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Study on added mass of a circular curved membrane vibrating in still air

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ABSTRACT

It is widely known that added mass has a significant influence on the natural frequency of membrane structures. Previously, some experimental studies on the added mass of flat membranes have been performed. However, the added mass of curved membrane vibrating in still air is unclear. In this study, first, vibration tests of a circular curved membrane in still air with various air pressures are conducted, and the natural frequencies of the circular curved membrane are identified with the Hilbert–Huang transform (HHT). An approximate estimation of the added mass coefficient of the circular curved membrane is given as 0.65 by fitting results of tests. Then, the efficiencies of two added mass models, one as simplified added mass method and the other as numerically analysis method established by using the Boundary Element Method (BEM), are verified by the circular curved membrane tests. At last, the Modal Assurance Criterion (MAC) values indicate that for uniform mass distribution of the circular curved membrane, there is little difference between the mode shapes of the membrane vibrating in vacuum and in air.

1. Introduction

When structures vibrate in a certain kind of fluid, part of the surrounding fluid will be invoked and will vibrate together with structures; this effect is called added mass. Generally, the added mass of building structures vibrating in air, such as steel structures or concrete structures, can be ignored, because their material densities are much greater than that of air. However, the added mass has a significant influence on the vibration of membrane structures due to the light weight of their material.

Early studies of added mass focused mainly on typical objects, such as cylinders and spheres, moving in fluid with acceleration. Maheri and Severn's [1] research on the added mass of cylinders vibrating in water showed that the added mass of the first mode is equal to the fluid mass displaced by the cylinder, but this is not true for higher modes. Han [2] proposed a simple added mass model for a cantilevered cylinder vibrating in water, and a formula for estimating the natural frequencies was presented. Some determinations of the fluid loading and the added mass for a supported plate are known from the slender wing theory [3], the travelling wave solution [4,5], two-dimensional linear aerodynamic theory [6], or three-dimensional linear aerodynamic theory [7].

For membrane structure, several theories have been developed to investigate the added mass. Irwin and Wardlaw [8] presented an empirical equation for estimating the added mass of the Montreal Stadium. Sygulski [9–11] analyzed the problem of interaction between membrane structure and the surrounding air by using the BEM and Finite Element Method (FEM). Minami [12] used thin aerofoil theory to deduce the added mass formula for a plane membrane vibrating in still air with a half-sine fundamental mode and found that the added mass was equivalent to the air uniformly distributed on the membrane with an estimated height equal to 68% of the length of the membrane. Kukathasan and Pellegrino [13] deduced the added mass formula for three-dimensional membranes in still air based on aerodynamic acoustics theory. Zhou et al. [14] estimated the added mass for open flat membranes vibrating in still air by using the BEM.

Some experimental studies on the added mass of membrane structures have been performed. Sewall et al. [15] undertook an experimental investigation of membrane vibrations and proposed a distribution model of the added mass of the membrane. Li, et al. [16] tested the vibration of a circular flat membrane in still air with varying air pressures, and a simplified added mass model was proposed based on the vibration mode shapes of the flat membranes, i.e., the added mass above each vibration region is equal to the uniformly distributed air with height of $0.65l$, in which l is the diameter of the inscribed circle of the region. The added mass coefficient, 0.65, was derived from the fitting analysis of the circular membrane results. Chen et al. [17]

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researched on the added mass of open-type one-way tensioned membrane structure in uniform flow.

However, those previous experiments just focused mainly on flat membrane structures. No experimental research on the values of the added mass for curved membranes has been conducted. The purpose of this paper is to investigate the added mass of a circular curved membrane in still air and verify the suitability of the added mass model for curved membranes. In this study, first, vibration tests of a circular curved membrane in still air with various air pressures is conducted. Second, based on the Hilbert–Huang spectral analysis [18,19], the natural frequency identification for circular curved membrane is obtained. Third, an approximate estimation of the added mass coefficient for circular curved membrane is given. Then, the accuracy of the simplified added mass method and numerically analysis method established by using the BEM is verified by the circular curved membranes test. Mode shapes of the circular curved membrane vibrating in air are discussed.

2. Experimental tests of curved membrane in still air

2.1. Test setup

An isotropic latex sheet, the thickness of which is 0.23 mm, was used in this experiment. The elastic modulus of the latex sheet was 1.4 MPa. The mass per unit area of the latex was 2.3 kg/m^2. The flat membrane was clipped by a top circle and a bottom circle. The prestress was imposed uniformly by lifting an inner circle, as shown in Fig. 1. Three levels of prestress stress in the circular flat membrane were considered by controlling the lifting displacement. Then, after lifting the central support, the shape of membrane could be transformed from the flat to the umbrella and prestress can be uniform except the central part, as shown in Fig. 2. Hence, measuring points of laser displacement sensors on the membrane model were arranged at the place with uniform prestress, as shown in Fig. 3.

It's a coupled vibration test of circular curved membrane under static wind that was conducted in a vacuum chamber. Due to the limitation of the vacuum pump and the chamber's leakproofness, a complete vacuum could hardly be achieved. Hence, vibration tests of the circular fat membrane in still air with various air pressures were conducted at 6 levels of air pressures, i.e.1.0, 0.8, 0.6, 0.4, 0.2 and 0.05 atm. Then, after raising the centre support, the vibration tests of the circular curved membrane were conducted in the same case. Table 1 shows the test cases.

2.2. Natural frequency identification

Based on the displacements of the curved membrane vibrating at various air pressures, HHT is used to identify fundamental frequency. The technique works through performing a time adaptive decomposition operation named Empirical Mode Decomposition (EMD) on the signal; and then the signal will be decomposed into a set of complete and almost orthogonal components named intrinsic mode function (IMF), which is almost monocomponent. However, there are possibilities that the different vibration modes are mixed in IMFs while carrying out EMD, with the result that it is impossible to identify the modal parameters of those submerged lower-energy modes. In order to solve the mode-mixing problem, the high order Butterworth bandpass filter (BBF) can be adopted to process the measured free vibration signal before using EMD. Based on obtained IMFs, the random decrement technique (RDT) is applied to get the random decrement signal of each vibration mode. The expression of random decrease sign can be denoted as $\delta(t)$, the Hilbert transform (HT) of $\delta(t)$, denoted as $\bar{\delta}(t)$, is determined by

$$\bar{\delta}(t) = \frac{1}{\pi} K \int \frac{\delta(\tau)}{t-\tau} d\tau \tag{1}$$

where K is Cauchy principal value.

The analytical signal $Z(t)$ of $\delta(t)$ is expressed as

$$Z(t) = \delta(t) + i\bar{\delta}(t) = a(t)e^{i\theta(t)} \tag{2}$$

in which instantaneous amplitude $a(t)$ is $a(t) = \sqrt{\bar{\delta}^2(t) + \delta^2(t)}$, the instantaneous phase angle $\theta(t)$ is $\theta(t) = \arctan(\bar{\delta}(t)/\delta(t))$, and $i = (-1)^{1/2}$.

Hence, the circular frequency ω_d of the signal can be obtained from the slope of the phase angle $\theta(t)$ vs time t plot, and can be expressed as $\omega_d = d\theta(t)/dt$. With ω_d estimated, the natural frequency f_d can be obtained as

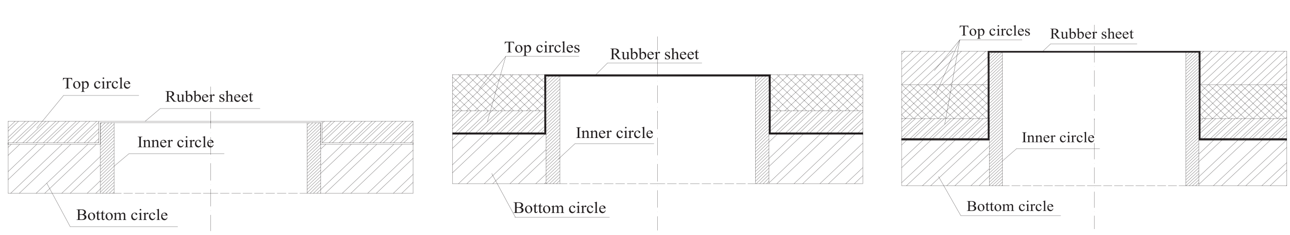
$$f_d = \frac{\omega_d}{2\pi} \tag{3}$$

Take case A62 as an example, the procedures of the natural frequency identification are as follows:

(1) As shown in Fig. 4, the FFT transformation is used to identify the approximate frequency of each mode.
(2) The BBF can be adopted to process the measured free vibration signal.
(3) EMD is applied for the decomposition of each filtered signal to get multiple IMF (Figs. 5 and 6). Based on the results, it can be found that IMF1 can reflect the signal of each vibration mode.
(4) The random decrease response of each mode (Fig. 7) can be obtained by the IMF1 identified with RDT.
(5) The HT is applied to random decrease response of each mode to obtain the phase angle time histories (Fig. 8). The plot of the phase angle $\theta(t)$ (t) vs time t is fitted by a straight line using the linear least-square fit procedure. Then, the slope of the straight line is ω_d, and the natural frequency f_d can be estimated by Eq. (3).

2.3. Test results

Table 2 shows the natural frequencies of the circular membrane vibrating at various air pressures. Apparently, the natural frequencies of the membrane increase as air pressure decreases. It seems that the 3rd vibration mode of the latex membrane was lost due to the arrangement of the displacement measuring points, which were located at the nodal lines of the 3rd vibration mode.



(a) Prestress level σ_1 (b) Prestress level σ_2 (c) Prestress level σ_3

Fig. 1. Sketch of the imposing prestess on the circular flat membrane.