from its equilibrium position at $\alpha = 0°$. Further, they associated the subsequent non-linear oscillation to a sub-critical mode, which is non-linearly excited.

The present study aims to understanding of the laminar separation flutter, by highlighting this divergent onset that leads the airfoil to a new equilibrium point where an unstable eigenvalue is then responsible for the non-linear onset dynamics.

MEAN FLOW ANALYSIS

We consider a flow described by the incompressible Reynolds-Averaged Navier–Stokes equations (RANS) with a closure obtained from the Spalart–Allmaras model. This model was intended to be used in a fully turbulent configuration where no laminar separation was able to appear. This turbulent behaviour is commanded by the inlet condition on the eddy viscosity which is recommended to be $\nu_t^\infty = 3\nu$.

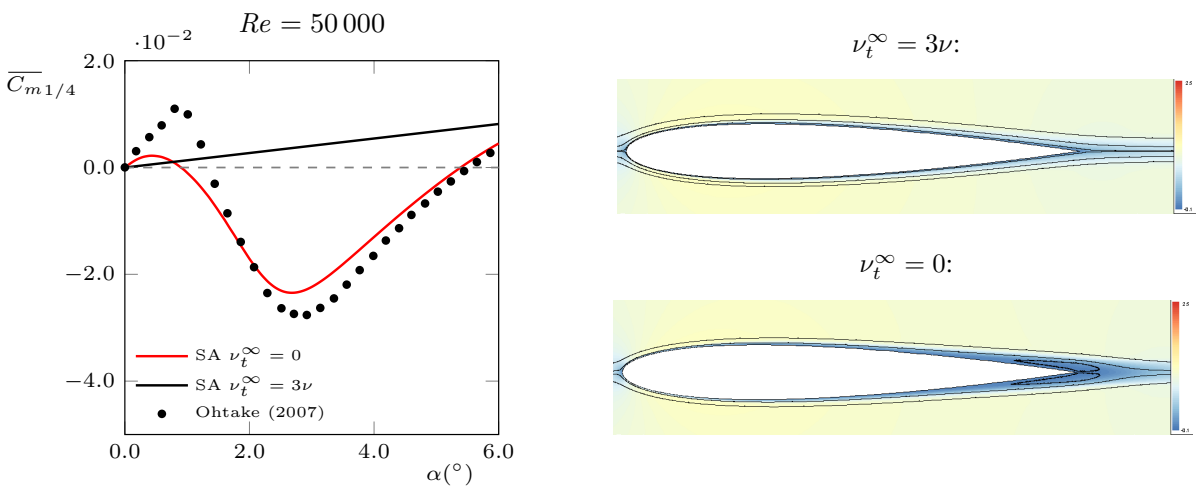

Figure 1: At right, the evolution of the mean flow moment coefficient with the incidence. At left, the streawise velocity for $Re = 50\,000$, $\alpha = 0°$ for $\nu_t^\infty = 3\nu$ and $\nu_t^\infty = 0$, showing a detached flow for the second set of parameters.

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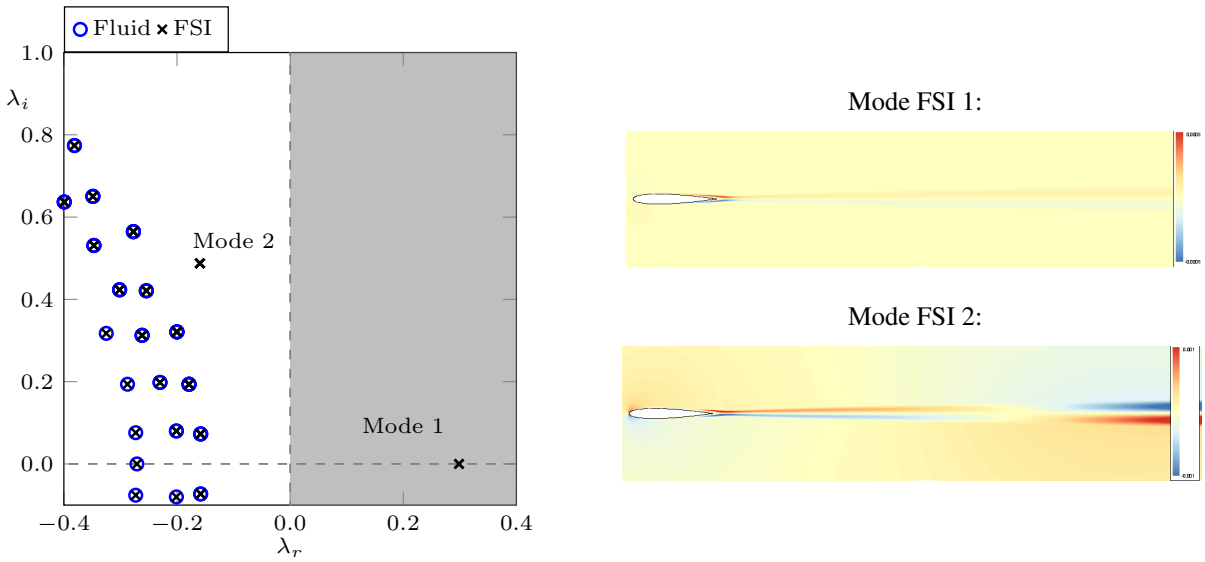

Figure 2: At left, a comparison between the fluid and a fluid structure spectra, the latter presenting a static unstable eigenvalue. At right, the streamwise velocity field for the two FSI modes.

However, recent studies have used this model to describe laminar separation flow, being able to capture the transition triggered by a separated flow (Crivillini & D'Alessandro 2014). The key ingredient of this procedure was the use of very small turbulent variable free-stream conditions, ideally at $\nu_t^\infty = 0$.

Following this idea, we carried out several RANS simulations for different airfoil incidences. The evolution of the mean flow moment coefficient is depicted in figure 1, for two different values of ν_t^∞.

It can be observed that the nonlinear behaviour of the flow field at low incidences cannot be captured by a fully turbulent simulation ($\nu_t^\infty = 3\nu$), whereas a laminar approach was able to capture it, when comparing with the experimental data from Ohtake (2007). The comparison between the flow fields is depicted at the left of figure 1, where a recirculation bubble can be observed for the laminar separated case.

FLUID STRUCTURE LINEAR STABILITY ANALYSIS

In a second time, a global stability analysis was carried out at $\alpha = 0°$ for the case where $\nu_t^\infty = 0$. The FSI stability analysis revealed two additional eigenvalues, associated to the pitching degree of freedom, that are not present when studying a pure hydrodynamic case. This comparison is detailed in figure 2, at left. The FSI stability analysis was carried out with a stiffness, damping and inertia coefficients of $K_s = 0$, $D_s = 0.0$ and $I_s = 0.00135$, respectively. The mode 1 is associated to the divergent linear departure from the equilibrium position. The correspondent spatial structure is depicted at right of figure 2. The second mode, although stable, and can be responsible for the onset of the pitching oscillation, by a non-linear excitation for large enough oscillation amplitudes.

CONCLUSIONS

A global linear stability analysis is performed for a torsion-spring airfoil configuration at the Reynolds number of 50 000. The mean flow field is obtained solving the RANS equations coupled to the Spalart–Allmaras turbulence model, with $\nu_t^\infty = 0$. The stability analysis around $\alpha = 0°$ shows a divergent eigenmode responsible for the departure of the airfoil from this equilibrium position. The subsequent the onset of the pitching oscillation could be explained by a non-linear excitation of a second structure mode.

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