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Aeroelastic scaling laws for gust load alleviation control system

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Abstract Gust load alleviation (GLA) tests are widely conducted to study the effectiveness of the control laws and methods. The physical parameters of models in these tests are aeroelastic scaled, while the scaling of GLA control system is always unreached. This paper concentrates on studying the scaling laws of GLA control system. Through theoretical demonstration, the scaling criterion of a classical PID control system has been come up and a scaling methodology is provided and verified. By adopting the scaling laws in this paper, gust response of the scaled model could be directly related to the full-scale aircraft theoretically under both open-loop and closed-loop conditions. Also, the influences of different scaling choices of an important non-dimensional parameter, the Froude number, have been studied in this paper. Furthermore for practical application, a compensating method is given when the theoretical scaled actuators or sensors cannot be obtained. Also, the scaling laws of some non-linear elements in control system such as the rate and amplitude saturations in actuator have been studied and examined by a numerical simulation.

1. Introduction

The design of modern flights vehicles requires the evaluation of dynamic loads in response to discrete and random gust excitations.[1] The gust excitations may disturb the regular operations of pilots and worsen the ride quality. In more grievous cases, flight mission cannot be completed and the flight safety may be disserved.[2] Therefore, gust load alleviation becomes a key topic in aeroelastic problems.[3]

Gust load alleviation (GLA) control systems attempt to attenuate aircraft loads caused by the aircraft flying through gust zone.[4] Active control technology (ACT) has been proved to be useful for alleviating the internal loads and accelerations at some particular stations of the aircraft while in turbulence.[5] Some control theories such as the proportional–integral–derivative (PID) control, the linear quadratic Gaussian (LQG) control, the H_∞ control and neuron-fuzzy control have been applied to GLA control system design and have been verified to be effective by numerical simulation.[6,7]

Compared to numerical simulation in theoretical study, wind tunnel test can provide a more real condition to validate GLA methods and control laws. In the aerodynamic efficiency improvement (AEI) program, GLA wind tunnel test on a semi

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span aeroelastic wind tunnel model was conducted. Two control methods (LQG control and LQR control) were employed in this effort and the peak wing bending moments due to gusts were successfully reduced by more than 50%.[8,9] Another work is the X-DIA aeroelastic test in Italy, which proved that adopting wing active control system can add damping to wing bending modes, either when wing was hit by discrete or stochastic gusts.[10] In China, studies on GLA wind tunnel test had been carried out by Wu et al. In this project, PID controller was applied to GLA and the accelerations at fuselage and wing tip were validated to be alleviated to a certain extent, as well as the bending moment of wing-root.[11,12]

Generally speaking, most GLA tests focus on studying the effectiveness of control methods and control laws. Some of the experimental models are specifically built for the certain tests, and some are scaled from the full-scale aircraft. The scaled models in these tests might be similar to full-scale aircraft in structural stiffness, inertial mass and other aeroelastic parameters, but the scaling of GLA control systems is always beyond reach.

Aeroelastic scaled models are designed and manufactured so that the results obtained from the wind tunnel tests or flight tests can be related to the aeroelastic behavior of the full-scale aircraft.[13] The physical parameters of scaled model are determined by aeroelastic scaling laws established on the basic governing equations. Aeroelastic scaling laws, first presented by Bisplinghoff and Ashley,[14] have been developed and improved ever since. Recently, Wan and Cesnik have elaborated the aeroelastic scaling method of linear and nonlinear structures. In the area of aeroservoelastic scaling, Freidman studied a 2-D airfoil combined with a trailing edge control surface, derived aeroservoelastic scaling requirements for the fixed and rotary-wing aircraft.[15,16] And Pototzky applied scaling laws to the modal formulation of the aeroservoelastic equations, and verified the scaling process by comparing the root-locus of both size models.[17]

So far for GLA tests, the available aeroelastic scaling laws can only ensure the similarity of gust response under open-loop condition. And no strict scaling laws have been put forward for GLA control system yet, which means the strict similarity of gust response under closed-loop condition is still unreachable. Note: the open-loop condition means that the GLA system does not work, while the closed-loop condition means the GLA system is taking effect.

The scaling laws of GLA control system are studied in this paper, along with some consideration for practical application. Starting from the aeroelastic equation of motion in generalized coordinates, the transfer function of a PID control system is derived. Through theoretical demonstration, a scaling criterion of the control system has been set up and a scaling method is provided and verified. The options of Froude number similarity have also been studied in this paper which gives us a more comprehensive understanding of the GLA scaling laws. In addition, considering the practical application, a compensating method is given for actuator or sensor when the theoretical scaled ones cannot be obtained. Another difficult problem, the scaling laws of saturations in actuator has been studied. All these scaling laws could be applied to GLA tests and play a critical role in making direct connections between scaled model and full-scale aircraft.

2. Scaling laws for GLA test model

The relations of gust response between the scaled model and the full-scale aircraft are governed by aeroelastic scaling laws. To meet the similarity of gust response of open-loop system, five general similarity criteria have been described in the following section. For closed-loop system, the general similarity criteria would not be sufficient any more. Necessarily, the scaling criterion for GLA control system should be studied and method should be given to ensure the similarity of alleviation results.

2.1. General scaling method for aeroelastic similarity

For low-speed aeroelastic wind tunnel tests, there are no more than three practical constraints, corresponding to the primary dimensions of length, time, and mass. To specify these constraints, three factors are chosen as the basic scaling factors, including the length scaling factor k_b, the speed scaling factor k_V and the air density scaling factor k_ρ.[18]

On the basis of these three scaling factors, there are different criteria that should be satisfied in different situations when scaling a model. For example in flutter study, the dynamic aeroelastic equation of full-scale model can be written as follows (neglecting the damping)[19]:

$$\left(-\omega^2 M + K - \frac{1}{2}\rho V^2 bA\right) q = 0 \tag{1}$$

where ω is the flutter frequency, V the air velocity, ρ the air density and b the reference length. Generalized mass M, generalized stiffness K and generalized displacement q are dimensional and the aerodynamic influence coefficient A is non-dimensional. Then the dynamic aeroelastic equation of scaled model can be written with the scaling factors:

$$\left[-k_\omega^2 k_m \omega^2 M + k_K K \frac{1}{2} k_\rho k_V^2 k_b k_A \rho V^2 bA\right] k_q q = 0 \tag{2}$$

Considering Eqs. (1) and (2), to get a similar flutter equation, the following similarity criterion is required:

$$k_\omega^2 k_m = k_K = k_\rho k_V^2 k_b k_A \tag{3}$$

Assuming that the Mach number, Reynolds number and specific heat ratio are the same between two models, and with similar aerodynamic configuration and vibration shape, there will be $k_A = 1$, and thus let the non-dimensional parameter, the reduced frequency k $\left(k = \frac{\omega b}{V}\right)$ be kept the same in both model:

$$k_\omega^2 k_m = k_\omega^2 k_\rho k_b^3 = k_\rho k_V^2 k_b k_A \rightarrow k_k = \frac{k_\omega k_b}{k_V} = \sqrt{k_A} = 1 \tag{4}$$

To summarize the similarity criteria for flutter test, basic scaling factors and other scaling factors according to the above criteria has been sorted in Table 1.[13]

The non-dimensional parameters k are kept the same in both models in order to ensure the flutter similarity. But in other kind aeroelastic scaling works, it would not be sufficient any more. For example, the static aeroelastic or gust response similarities ask for one more non-dimensional parameter: the Froude number. Considering the effect of gravity, the static aeroelastic equilibrium equation can be written as