Aerospace Science and Technology 74 (2018) 112–119

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Gust response of rigid and elastically mounted airfoils at a transitional Reynolds number

Caleb J. Barnes *, Miguel R. Visbal

Air Force Research Laboratory, Wright-Patterson AFB, OH 45433, United States

A R T I C L E I N F O

Article history:
Received 22 August 2017
Received in revised form 15 December 2017
Accepted 18 December 2017
Available online 2 February 2018

Keywords:
Gust response
Fluid–structure interaction
Aeroelastic
Flutter
Transitional Reynolds number

A B S T R A C T

This article explores the evolution of the unsteady flow structure for rigid and elastically mounted NACA0012 airfoils subject to a parallel vortical gust disturbance at a Reynolds number of Re = 150,000 using implicit large-eddy simulation coupled with a structural dynamics model. A Taylor vortex is supplied upstream of the airfoil and shown to be successful at eliciting laminar separation flutter in the elastically mounted system under conditions which normally require an artificial disturbance. Much of the gust-induced moment responsible for flutter excitation is supplied by a two-stage flow transition process on the undersurface of the wing after the gust passes the airfoil. The gust response triggers transition of the separated lower-surface boundary layer into spanwise coherent vortices followed by a laminar separation bubble accompanied by a secondary emergence of flow transition. These events appear to be analogous in some ways to the processes that appear during fully developed flutter but occur over a shorter timescale.

Published by Elsevier Masson SAS.

1. Introduction

A number of technologies have been proposed in recent years to meet energy efficiency and sustainability requirements of future aircraft. Extension of laminar flow through either natural airfoil design or flow control represents one promising strategy to reduce skin friction drag. Creative design of light-weight multi-functional airframes represents a second realistic approach for meeting endurance goals. The complex aeroelastic scenarios incurred by the intersection between aggressive use of laminar flow and highly flexible structures are poorly understood to date.

Experimental evidence [1,2] of a flutter phenomenon at transitional Reynolds numbers, directly relevant to the aforementioned scenario and distinct from the more classic transonic flutter and stall flutter, has recently emerged in the literature. These studies have indicated that the so-called laminar separation flutter only exists when laminar/transitional flow prevails [1,3] as opposed to artificially tripped flows under the same conditions. Poirel and Mendes [2] suggested stiffening of the torsional mode due to laminar separation flutter in pitch-heave configurations could lead to a more catastrophic coalescence type flutter at lower flow speeds than predicted by existing aeroelastic theory.

These observations complicate the aeroelastic design of future aircraft and merit further investigation into fluid–structure interactions within the transitional flow regime. To this end, Barnes and Visbal [4] explored the role of flow transition in laminar separation flutter using high-fidelity implicit large-eddy simulation (ILES) coupled with structural dynamics. Notably, Reynolds numbers at the high end of the flutter regime demonstrated a resilience to limit-cycle oscillation requiring an increasingly large artificial disturbance as flow speed increased. From a practical standpoint, external disturbance could be provided by atmospheric turbulence, abrupt changes in flight conditions, or gusts.

Vortical gusts, encountered regularly in flight, have the potential to further confound flow–structure interactions in the transitional flow regime by inducing unsteady separation and disruptions to laminar flow. Rockwell [5] provides a review of general vortex–body interactions where the parallel or spanwise-oriented type is of particular interest in this article. Parallel vortex interactions in the transitional flow regime have been more recently explored for an SD7003 wing section at a low Reynolds number of Re = 60,000 [6,7] and for a rigid finite NACA0012 wing at a moderate Reynolds number of Re = 200,000 [8,9]. All of these scenarios have demonstrated significant gust-induced variations in aerodynamic loads during and after vortex impingement which may be relevant in the aeroelastic context.

This paper explores a vortical-gust/wing interaction in the context of laminar separation flutter using high-fidelity ILES coupled with structural dynamics. The one-degree-of-freedom (1-DOF)

* Corresponding author.
E-mail address: caleb.barnes.1@us.af.mil (C.J. Barnes).

https://doi.org/10.1016/j.ast.2017.12.025
1270-9638/Published by Elsevier Masson SAS.

aeroelastic configuration of Ref. [4] is subjected to direct impingement with a counterclockwise Taylor vortex gust and compared with the same scenario for a rigid airfoil at a Reynolds number of Re = 150,000 and initial angle of attack of $\alpha = 0°$. The ability for a gust interaction to induce laminar separation flutter in lieu of an artificial disturbance is evaluated and the underlying physics responsible for excitation is revealed.

2. Computational framework

2.1. Aerodynamics

The high-order ILES solver *FDL3DI* [10,11] is used for all simulations 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 [12] and simplified through the diagonalization of Pulliam and Chaussee [13]. The time-integration scheme is augmented through a Newton-like sub-iteration procedure to maintain temporal accuracy [14,15]. Fourth-order, nonlinear dissipation terms [16,17] are appended to the implicit operator to improve stability.

The explicit operator of the iterative 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 [18]. High-order one-sided formulas, designed to retain the tri-diagonal form of the system of equations, are applied at the computational boundaries [10,11].

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 [18] and Alpert [19], 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 [10] and Gaitonde and Visbal [20] are applied at near-boundary points. The high-order low-pass filtering used in conjunction with high-order spatial discretization provides an effective alternative to the use of SGS models as shown by Visbal et al. [21,22], and more recently by Garmann et al. [23]. A reinterpretation of this ILES approach in the context of an Approximate Deconvolution Model [24] has been presented by Mathew et al. [25]. As the grid resolution increases or Reynolds number decreases, the ILES approach is effectively direct numerical simulation (DNS).

2.2. Structure dynamics and coupling

The structural component solves the generic linear system of equations of motion,

$$\mathbf{M}\ddot{\mathbf{d}} + \mathbf{C}\dot{\mathbf{d}} + \mathbf{K}\mathbf{d} = \mathbf{r} \tag{1}$$

where $\mathbf{d}$ is the vector of degrees of freedom, $\mathbf{M}$ is the mass matrix, $\mathbf{C}$ is the damping matrix, $\mathbf{K}$ is the stiffness matrix, and $\mathbf{r}$ is the external load vector. The specific values contained in $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ in Eq. (1) are problem dependent and introduced for each case as needed. Equation (1) is expanded to a $2N$ system in state-space form as a series of 1st-order ordinary differential equations by introducing a new set of variables $\mathbf{a} = \{d_1, \dot{d}_1, \ldots, d_N, \dot{d}_N\}^T$ where N is the degrees of freedom of the original system. The resulting system of equations is integrated in time using the 2nd-order implicit scheme of Beam and Warming [12] augmented with Newton-like sub-iterations. Greater detail on the structural solution procedure employed can be found in Refs. [26,27].

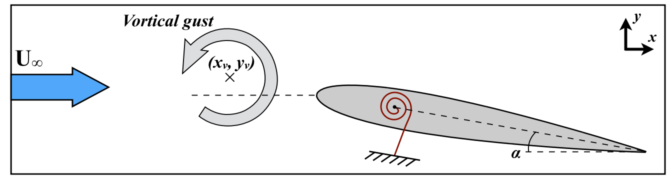

Fig. 1. Gust interaction configuration.

Loose temporal coupling between the aerodynamic and structural models can adversely affect solution integrity [28]. The time lag in the present system of equations is eliminated by implicitly coupling the two physics models through the global sub-iteration procedure. Because both physics models are cast in iterative form, a fully implicit coupling between the aerodynamic and structural models can be obtained. Within each sub-iteration, aerodynamic forces are integrated on the airfoil surface and then passed to the structural model. The resulting displacements are then returned to the aerodynamics solver and used to move the fluid dynamics mesh. This interchange is repeated within each time step thereby synchronizing the two procedures and preserving second-order temporal accuracy for both the fluid and structural dynamics models.

3. Details of the computations

3.1. Configuration

This work explores the interaction of a parallel vortical gust with a NACA0012 airfoil operating at an initial angle of attack of $\alpha = 0°$ and chord-based Reynolds number of Re = 150,000. Two cases are considered: rigid and elastically mounted in pitch as depicted in Fig. 1. The aeroelastic configuration is the same as that described by Barnes and Visbal [4].

Gust interaction cases were initiated by superimposing a vortex model upstream of the airfoil on a previously computed static solution [6,7]. The Taylor vortex [29] serves as a reasonable choice for a canonical parallel vortex-gust interaction. The circumferential velocity, u_v, is given by

$$u_v = q_v r \exp\left(-\frac{r^2}{2}\right) \tag{2}$$

where q_v is a nondimensional magnitude for the velocity. A positive value for q_v prescribes a clockwise vortex in this work. The radial position, r, is defined by

$$r = \left[\frac{(x - x_v)^2 + (y - y_v)^2}{r_v^2}\right]^{1/2} \tag{3}$$

where the coordinates x_v and y_v locate the vortex center and r_v scales the vortex core. This model is further attractive because its velocity profile satisfies the governing continuity equation and the pressure can be derived from the momentum equation. Therefore, the Taylor vortex can be superimposed upon a previously computed static solution and restarted without generating unphysical startup transients that could pollute the evolving unsteady flow. The perturbation to velocity components and pressure used for superposition are provided in Gordnier and Visbal [9] where density