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Gust analysis using computational fluid dynamics derived reduced order models

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ABSTRACT

Time domain gust response analysis based on large order nonlinear aeroelastic models is computationally expensive. An approach to the reduction of nonlinear models for gust response prediction is presented in this paper. The method uses information on the eigenspectrum of the coupled system Jacobian matrix and projects the full order model, through a series expansion, onto a small basis of eigenvectors which is capable of representing the full order model dynamics. The novelty in the paper concerns the representation of the gust term in the reduced model in a manner consistent with standard synthetic gust definitions, allowing a systematic investigation of the influence of a large number of gust shapes without regenerating the reduced model. Results are presented for the Goland wing/store configuration.

1. Introduction

Aircraft regularly encounter atmospheric turbulence, inducing changes in forces and moments, which cause rigid and flexible dynamic responses. These responses introduce loads on the structure which must be accounted for during the design stage to ensure structural integrity. The turbulence is regarded, for linear analysis, as a set of component velocities (gusts) superimposed on the background steady flow. The loads encountered form some of the critical cases used in the structural sizing of a passenger jet. The capability to calculate design loads with a high degree of accuracy would potentially allow reduced conservatism without compromising safety. Currently, conservatism is necessary because of the limited certainty of the possible forms of atmospheric gusts and the limited realism for some flow regimes of linear methods used to predict the aircraft response.

The well–established methods for gust load calculations are based on linear aerodynamic models which are solved in the frequency domain. The use of high–fidelity models based on computational fluid dynamics (CFD) in the research setting has been reported, for example, in Raveh (2011). Grid velocities are used to apply a disturbance in a time domain CFD calculation Parameswaran and Baeder (1997), overcoming the problems associated with numerical dissipation of the disturbance but also missing the influence of the aircraft flow field and motion on the gust.

The cost of time domain calculations makes the routine use of CFD in gust response analysis impractical, and system–identification methods have been used as a cheaper alternative. Proper orthogonal decomposition has been used as a model

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reduction technique (Zhou et al., 2016) to generate reduced models for gust simulations, but this method suffers from the usual limitations associated with the necessity for a set of training data closely related to the final application cases, and the difficulty of accounting for nonlinearity in the reduced model. A systematic and cost effective approach to developing reduced models capable of describing both linear and nonlinear effects for a range of cases based on limited development cost has, to date, proved elusive.

An approach to calculating a reduced order model from a large dimension CFD model which can calculate a nonlinear response has been reviewed in Badcock et al. (2011b). The method first calculates the important modes of the problem from a large order eigenvalue problem. For an aeroelastic limit–cycle oscillation (LCO), the system responds in the critical mode close to the bifurcation point. The approach presented in Woodgate and Badcock (2007) and Badcock et al. (2008) is to project the full order model onto the critical mode and expand the residual in a Taylor series, retaining quadratic and cubic terms. The influence of the non–critical space on the critical mode is included through a centre manifold approximation. The method has been successfully applied to various test cases, including the LCO prediction dominated by the motion of a shock wave (Woodgate and Badcock, 2007) and a prototype flight dynamics instability of a delta wing (Badcock et al., 2008). The approach to model reduction has been generalised in Da Ronch et al. (2012) by using multiple coupled system eigenmodes for model projection and introducing control deflection and gust interaction effects in the formulation. Tantaroudas et al. (2015) introduced the flight mechanics degrees of freedom to predict the dynamics of flexible flying aircraft. The method has several strengths, namely: (i) it exploits information from the stability (flutter) calculation for the development of a reduced order model (ROM) for dynamic response analyses; (ii) linear or nonlinear reduced models can be developed within the same framework; (iii) the reduced model can be parameterised to avoid ROM regeneration; and (iv) the ROM in state–space form is suitable for control design studies.

The current paper tackles the problem of how to introduce gust terms into the reduced model to allow a gust load analysis to be carried out. The objective is to develop a methodology that allows the reduced model to consider a whole range of gust excitations without recourse to the full order model. The outgrowth of this work is the capability to carry out the search of the worst case gust at no additional costs than those initially encountered in generating the reduced model.

The paper continues with the formulation of the full order aeroelastic model in Section 2. The procedure to obtain a reduced model is discussed in Section 3. Then a new approach to calculating the gust term in the ROM is proposed. Results are then given in Section 4 for a test case to evaluate the method from the point of view of accuracy and computational efficiency. Finally, conclusions are drawn in Section 5. The important features of the method developed are: (i) linear and nonlinear ROMs can be derived; and (ii) the model reduction is performed once, with application of any gust made without further recourse to the CFD code.

2. Full order model

The Euler equations are solved in the curvilinear form on block–structured body–conforming grids:

$$\frac{\partial \hat{\mathbf{W}}}{\partial t} + \frac{\partial \hat{\mathbf{F}}}{\partial \xi} + \frac{\partial \hat{\mathbf{G}}}{\partial \eta} + \frac{\partial \hat{\mathbf{H}}}{\partial \zeta} = 0. \tag{1}$$

The transformation from Cartesian coordinates defines a curvilinear coordinate system from:

$$\xi = \xi(x, y, z, t), \qquad \eta = \eta(x, y, z, t), \qquad \zeta = \zeta(x, y, z, t) \tag{2}$$

with the Jacobian determinant of the transformation given by:

$$J = \left| \frac{\partial(\xi, \eta, \zeta)}{\partial(x, y, z)} \right|. \tag{3}$$

The conserved variables, $\hat{\mathbf{W}}$, and the flux vectors, $\hat{\mathbf{F}}$, $\hat{\mathbf{G}}$ and $\hat{\mathbf{H}}$, are then defined as follows:

$$\hat{\mathbf{W}} = \frac{1}{J}\mathbf{W} \tag{4}$$

$$\hat{\mathbf{F}} = \frac{1}{J}\left(\xi_x \mathbf{F} + \xi_y \mathbf{G} + \xi_z \mathbf{H}\right) \tag{5}$$

$$\hat{\mathbf{G}} = \frac{1}{J}\left(\eta_x \mathbf{F} + \eta_y \mathbf{G} + \eta_z \mathbf{H}\right) \tag{6}$$

$$\hat{\mathbf{H}} = \frac{1}{J}\left(\zeta_x \mathbf{F} + \zeta_y \mathbf{G} + \zeta_z \mathbf{H}\right) \tag{7}$$

where the subscripts $\bullet_x$, $\bullet_y$ and $\bullet_z$ denote differentiation with respect to x, y and z, respectively. The terms $\mathbf{F}$, $\mathbf{G}$ and $\mathbf{H}$ are given by:

$$\mathbf{W} = [\rho, \rho u, \rho v, \rho w, \rho E]^T \tag{8}$$

$$\mathbf{F} = \left[\rho u, \rho u^2 + p, \rho u v, \rho u w, u(\rho E + p)\right]^T \tag{9}$$