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(Research Article)

Aerodynamic damping identification for aircraft models in transonic wind tunnels

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Abstract

During the transonic wind tunnel tests, vibration phenomena often appear on aircraft models, which has adverse effects on the wind tunnel test. This kind of vibration is often related to the modal damping information of the aircraft model. In this paper, the balance signal is used as the time-domain response of the aircraft model. Firstly, the random decrement method is used to extract the free vibration signal from the balance signal, and then the ITD method is used to estimate the modal damping parameters of the aircraft model. The effectiveness of the proposed modal damping estimation method is verified by the wind tunnel test data, and a comparative analysis is made with active damping system on and off. Based on the estimated aerodynamic damping information, corresponding measures can be taken to effectively avoid the vibration phenomenon that may occur during the wind tunnel test, and ensure the progress of the wind tunnel tests.

Keywords: Aerodynamic damping; Transonic wind tunnel; Random decrement method; ITD; Active damping

1. Introduction

The aircraft models in transonic wind tunnel may undergo different degrees of vibration[1-3] under high angle of attack test conditions. This vibration will not only suddenly interrupt the ongoing wind tunnel test, resulting in the forced suspension of test data collection, but also cause certain damage to the test equipment and aircraft model itself. Such interruption and damage affect the smooth progress of the test, and may adversely affect the subsequent test result analysis and aircraft design optimization. To solve this challenging problem, researchers have proposed many different types of damping systems[4-7].

This vibration problem essentially belongs to the field of aeroelasticity, and the core lies in the damping characteristics of aircraft model. As a key factor affecting the dynamic response of aircraft, damping directly determines the stability and safety of the model in wind tunnel test. If damping parameters of aircraft model in the process of wind tunnel test could be accurately grasped, its motion characteristics, including the frequency, amplitude and attenuation rate of vibration then would be deeply analyzed. Based on these detailed data, researchers can take corresponding measures to effectively avoid the vibration phenomenon that may occur during the wind tunnel test.

There are two main methods for damping identification, namely, frequency domain method and time domain method. Among them, the frequency domain damping identification methods[8] basically use the frequency response function as the input to identify the modal parameters, but during the wind tunnel testing process, the excitation signal is not measurable, so it cannot meet the requirements. The time domain identification method can directly use the response data under environmental excitation for identification, and has good adaptability for aerodynamic damping

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identification. In this paper, the random decrement method[9] is used to extract the free vibration signal from the dynamic signal of the balance, and then combined with the ITD (the Ibrahim time domain technology) method[10] to identify the modal parameters of the structure from the free attenuation signal.

In this paper, the balance signal is used to identify the aerodynamic damping. The core idea of this method is to extract the information related to the aerodynamic damping by analyzing and processing the dynamic signal of the balance, so as to realize the accurate identification of the aerodynamic damping. In addition, the influence of active damping system on aerodynamic damping is further analyzed.

2. Material and methods

Motion Equations for aircraft models could be expressed as

$$M\ddot{q}+B\dot{q}+Kq=F_a \quad \text{..........} \tag{1}$$

It can be seen that the damping term B of the corresponding mode decreases from positive damping to 0 or even negative damping under the action of medium in the wind tunnel. The criterion of single degree of freedom flutter is that the damping is equal to 0, and the damping is composed of aerodynamic damping and structural damping, which could be defined as

$$\zeta=\gamma+g/2 \quad \text{.........} \tag{2}$$

where γ is aerodynamic damping, $g/2$ is structural damping. The damping ratios of stings in the Royal Institute of Aeronautics and Astronautics 8ft × 8ft wind tunnel[11] are only about 0.4%, and the damping ratio of sting in the VIGYAN low-speed wind tunnel[12] is about 0.8%. This very small structural damping makes it easy to make the total damping equal to 0 when the aerodynamic damping changes, which leads to structural divergence.

2.1. Damping identification method

The principle of random decrement method is to separate free attenuation vibration response signals from multiple random response results of linear system by using the zero mean value property in stationary random vibration. Consider a linear structure whose response under arbitrary load excitation can be expressed as

$$y(t)=y(0)D(t)+\dot{y}(0)V(t)+\int_0^t h(t-\tau)f(\tau)d\tau \quad \text{.......} \tag{3}$$

where $D(t)$ is the free vibration response of the system with unit displacement and zero initial velocity, $V(t)$ is the free vibration response of the system with unit velocity and zero initial displacement, $h(t-\tau)$ is the unit impulse response function.

Select a constant *C* that intersects the structural response $y(t)$ at a series of moments $t_i(i=1,2,\ldots,N)$. The response from time t_i can be expressed in a form similar to equation (3)

$$y(t-t_i)=y(t_i)D(t-t_i)+\dot{y}(t_i)V(t-t_i)+\int_{t_i}^t h(t-\tau)f(\tau)d\tau \quad \text{.......} \tag{4}$$

Moving the time t_i to the origin, *N* response curves $z_i(t)=y(t-t_i)$ can be obtained, which can be regarded as sub sample functions of the whole random process. At the same time, the excitation $f(t)$ is stationary, and the translation in time does not affect its random characteristics. Average *N* time translation response curves to obtain

$$\begin{aligned} z(t)&=\frac{1}{N}\sum_{i=1}^{N}z_i(t) \\ &=E\left[y(t_i)D(t)+\dot{y}(t_i)V(t)+\int_0^t h(t-\tau)f(\tau)d\tau\right] \end{aligned} \quad \text{.......} \tag{5}$$

The response and excitation of the system are stationary random vibration signals with a mean value of zero. So $E\left[\dot{y}(t_i)\right]=0$, $E\left[f(t)\right]=0$ and then

$$z(t) = E\left[y(t_i)D(t)\right] \quad \text{........(6)}$$

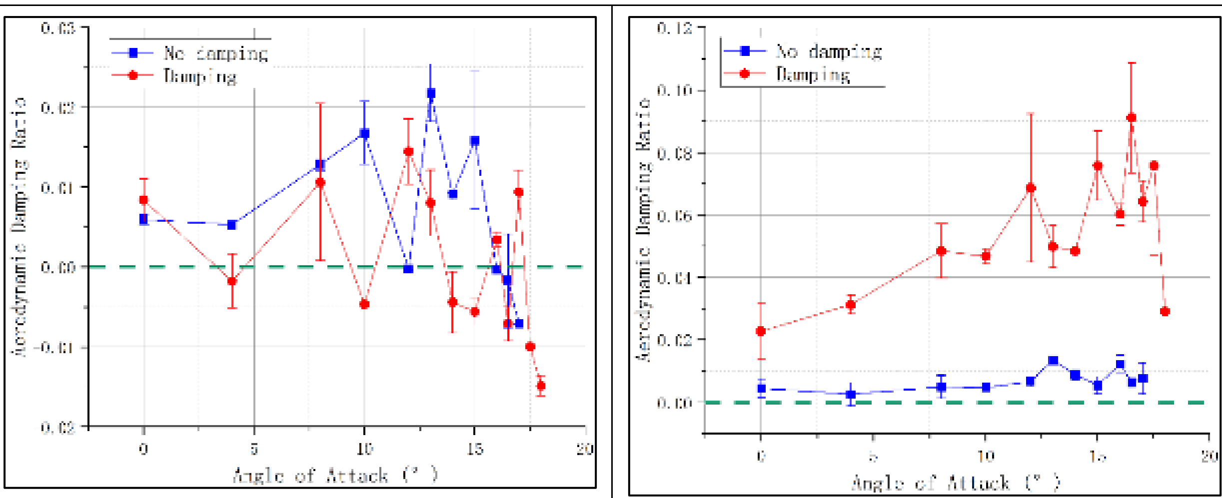
The displacement at time t_i is constant *C*, and then we can get

$$z(t) = C \cdot D(t) \quad \text{........} \quad (7)$$

Thus, the free vibration response signal with initial displacement C and zero initial velocity is obtained. ITD method can be then used for time domain identification. ITD method was proposed by S.R. Ibrahim in 1973 to identify structural modal parameters using free vibration response signals. The free vibration response signal of the linear system can be expressed as the superposition of its various modal solutions. The free vibration response signal obtained by the random decrement method is sampled twice to construct the corresponding augmented matrix, and the modal parameters are obtained by using the relationship between the two augmented matrices and the structural characteristic equation.

3. Result and Discussion

The results of the aerodynamic damping of the aircraft model varying with the angle of attack are shown in Figure 1.



(a) first order   (b) second order

Figure 1 Aerodynamic damping of aircraft model

Figure 1 shows that in the first-order mode, the aerodynamic damping is small, and its values are all below 0.025, and there is no obvious change relationship with the angle of attack. However, at high angles of attack, the aerodynamic damping under both uncontrolled and controlled conditions changes to negative values, which leads to the interruption of the wind tunnel testing. In the second-order mod, the aerodynamic damping is positive, and the value of the uncontrolled aerodynamic damping basically does not change with the angle of attack, while the aerodynamic damping under control increases first with the increase of the angle of attack, and then decreases. In addition, at the same angle of attack, the aerodynamic damping value with control is larger than that without control.

The aerodynamic damping ratio is calculated by the difference between the overall damping ratio and the structural damping ratio at static state. The structural damping at static state is shown in Table 1.

Table 1 Structural damping ratio of model

Active damping	first-order/	second-order/
No	0.2%	0.2%
Yes	1.2%	1.4%

The corresponding aerodynamic damping of aircraft model with and without active damping is different. This shows that the dynamic displacement of the wind tunnel model driven by active damping system makes the dynamic flow field around the model redistribute, and the changed air flow acts on the model, changing its structural dynamic properties, reflecting the characteristics of fluid structure coupling.

The aerodynamic damping value can be used to guide the algorithm design of the wind tunnel active damping system. The first-order aerodynamic damping ratio is reduced to a negative value at high angles of attack, while the second-order aerodynamic damping ratio is basically positive, which can improve the first-order control effect and further expand the range of angles of attack.

4. Conclusion

In this paper, the random decrement method and ITD method were utilized to identify and analyze the aerodynamic damping. The corresponding aerodynamic damping of aircraft model with and without active damping is obtained. The different aerodynamic damping values indicate that the system drives the wind tunnel model to produce dynamic displacement, so that the dynamic flow field around the model is redistributed, and the changed air flow acts on the model and changes its dynamic characteristics. It demonstrates that there is a complex coupling relationship between the active damping system (including structure) and the flow field.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors report no conflicts of interest in this work.

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