

## **WIND TUNNEL TESTS ON THE AEROELASTIC BEHAVIORS OF TENSION STRUCTURES**

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**ABSTRACT:** Cable/membrane structures are characterized by their lightweight and flexibility, which makes them rather sensitive to wind. In some cases, the interaction of structure and wind may play an important role to the wind induced response, which can not be accounted by conventional analysis methods. To solve this problem, a simplified aeroelastic model, based on theoretical analysis and wind tunnel tests, was put forward firstly. Some important parameters, such as aerodynamic damping and added mass, were introduced to describe the additional aerodynamic feedback terms involved in this aeroelastic model. Then, a series of wind tunnel test of saddle-shaped cable net structures and membrane structures with rhombic plans were carried out to study the couple effects of wind and tension structures. Random decrement technique was adopted to identify these parameters. The variation of aerodynamic damping and added mass with wind speed, exposure, structural stiffness and vibration mode shape were analyzed especially, and the mechanics of wind-structure interaction were discussed.

**Key Word:** Tension structure; Wind-induced vibration; Wind tunnel test; Aeroelastic effect; Aerodynamic damping

### **1. Introduction**

Tension structures, such as cable net and membrane structures, are the most widely used long-span tension structures. As being characterized by lightweight and flexibility, they are highly susceptible to the wind action. How to determine the aerostatic and aerodynamic response due to the wind action is a major concerned problem for the design of tension structures. Up to now, comprehensive studies have been performed, but the mechanism of wind-induced vibration of membrane structures has not been recognized in enough detail (Kassem1992, Kimoto and Kawamura 1986, Daw and Davenport 1989, H. Kawai 1999). The main reasons lie in two aspects: one is the strong geometrical nonlinearity, which make the dynamic characteristics of tension structures are obviously different from those of bridges and high-rising buildings, so traditional methods of random vibration analysis in frequency domain can not be used directly. The other reason is the weak local rigidity, which can make membrane structures produce rather large vibration under wind excitation. Sometime, these large vibrations can even affect the surrounding fluid field remarkably; that is to say, the wind-structure interaction or the aeroelastic effects can not be neglected. To solve this problem, a simplified aeroelastic model, based on theoretical analysis and wind tunnel test, was put forward firstly. Some important parameters, such as aerodynamic damping and added mass, were introduced to describe the additional aerodynamic feedback

terms involved in this aeroelastic model. Then, a series of wind tunnel test of saddle-shaped cable net structures and membrane structures with rhombic plans were carried out to study the couple effects of wind and tension structures. Random decrement technique was adopted to identify these parameters. The variation of aerodynamic damping and added mass with wind speed, exposure, structural stiffness and vibration mode shape were analyzed especially, and the mechanics of wind-structure interaction were discussed.

**2.Simplified aeroelastic model method**

The dynamic response of structures under wind action can be described by the equation of motion:

$$M_s \ddot{x}(t) + C_s \dot{x}(t) + K_s x(t) = F(t, x(t), \dot{x}(t), \ddot{x}(t)) \tag{1}$$

Where  $M_s$ ,  $C_s$  and  $K_s$  are the matrix of structural mass, damping and stiffness, respectively.  $F(\cdot)$  characterizes the wind load actions, which is the function of time  $t$ , structural displacement vector  $x(t)$  and its time derivatives. It means that the wind force in a particular turbulent flow field at time  $t$  depends on the collective action of flow induced forces on structural surface and the effects of the motion of structure.

Progress is difficult without some simplifying assumptions. It is common to assume that the motions of the structures do not appreciably change the wind-induced field or the aerodynamic input. In other words, the aerodynamic forces on a moving structure are the same as those on a static or stationary one of identical external geometry. For most cases, these pseudo-static aerodynamic forces provide good approximations. Beside the pseudo-static assumption, the strong correlation assumption is also important for simplification. Here, the strong correlation means that the structural response is mainly caused by the component of vibration-induced forces which natural frequencies are close to the structural response in frequency domain.

Based on these two assumptions, the formula (1) can be decoupled into four parts, which capture the effects of  $t$ ,  $x(t)$ ,  $\dot{x}(t)$  and  $\ddot{x}(t)$  respectively. Then, we can deduced the equation of simplified aeroelastic model as follow:

$$(M_s + M_a) \ddot{x}(t) + (C_s + C_a) \dot{x}(t) + (K_s + K_a) x(t) = p(t) \tag{2}$$

where  $M_a$  is called added mass, it represents the air mass being accelerated by the motion of the structure;  $C_a$  is called aerodynamic damping, it represents the energy exchange between external pressure and structural motion, if this term is negative, aerodynamic instability can arise;  $K_a$  is called aerodynamic stiffness, it represents the compressibility of the internal air space, arising from the deformation of structural surface.  $K_a$  is important to those airproof structures, such as air supported membrane structures, and can be neglected for the other cases. The sources of these three terms are depicted in Fig. 1.

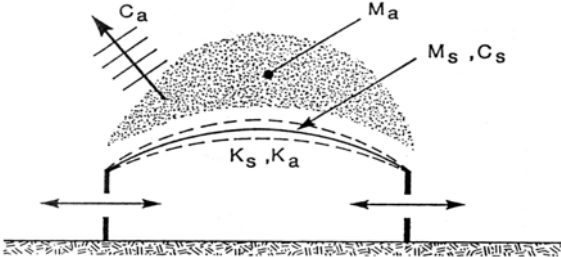


Fig. 1 Sketch of additional aerodynamic feedback terms (Daw and Davenport1989)

In the simplified aeroelastic model, the fluid and structure can not be considered specially but

as a whole system, and relate the aerodynamic forces with structure motion by mathematical model. However the added aerodynamic forces term can not be accounted by conventional analysis methods but by wind-tunnel test because of the complexity of flow around cable/membrane structure.

### 3. Aeroelastic model wind-tunnel test

To determine the magnitude of added mass and aerodynamic damping, Wu et al (2003, Shen and Wu, 2002. Wu and Wang et al. 2002) carried out a series of wind tunnel tests of saddle-shaped cable net structures and membrane structures with rhombic plans.

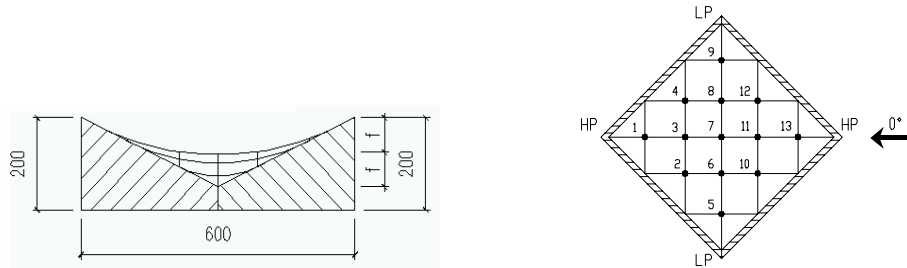


Fig.2 Sketch of elevation view and measuring points

The two saddle-shaped models were designed. Geometric scale is 1:50, model span is  $L=60\text{cm}$ , the prestressing force of membrane is  $0.5\text{N/cm}$ ; the rise-span ratio of Model-1 is  $1/12$ , natural frequency is  $11.5\text{Hz}$ ; the rise-span ratio of Model-2 is  $1/8$ , natural frequency is  $14.7\text{Hz}$ . The material of membrane adopts waterproof cloth. Sketch of elevation view and measuring points of structure are depicted in Fig. 2. It is emphasized that the model parameters mentioned above take into account the similarity ratio of kinematics and dynamics.

The tests were performed in the TJ2 wind tunnel in Tongji University. Pressure measure system adopted SPC-3000 electronic piezometer scanning valve. Vibration measure system adopted IVN306DF intelligence signal data acquisition and processing system. Measure results were real-time monitored by using HP35670 signal analytical apparatus. Nine subminiature touch acceleration sensors ZF-01 are equally arranged on the test model whose mass is  $0.5\text{g}$ .

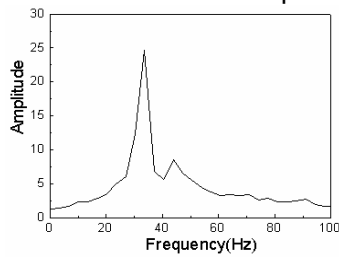


Fig.3 Amplitude frequency plot of acceleration

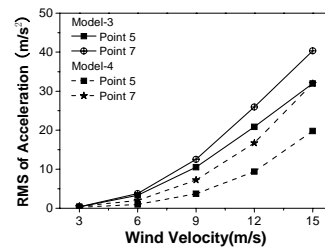


Fig.4 RMS of acceleration versus wind velocity

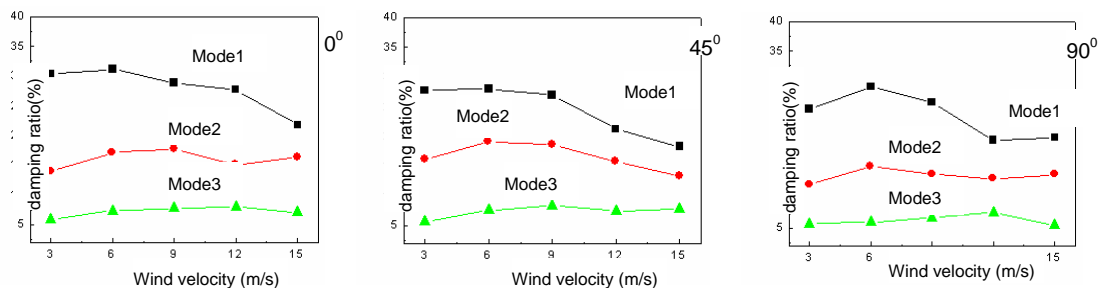


Fig.5 Aerodynamic damping versus wind velocity

Fig.3 shows the amplitude frequency plot of acceleration on Node 7 under the wind velocity of  $9\text{m/s}$  in the wind direction of  $0^\circ$ . It indicates that the vibration of flexible model represents obvious forced vibration. Fig.4 shows the RMS of acceleration versus wind velocity of Model-1 and Model-2

in the wind direction of  $0^{\circ}$ .

The random decrement technique was adopted to identify the added mass and the dynamic damping. Their variation with wind speed, exposure, structural stiffness and vibration mode shape were analyzed especially. From these researches, it shows that the wind-induced dynamic responses of tension structures can be characterized by broadband and forced vibration process; the dominant vibration modes of structure is strongly effected by the distribution of wind load; the effect of aerodynamic damping is more significant than added mass, especially for lower vibration modes of structures, in that case, the damping ratio can reach to about 15%(showed in Fig.5); the magnitude of added mass is only about 1 time of structural mass(showed in Fig.6); aeroelastic instability of entire structure haven't occurred in all of the experiments, but for some cases, some measurement point appeared local aeroelastic instability(showed in Fig.6).

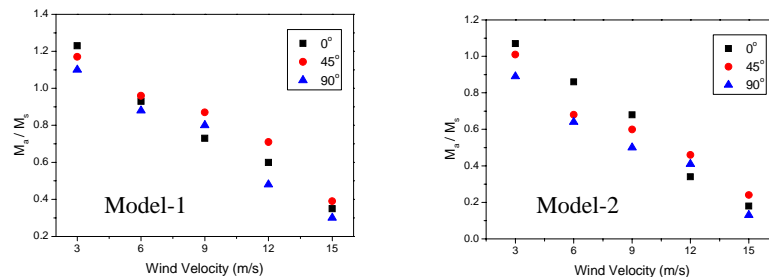


Fig.10 Added mass versus wind velocity

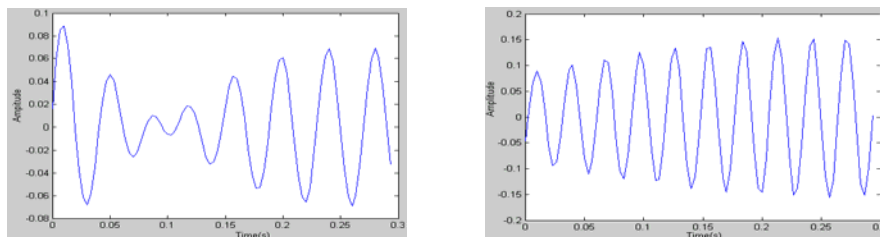


Fig.11 Random decrement signature of point with negative aerodynamic damping

#### 4. Conclusions

This study focused on the interaction between wind and cable/membrane structure. The following conclusions are made:

- (1) The dominant vibration modes of structure are strongly effected by the distribution of wind load.
- (2) The effect of aerodynamic damping is more significant than added mass, especially for lower vibration modes of structures, in which case the damping ratio can reach 15%.
- (3) The magnitude of added mass is only about 1 time of structural mass.
- (4) Aeroelastic instability of entire structure haven't occurred in all experiments, but in some cases local aeroelastic instability appeared in individual measurement points.

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