Journal of Fluids and Structures 77 (2018) 213–230

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

# On the role of flow transition in laminar separation flutter

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## HIGHLIGHTS

- Well-resolved ILES of 'laminar separation flutter' at multiple Reynolds numbers.
- Behavior driven by alternating pattern of separation, transition and reattachment.
- Reynolds number dictates the timing and strength of the aforementioned events.
- Flutter decays at high Reynolds number due to earlier onset of transition damping.
- Apparent bifurcation in solution states at the high-end of flutter regime.

ARTICLE INFO

*Article history:*
Received 9 March 2017
Received in revised form 29 November 2017
Accepted 6 December 2017

*Keywords:*
Aeroelasticity
Laminar separation flutter
LCO
Low-to-moderate Reynolds number

ABSTRACT

This work explores self-sustained pitching oscillations of a NACA0012 airfoil operating at low-to-moderate Reynolds numbers in which the aerodynamic flow is in a transitional regime. One-degree of freedom (DOF) pitching oscillations were explored over a range of Reynolds numbers ($7.7 \times 10^4 < Re_c \leq 2.0 \times 10^5$) using high-order implicit large-eddy simulation coupled with structural dynamics. Limit-cycle oscillation is observed at all Reynolds numbers tested but requires a disturbance to initiate at the highest flow speeds identifying a bifurcation in possible solution states. In all cases, aerodynamic loading is dominated by primarily two features. Negative aerodynamic damping is largely provided by suction beneath a separation bubble located behind the elastic axis. This feature induces a moment that reinforces the pitch-rate at small angles of incidence and is directly influenced by flow transition at different Reynolds numbers. Open trailing edge separation on the opposite surface transitions and reattaches immediately preceding the largest angles of incidence. This process imparts a spike in the pitching moment that opposes the pitch-rate and briefly damps oscillations. Transition of the detached shear layer occurs at smaller angles of incidence as Reynolds number is increased, attenuating oscillation amplitude as Reynolds number is increased.



## 1. Introduction

The increasing need for better fuel efficiency in aircraft presents one of the most pressing modern challenges for the aerospace community. Reductions in skin friction drag through the exploitation of extensive laminar/transitional regions of flow over a wing has emerged as one feasible approach to meet future challenges for practical air vehicles. Designs for long-endurance aircraft may benefit from an extension of laminar flow, perhaps controlled by active or passive mechanisms. Small unmanned air vehicles are also naturally prone to similar flow regimes due to their small size and low flight speeds. However, low-to-moderate Reynolds number aerodynamics can be adversely affected by a number of flow disruptions: gusts, vehicle

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https://doi.org/10.1016/j.jfluidstruct.2017.12.009
0889-9746/Published by Elsevier Ltd.

dynamics, or in the present work, aeroelastic response. Mueller and DeLaurier (2003) as well as the references contained therein provide an overview of the aerodynamic complications of airfoils operating at transitional Reynolds numbers. The most relevant of these factors include laminar separation and laminar separation bubbles (LSBs).

Accompanying the need for more fuel-efficient/longer-range air vehicles is the design of lighter-weight airframes which can be susceptible to aeroelastic effects. The potential for coupling between low-to-moderate Reynolds number aerodynamics with elastic structural response is poorly understood to date. Dynamics related to flow-induced oscillations of an elastic airframe could lead to abrupt changes in the complex viscous phenomena experienced in the transitional flow regime. Coupling between flow and structural dynamics could lead to undesirable aerodynamic load hysteresis and flutter at low-to-moderate Reynolds numbers. A better understanding of these potential outcomes is necessary to mitigate design risks for laminar flow aircraft.

Experimental evidence of limit-cycle-oscillation (LCO) related to the transitional flow regime exist in the wind tunnel experiments of Poirel et al. (2008). They revealed small-amplitude self-sustained oscillations of a NACA0012 airfoil elastically mounted in one-degree-of-freedom (1-DOF) pitch operating at an initial $\alpha = 0°$ angle of attack. Oscillations were restricted to a range of Reynolds numbers of $4.5 \times 10^4 \leq \text{Re}_c \leq 1.3 \times 10^5$ in the transitional regime. This phenomenon was attributed to nonlinearity in the aerodynamic loads provided by laminar boundary layer separation (Poirel et al., 2008; Poirel and Yuan, 2010; Yuan et al., 2013) leading to the so-called *laminar separation flutter*. Negative aerodynamic damping was confirmed through large-eddy simulations (LES) of an airfoil under prescribed pitching motion (Poirel and Yuan, 2010) and later with an aeroelastic LES simulation of the airfoil in 1-DOF pitch (Yuan et al., 2013). The unsteady processes that appear to drive the sustained oscillations are sensitive to a number of external factors. For instance, tripping the laminar boundary layer or introducing free stream turbulence can suppress pitching oscillations (Poirel et al., 2008, 2011; Yuan et al., 2015). High frequency instabilities or von Kármán shedding are not believed to be necessary or influential to the LCO behavior (Poirel et al., 2008). Recently, pitch-heave oscillations have been explored computationally by Yuan et al. (2013) and experimentally by Poirel and Mendes (2014).

Laminar separation flutter represents a new type of aeroelastic phenomenon in contrast with the well-known stall flutter (Dowell et al., 2003) resulting from flow separation that occurs at high angles of attack, or transonic flutter (Dowell et al., 2003) due to large shock motions. The precursory works by the authors (Barnes and Visbal, 2016a, b) report preliminary efforts toward extending the understanding of the complex unsteady fluid–structure interaction through a series of high-fidelity implicit large-eddy simulations (ILES). This manuscript presents a comprehensive study on the effects of flow transition on laminar separation flutter. High-fidelity ILES methodology is implicitly coupled with 1-DOF pitching dynamics and then the effects of Reynolds number are evaluated for a NACA0012 wing section operating at an initial angle of attack of $\alpha = 0°$ and elastically mounted in pitch. While previous LES studies (Poirel and Yuan, 2010; Yuan et al., 2013) have largely focused on the single case of $\text{Re}_c = 7.7 \times 10^4$, a range of Reynolds numbers $7.7 \times 10^4 \leq \text{Re}_c \leq 2.0 \times 10^5$ are considered here which captures a broad spectrum of the LCO regime. This range of Reynolds numbers presents transitional flow behaviors that range from poorly developed at the low end to highly transitional at the high end. Evolution of flow behavior with increasing Reynolds number helps to reveal specific roles of flow transition events on self-sustained oscillations which is the focus of this article.

## 2. Computational setup and configuration

### 2.1. Aerodynamics

The high-order implicit large-eddy simulation (ILES) solver *FDL3DI* (Visbal and Gaitonde, 1999; Gaitonde and Visbal, 1998) is used for all computations in the present study. This computational framework solves the full, unfiltered, compressible Navier–Stokes equations cast in strong conservation form on a general time-dependent curvilinear coordinate system. The system of equations are integrated in time using the implicit, approximate factorization of Beam and Warming (1978) and simplified through the diagonalization of Pulliam and Chaussee (1981). The time-integration scheme is augmented through a Newton-like sub-iteration procedure to maintain temporal accuracy (Rai and Chakravarthy, 1986; Rai, 1989). Fourth-order, nonlinear dissipation terms (Jameson et al., 1981; Pulliam, 1986) are appended to the implicit operator to improve stability.

The explicit operator of the implicit time-integration scheme represents the numerical approximation and dictates the formal order of accuracy for the chosen scheme. Spatial derivatives in the explicit operator are discretized along a coordinate line in the computational domain using the implicit, 6th-order, formulation of compact-differencing (Lele, 1992). High-order one-sided formulas, designed to retain the tri-diagonal form of the system of equations, are applied at the computational boundaries (Visbal and Gaitonde, 1999; Gaitonde and Visbal, 1998).

The solution procedure for the Navier–Stokes equations described above is used to solve laminar, transitional, and turbulent flow regions without change using an ILES procedure. The ILES approach does not require sub-grid-scale (SGS) models or additional heat flux terms required by standard large-eddy-simulations (LES). Alternatively, a high-order, low-pass Padé-type filter, based on the templates proposed by Lele (1992) and Alpert (1981), is applied to eliminate spurious components. The filter is applied to the conserved variables along each transformed coordinate direction once after each time step or sub-iteration. An 8th-order filter is used for the interior points in the present work which selectively damps only the poorly resolved high-wavenumber content. The one-sided filtering strategies described by Visbal and Gaitonde (1999)