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Gust Response and Active Suppress based on Reduced Order Models

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Abstract: A gust response analyses method based on Reduced Order Models (ROMs) was developed in the paper. Firstly, taken random signal as the input signal and adopt Single Input-Multi-Output (SIMO) training fashion, a ROM based on Auto-Regressive and Moving Average model (ARMA) was established and validated with the comparison of CFD/CSD and experiment. Then, by introducing control surface deflection and control laws, flutter active suppress was studied. Lastly, through filtering and transferring function, the gust temporal signal is obtained based on Dryden gust model, and gust response and suppress were simulated.

Key Words : CFD/CSD, Aeroelasticity, ROMs, Flutter suppress, Gust response, Gust suppress

1. Introduction

As the development of Computational Fluid Mechanics (CFD) and Computational Structure Mechanics (CSD), flutter calculation based on CFD/CSD has become a general research method [1-3], however, the computational efficiency is still a key problem when it uses as a design tool. Because unsteady aerodynamic forces calculated with CFD cost large number of time, how to improve CFD efficiency for CFD/CSD coupled solution becomes one of the current focuses.

In the last decades, as the investigation progress of ROMs, CFD/CSD based on ROMs tends to be possible as a design tool. ROMs are deduced under the hypothesis of static nonlinear and dynamic linear flow fields, which is accord with the small perturbation assumption of flutter analyses. ROMs are mainly divided into two kinds: one is the system identification model, such as Auto-Regressive and Moving Average model (ARMA) [4],Volterra series-based model [5] and Artificial Neural Nets model(ANN) et al, the other is Proper Orthogonal Decomposition model(POD). For these system identification models, excitation signal needs to be chosen. Gupta et al and Cowan et al [3] used 3211 signal as the excitation signal, and Raveh et al [6] studied the random signal. Because the random signal contains all interesting frequency ranges, it should be a best signal excitation method. After ROMs is obtained, the aeroelastic state space mode can be deduced. The flutter boundary can be easily analyzed with time-marching or root locus method. Further, by introducing control model, the aeroelastic closed-loop control state space model can also be deduced and the flutter active suppress can be investigated.

In addition, gust suppress can alleviate the

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structural fatigue and reduce structural weight. Currently, the gust is commonly described as discrete and continuous models. Since the discrete gust model gives the temporal function of gust velocity, it can be easily coupled with CFD/CSD method [7]. The continuous gust models are described as Power Spectral Density function (PSD) such as Von Karman and Dryden models. As we all known, comparing with discrete gust model, the continuous gust models can accurately describe the real atmospheric turbulence. How to get the temporal gust signal based on PSD model needs to be investigated.

In the paper, ROMs based on ARMA are established. The open or closed-loop aeroelastic state space models with gust and control law are constructed. For the standard AGARD 445.6 aeroelastic wing [8], flutter boundary, flutter active suppress, gust response and gust suppress are studied.

2. Computational Model and Method

2.1. Dryden Gust Model

The continuous Dryden gust models are described as Power Spectral Density function (PSD),

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

Here σ_z and L_z represent gust turbulence strength and scale in the z direction, respectively, and V the flight speed.

The corresponding relative function of Eq. (1) is

$$R_{w_z}(\tau)=\sigma_z^{2}\left(1-\frac{v}{4L_z}|\tau|\right)\exp\left(-\frac{v}{2L_z}|\tau|\right) \quad (2)$$

For the CFD/CSD coupled solution, the temporal gust signal should be obtained from Eq. (1) and satisfies the condition of relation function of Eq. (2).

2.2. ROM Model

The discrete ROM based on ARMA is taken as

$$\mathbf{y}_a(k)=\sum_{i=1}^{na}\mathbf{A}_i\mathbf{y}_a(k-i)+\sum_{i=0}^{nb-1}\mathbf{B}_i u(k-i) \quad (3)$$

Here na and nb represent the number of delay steps, K is the discrete time and A, B identification matrixes.

In order to obtain the ROM, first, given 3211 or random excitation signal, which should contain the interesting structural frequencies, the generalized aerodynamic forces are solved based on CFD/CSD coupled solution. Then, through the systemic identification, the unknown variables of na, nb, A, B in Eq. (3) are determined. Lastly, the constructed ROM is expressed as the state space model.

$$\begin{aligned}\mathbf{x}_a(k+1)&=\mathbf{G}_a\mathbf{x}_a(k)+\mathbf{H}_a u(k)\\ F_a(k)&=\mathbf{C}_a\mathbf{x}_a(k)+\mathbf{D}_a u(k)\end{aligned} \quad (4)$$

Temporal gust signal w_g obtained from the Dryden model of Eq. (1) is treated as the excitation signal, similarly, under the approximation of rigid structure, the ROM of rigid gust response can be constructed and the relative state space model is

$$\begin{aligned}\boldsymbol{x_g}(n+1)&=\boldsymbol{A_g}\boldsymbol{x_g}(n)+\boldsymbol{B_g}w_g(n)\\ \boldsymbol{F_g}(n)&=\boldsymbol{C_g}\boldsymbol{x_g}(n)+\boldsymbol{D_g}w_g(n)\end{aligned} \quad (5)$$

For the active control investigation, considering control surface deflection, the state space model of aerodynamic control force is written as

$$\begin{cases}x_c(n+1)=A_c x_c(n)+B_c\beta(n)\\ y_c(n)=C_c x_c(n)+D_c\beta(n)\end{cases} \quad (6)$$

2.3. Aeroelastic Open and Closed-Loop Models

Under the gust excitation, the flexible structural dynamic equation is written as

$$\boldsymbol{M}\ddot{\boldsymbol{\xi}}+\boldsymbol{K}\boldsymbol{\xi}=\boldsymbol{q}\left(\boldsymbol{F_a}+\boldsymbol{F_g}\right) \quad (7)$$

Taken $\boldsymbol{x_s}=\left[\xi\ \dot{\xi}\right]^T$ and $\boldsymbol{F_a}$, $\boldsymbol{F_g}$ of Eq. (4) and Eq. (5) are substitute in Eq. (7). The state space model of flexible gust response is written as

$$\begin{aligned}\boldsymbol{x_s}(n+1)&=\boldsymbol{A_s}\boldsymbol{x_s}(n)+q\boldsymbol{B_s}\boldsymbol{F_a}(n)+q\boldsymbol{B_s}\boldsymbol{F_g}(n)\\ \xi(n)&=\boldsymbol{C_s}\boldsymbol{x_s}(n)+\boldsymbol{D_s}\boldsymbol{F_a}(n)+\boldsymbol{D_s}\boldsymbol{F_g}(n)\end{aligned} \quad (8)$$

Ignored the rigid gust aerodynamic force of $\boldsymbol{F_g}$, Eq. (7) can be used for the flutter calculation, namely aeroelastic open-loop flutter model.

Further, Eq. (6) is substituted into Eq. (8) and introducing the relative control law, the aeroelastic loop active suppress model can be gotten as

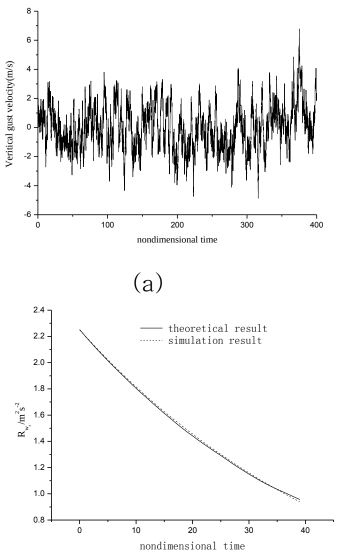
$$\begin{aligned} \boldsymbol{x}(n+1) &= \boldsymbol{A}\boldsymbol{x}(n)+\boldsymbol{B}\beta(n)+\boldsymbol{B}_v\boldsymbol{v}(n)+\boldsymbol{B}_d\boldsymbol{d}(n) \\ \boldsymbol{y}(n) &= \boldsymbol{C}\boldsymbol{x}(n)+\boldsymbol{D}_v\boldsymbol{v}(n)+\boldsymbol{D}_d\boldsymbol{d}(n)+\boldsymbol{D}_w\boldsymbol{w}(n) \end{aligned} \tag{9}$$

Here $\boldsymbol{v}(\boldsymbol{n})$ represents the random measuring noise or turbulence signal in gust response, $\boldsymbol{d}(\boldsymbol{n})$ random immeasurable noise and $\boldsymbol{w}(\boldsymbol{n})$ random measuring noise when introducing state observer. In the paper, the control methods are simulated with MATLAB/SIMULINK environment and can refer its Matlab software manual.

3. Results and Analyses

3.1. Temporal gust signal

By the Dryden gust PSD model of Eq. (1), introducing filtering and transfer function, temporal the gust signal can be obtained by Euler difference calculation. Fig.1 gives the generated gust signal and the comparison between calculation and Eq. (2). It indicates the generated gust signal is reasonable.



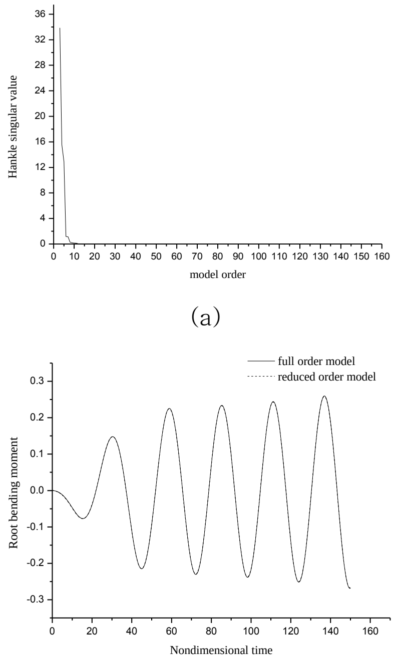
(a)

(b)

Fig. 1 The generated temporal gust signal and the comparison of relative function

3.2 Model Reduced Order

The state space model of Eq. (8) belongs to higher-order model. To realize the lower-order control, we need to reduce the order of the model. The distribution of Hankle singular values of Eq. (8) is given in Fig. (2a). Its energy attenuates very quickly, and taken the first 16 order modes can reflect the real control system. Fig. (2b) shows the comparison of full and reduced model of wing root bending moment, which agrees very well. It is indicated that the reduced model can be used for the active control investigation.



(a)

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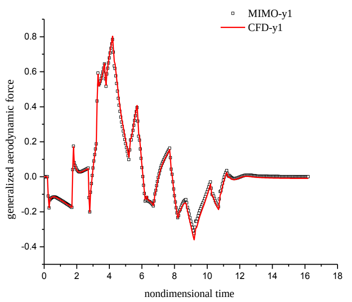
Fig. 2 Hankle singular values and wing root bending moment

3.3 Flutter ROM validation

Taken the filtering random signal as input signal for the each structural mode of AGARD445.6 aeroelastic wing [9], 4 SIMO ARMA models can be obtained. By linear superposition, one MIMO ARMA model can be constructed. Fig. 3 gives the response comparison between ROM prediction and CFD/CSD coupled solution under the 3211 signal excitation. It indicates the developed flutter ROM model is reasonable.



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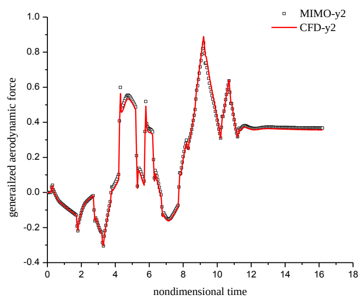

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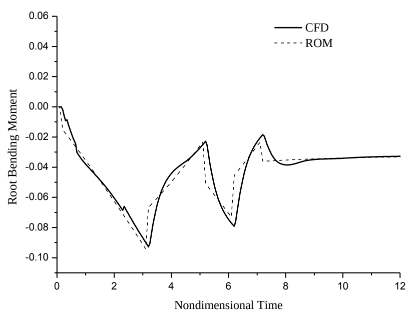
Fig. 3 The comparison of generated aerodynamic forces

3.4 Gust ROM Validation

Aircraft structure is approximated to be rigid, and in similar, taken random signal as gust excitation signal, one gust ROM can be constructed. In the paper, 3211 signal and temporal gust signals of Fig. 1a are instituted into the ROM, respectively. The wing root bending moment comparison of ROM calculation and CFD solution with gust is shown in Fig. 4. They agree very well. It indicates that the gust ROM is reasonable and can be used for the gust suppress investigation.



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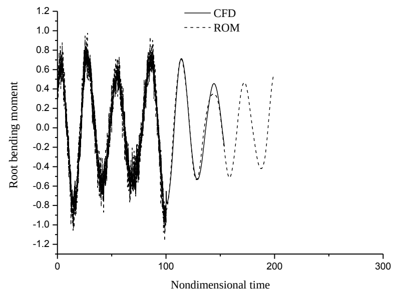


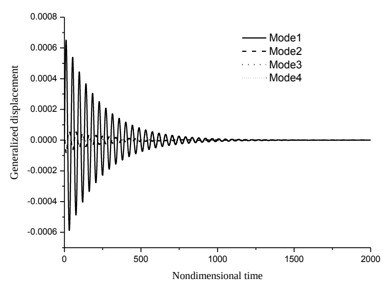
(b)

Fig. 4 The response of wing root bending moment with 3211 and Dryden gust signals

3.5 Flutter and Gust Active Suppress

For AGARD 445.6 aeroelastic wing, at Mach number of 0.96, the flutter dynamic pressure is 55.78lbf/ft2 .In order to investigate flutter active suppress effect, divergence dynamic pressure of 85 lbf/ft2 is taken as input value, the flutter active suppress with control surface deflection is studied. Fig. 5 shows the time histories of structural response and control surface deflection angle with LQG control method. It indicates that the flutter can be suppressed effectively.

Further, to investigate gust response active suppress, at Mach number of 0.9, flight attitude of 6000m, and taken $\sigma_z = 1.5m/s$, $L_z = 533m$ in the Dryden model of Eq.(1). Time histories of gust response with and without active control are shown in Fig. 6a, and control surface deflection angle in Fig. 6b. It indicates that the gust response can be suppressed effectively.



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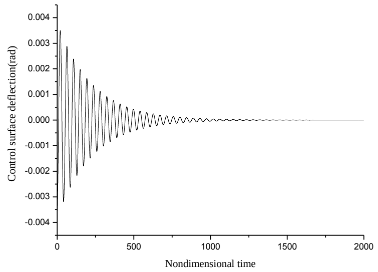

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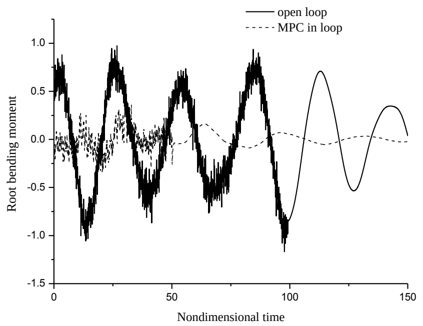
Fig. 5 Time histories of structural response and control surface deflection



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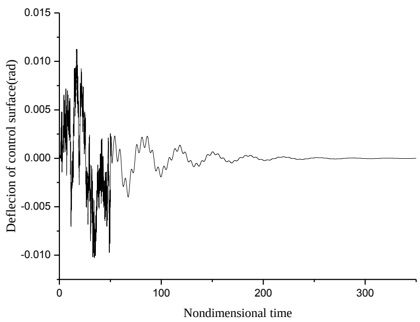

(b)

Fig. 6 Time histories of gust response and control surface deflection

4. Conclusions

Temporal gust signal is generated based on Dryden PSD. ROMs based on ARMA systemic identification method are established for aeroelasticity, rigid gust response. Open and closed-loop state space model are obtained based on structural dynamic equations and linear superposition of ROMs. The flutter, flutter and gust active suppresses are simulated. The results indicate that the developed method is effectively and high efficiency.

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References

[1] Zheng GN, Yang GW, Qian W. "Flutter Analyses of Complete Aircraft based on Hybrid Grids and Parallel Computing" . *Science China-technological Sciences*, 2013, 56(2):398-404.

[2] Yang GW, Zheng GN, Li GB. "Computational Methods and Engineering Applications of Static/dynamic Aeroelasticity Based on CFD/CSD Coupling Solution", Science *China-technological Sciences*, 2012, 55(9):2453-2461.

[3] Yang GW, Obayashi S., Nakamichi J., "Aileron Buzz Simulation Using an Implicit Multibolk Aeroelastic Solver", *Journal of Aircraft*, Vol. 40, No. 3, p.580-589, 2003.

[4] Cowan T J, Jr A S, and Gupta KK."Accelerating CFD-based aeroelastic predictions using systems identification", *36th AIAA atmoshperic flight mechanics conference and exhibit*, No.2001-0712, Boston, MA, 1998：85-93,AIAA-98-4152.

[5] Silva W A. "Simultaneous excitation of multiple-input multiple-output CFD-based unsteady aerodynamic systems". *Journal of Aircraft*, 2008,45(4):12 67-1274.

[6] Raveh D. "CFD-based models of aerodynamic gust response", AIAA 2006-2022,2006.

[7] Yang GW and Obayashi A, "Numerical Analyses of Discrete Gust Response for an Aircraft", *Journal of Aircraft*, Vol. 41, No. 6, pp.1353-1359, 2004.

[8] Carson Y J E. "Agard standard aeroelastic configurations for dynamic response I-Wing 445.6[R]". *AGARD-R-756, 1988.*

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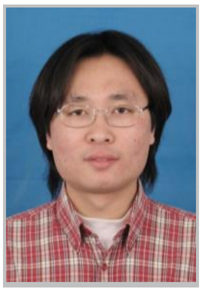

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