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Identification of Aerodynamic Model CFD-Based for Gust Response Analysis

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Abstract : Aeroelastic gust response analysis plays an important role in design of aircrafts. For gust response analysis, frequency domain aerodynamics method has been typically used with generalized aerodynamic influence coefficient matrices at various reduced frequencies. However, it cannot be applied to the aeroservoelastic analysis, such as gust alleviation control. Time-domain state space (SS) models must be built. It attacks little attention that gust response analysis relies on continuous gust time-domain input signal in terms of its PSD function. The aim of the current study is to provide a reduced-order modeling (ROM) method based on CFD to model gust responses for continuous gust inputs in time domain. The paper analyzed the gust response of AGARD445.6 wing subjected to the Dryden gust with ROMs and compared the difference between the rigid structure and elastic one. The results demonstrate that structure elastic effect should be considered in the design of the aircraft.

Key Words : Unsteady aerodynamic identification, Reduced-order models, Gust response, Aeroelastic analysis, CFD, continuous gust

1. Introduction

Aeroelastic gust response analysis plays an important role in design of aircrafts. As the aircraft tends to have the weight as small as possible, it leads the aircraft to be very flexible. In addition to affecting the rigid-body flight, the gust turbulence can also cause the elastic vibration of the structure. Aeroelastic effects also have significant influence on gust loads. The Federal Aviation Regulations (FAR) in particular specifies the discrete gust and continuous gust design criteria to which the aircraft must be subjected.

For gust response analysis, frequency domain aerodynamics method has been typically used with generalized aerodynamic influence coefficient matrices at various reduced frequencies. However, it cannot be applied to the aeroservoelastic analysis. Time-domain state space (SS) models must be built. At present, two types of gust models are used usually. One is discrete gust model and another is continuous gust model. The former considers gust as determined signal, and give the corresponding time domain functions. Continuous gust analysis depends on one of two statistical atmospheric gust model, namely Dryden gust and Von Karmon gust model. They are given the power spectrum density of the gust velocity. Since discrete gust time domain model is known in advance, as a result, gust response has usually been analyzed based on discrete gust model [1-3]. It attacks little attention that gust response analysis relies on continuous gust time-domain input signal in terms of its PSD function.

In recent ten years, unsteady areodynamic forces reduced order models (ROMs) based on CFD have been developed for aeroelastic analysis and

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parameters optimization design. However there is limited amount of work done in applying ROM approaches to gust responses analysis. The aim of the current study is to provide a method based on CFD to model gust responses for continuous gust inputs in time domain. Then system identification technique was adopted to model input-outputs Auto Regressive Moving Average (ARMA) ROMs. Finally, the paper analyzed the gust response of AGARD445.6 wing subjected to the Dryden gust with ROMs.

2. Continuous gust time-domain model

2.1. Title of Section 2.1

There are two continuous gust models, namely, the Dryden and Von Karman models. They are generated by different procedures. The Dryden gust model first gets correlation function of atmospheric turbulence, then deduces its power spectrum density(PSD) function, whereas the Von Karman model first builds turbulence PSD function based on atmospheric measurements, then deduces its correlation function. Obviously, the Von Karman model can reflect the atmospheric turbulence behavior more veritably. But the Dryden model has simple rational function formulation and is easy to be factorized. Moreover, the gust from the nature is usually low frequency signal. As a result, in the paper the Dryden gust model is used as continuous gust. The Dryden PSD for a vertical gust is,

$$\Phi_{w_z}(\omega) = \sigma_z^2 \frac{L_z}{\pi V} \left(1 + 12\left(L_z \frac{\omega}{V}\right)^2\right) \Big/ \left[1 + 4\left(L_z \frac{\omega}{V}\right)^2\right]^2 \tag{1}$$

where σ_z is turbulence strength in z direction, L_z is turbulence scale and V is flight velocity.

The general principle for design stochastic process is described as follows [4]. White noise signal r(t) is through a part, called a shaping filter, and the color noise signal x(t) is output. It's well known that white noise PSD is constant, the unit strength white noise signal is used, then color noise generated PSD is

$$\Phi_x(\omega) = \left\|G(jw)\right\|^2 = G^*(jw)G(jw) = \Phi_{w_z}(\omega) \tag{2}$$

Therefore, the Dryden PSD function is factorized by Eq.(2), the shaping filter G(jw) for Dryden gust can be obtained. According to reference [4], a time-domain Dryden gust input signal can be written by

$$w_{z_{i+1}} = K_P \cdot P w_{z_i} + K_Q \cdot Q r_{i+1} \tag{3}$$

where i represents the ith sample time, $P = e^{-\Delta t / T_z}, Q = \sigma_z \sqrt{1 - e^{-2\Delta t / T_z}}$, Δt is sampling time, Q is the function of and K_P, K_Q are coefficients of correction.

3. Gust Response Model Based on CFD ROMs

In the section, the aerodynamic loads ARMA ROMs caused by gust excitation and elastic deformation are built using system identification technique base on CFD. Assumed that the gust travels over a wing at the constant flight speed, starting from the wing root leading edge at time zero. The method, named the field velocity method, introduces vertical gust velocities to the CFD computation by assigning the gust velocities to the CFD grid time metrics, without actually moving the grid. In the paper, the gust velocity w_{z_i} described by Eq.(3) is added to the CFD grid velocity.

The aeroelastic equation of structure motion in response to gust excitation in generalized coordinates, neglecting damping, is stated as

$$\boldsymbol{M}\ddot{\boldsymbol{\xi}} + \boldsymbol{K}\boldsymbol{\xi} = \boldsymbol{q}\left(\boldsymbol{F_a} + \boldsymbol{F_g}\right) \tag{4}$$

where M, K are generalized mass matrix and stiffness matrix, respectively. ξ represents the generalized structure displacement. $\boldsymbol{F_a}, \boldsymbol{F_g}$ are generalized aerodynamic forces (GAF) and gust generalized aerodynamic forces, respectively. q is flow dynamic pressure. Eq.(4) can be depicted by Fig.1.

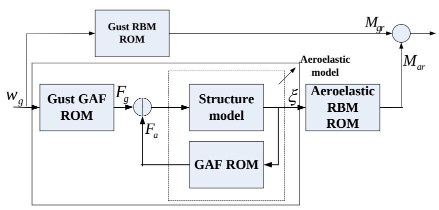


Fig. 1 Aeroelastic Model With Gust Excitation

Define state vector $x_s = \left[\xi \ \dot{\xi}\right]^T$,and discretize the continuous system Eq.(4) with zero-order holder. then couple generalized aerodynamic forces ARMA model(see [5]) with the above discrete model, the aeroelastic model with state-space form for the system depicted by dotted box in Fig.1 can be obtained

$$x_{sa}(n+1)=A_{sa}x_{sa}(n)+B_{sa}F_g(n)$$
$$\xi(n)=C_{sa}x_{sa}(n) \qquad (5)$$

where $x_{sa}(n+1)=\begin{bmatrix} x_s(n+1) \\ x_a(n+1) \end{bmatrix}$,

$$A_s=\begin{bmatrix} 0 & I \\ -M^{-1}K & 0 \end{bmatrix}, B_s=B_g=\begin{bmatrix} 0 \\ M^{-1} \end{bmatrix}, C_s=\begin{bmatrix} I & 0 \end{bmatrix}, D_s=D_g=[0],$$

$$A_{sa}=\begin{bmatrix} A_s+qB_sD_aC_s & qB_sC_a \\ B_aC_s & A_a \end{bmatrix}, B_{sa}=\begin{bmatrix} qB_g \\ 0 \end{bmatrix}, C_{sa}=\begin{bmatrix} C_s & 0 \end{bmatrix}$$

To obtain the gust generalized aerodynamic force model, the white noise used as excitation and the gust responses computed by CFD as output are used to identify corresponding ARMA model. The aeroelastic model with gust excitation can be obtained as

$$\boldsymbol{x}_{sag}(n+1)=\boldsymbol{A}_{sag}\boldsymbol{x}_{sag}(n)+\boldsymbol{B}_{sag}w_g(n)$$
$$\xi(n)=\boldsymbol{C}_{sag}\boldsymbol{x}_{sag}(n) \qquad (6)$$

where

$$\boldsymbol{x}_{sag}(n+1)=\begin{pmatrix} \boldsymbol{x}_{sa}(n+1) \\ \boldsymbol{x}_g(n+1) \end{pmatrix}, \quad \boldsymbol{A}_{sag}=\begin{bmatrix} \boldsymbol{A}_{sa} & \boldsymbol{B}_{sa}\boldsymbol{C}_g \\ \boldsymbol{0} & \boldsymbol{A}_g \end{bmatrix},$$

$\boldsymbol{B}_{sag}=\begin{bmatrix} \boldsymbol{B}_{sa}\boldsymbol{D}_g \\ \boldsymbol{B}_g \end{bmatrix}$, $\boldsymbol{C}_{sag}=[\boldsymbol{C}_{sa}\ \boldsymbol{0}]$, w_g is gust input.

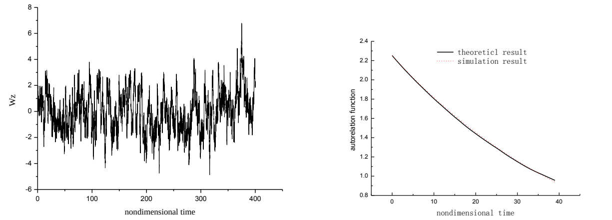
In addition, root bending moment (RBM)are often used the controlled variation in gust alleviation control and the model is also built in the paper. The root bending moment model can be divided to two parts, one is caused by aeroelastic effect , and another is caused by gust excitation. Augment the two models into Eq.(6), the total root bending moment model with gust excitation can be obtained in Eq.(7).

$$\boldsymbol{x}_{sagr}(n+1)=\begin{bmatrix} \boldsymbol{A}_{sag} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{A}_{gr} & \boldsymbol{0} \\ \boldsymbol{B}_{ar}\boldsymbol{C}_{sag} & \boldsymbol{0} & \boldsymbol{A}_{ar} \end{bmatrix}\boldsymbol{x}_{sagr}(n)+\begin{bmatrix} \boldsymbol{B}_{sag} \\ \boldsymbol{B}_{gr} \\ \boldsymbol{0} \end{bmatrix}w_g(n)$$
$$\boldsymbol{M}(n)=\begin{bmatrix} \boldsymbol{D}_{ar} & \boldsymbol{C}_{gr} & \boldsymbol{C}_{ar} \end{bmatrix}\boldsymbol{x}_{sagr}(n)+\boldsymbol{D}_{gr}w_g(n) \qquad (7)$$

where $\boldsymbol{A}_{gr},\boldsymbol{B}_{gr},\boldsymbol{C}_{gr},\boldsymbol{D}_{gr},\boldsymbol{A}_{ar},\boldsymbol{B}_{ar},\boldsymbol{C}_{ar}$ and $\boldsymbol{D}_{ar}$ are coefficient matrix of two models of root bending moment.

4. Numerical Example

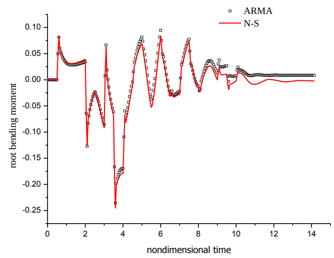
The Agard 445.6 wing configuration is tested to demonstrate the ROM method. Assumed that the flight height is 6km at Mach number 0.49. According to USA Military Standards MIL-F-8785C, it's known that turbulence strength σ_z is 1.5m/s and L_z is 533m. With the method proposed in section 2, the Dryden signal in time-domain is plotted in Fig.2a. To verify the signal , its autocorrelation is compared with the theoretical model shown in Fig.2b.



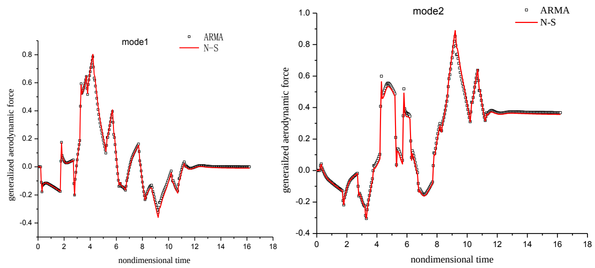
(a) (b)

Fig. 2 Dryden Signal in Time-domain

Fig.3 compares the root bending moment model a nd the first two elastic modes of GAF model with CF D method with 3211 excitation.



(a) Root Bending Moment



(b) mode1 (c) mode2

Fig. 3 Comparison of ARMA model and CFD Responses to 3211 Excitation

Fig.4 compares the identified RBM responses with CFD response to Dryden gust input. RBM responses t o Dryden gust with the rigid and elastic structure are shown in Fig.5.

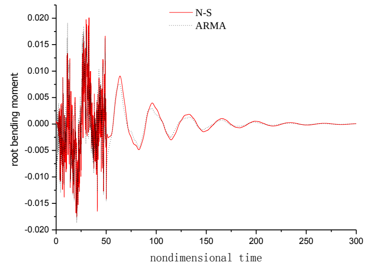


Fig.4 Comparison RBM with CFD response to Dryden gust

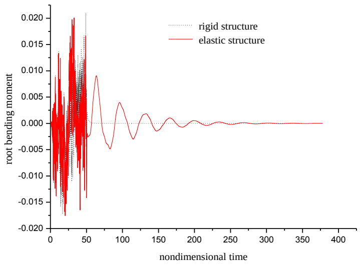


Fig.5 RBM Responses to Dryden Gust

5. Conclusion

The objective of the study was to develop an efficient discrete-time aerodynamic modeling method for use in ASE anaysis, such as gust alleviation. The paper firstly presented a method used to get the turbulence signal in time-domain based on its PSD function. Then the ROMs based on system identification approach was introduced. The accuracy of ROMs for gust response were compared with direct CFD responses. The results showed that responses computed using ROMs and CFD had a good agreement. Based on the work here, this approach will be used in the gust alleviation control in the future.

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