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An Experimental Study of Flow Induced Vibration on a Tensioned Membrane

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Abstract

In pursuing noise and wave control with minimal aerodynamic or hydrodynamic sacrifice, a tensioned membrane is used to line the otherwise rigid duct wall. The membrane vibrates in response to the grazing incident waves and the vibration serves to reflect the wave towards its source. The mechanism is identical to what happens in a rig of active wave control, but the difference is that the current rig has no active component. For the purpose of wave control, the device has been tested successfully without flow and with moderate flow conditions commonly found in air ventilation systems. When the flow speed is further increased, flow induced vibration occurs. This study reports the phenomena of such vibration under various flow speeds and membrane tensions. Transient process of exponential vibration growth is recorded and analysed together with the boundary layer measurements. The effects of an external cavity as well as the lateral membrane tension are also found to be significant. Other possible mechanisms for the flow induced vibration are also explored and discussed.

Keywords: Flow-induced vibration; Tensioned membrane; Boundary layer

1. Introduction

Duct walls in all air conditioning system are flexible to some extent. Turbulent flows of very low Mach number appear very frequently in the air conditioning systems. The aerodynamic pressure fluctuation created by turbulent flow inside an air duct will cause the duct wall to vibrate and consequently create the break-out noise problem. Such noise may also be radiated inward into the downstream side of the duct. The noise will be propagated to the working area through the duct and the noise with low frequency component is very annoying. The occurrence of the large-amplitude vibration of the duct wall would be a serious issue.

Recently, many products using panels or perforated panels to achieve noise reduction are commonly adopted in the ventilating system. The membrane absorber box used in the splitter type silencer is one such example (Ackermann *et al.*, 1988). Many researchers endeavor to study the interaction between sound and panel in order to achieve noise reduction over a wide frequency range, often with a price of increased back pressure, or even flow induced vibration of the panel or the duct wall. Despite the huge volume of work available on the topic of the interaction between flow and the panel, much remains to be learned in this inter-disciplinary field. Dowell (1970; 1975) has made various contributions theoretically and sometimes experimentally on the aeroelasticity of panels. Dugundji *et al.* (1963) and Ishii (1965) studied the flow induced vibration of the simply supported panels in the subsonic flow experimentally and theoretically. Ishii (1965) found that the

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occurrence of the flutter is shifted to higher flow speed when the tension of the thin panel is increased. Gaster (1987) and Lucey and Carpenter (1995) investigated theoretically the evolution of both the Tollmien-Schlichting waves and flutter instability in the boundary layer over compliant panels in water. Watanable *et al.* (2002) conducted an experimental study on paper flutter with the aim to enhance the performance of paper printing machines.

In a related field of noise control in flow ducts, a new approach of wave reflection has been proposed by Huang (2002). This approach attempts to eliminate the back pressure of reactive silencer in flow by using tensioned membranes lining part of the duct wall. When grazing incident excites the membrane to vibrate, reflecting sound waves are radiated towards the upstream and the sound transmitted through to the downstream region would be reduced. The theoretical concept (Huang, 2002; 2004) has been validated by experiments (Choy and Huang, 2003). The stainless membrane with the thickness of 0.025 mm is used, and the ratio of the membrane length to the channel height is 5. It can achieve a desirable transmission loss in the relatively low frequency range. Such performance can also be maintained so long as the higher tension is applied on the membrane in case of moderate flow rate (Choy and Huang, 2005) in the traditional ventilation and air conditioning systems. A question arises as to whether flow-induced vibration would occur when the flow speed exceeds that found in normal ventilation ducts. Should such vibration exist under certain parametric conditions, what can be done to avoid it? This paper describes the results of several tests conducted to answer these ques-tions under various flow speeds and membrane tensions.

2. Experimental rig and procedure

In order to describe the phenomena of flow induced vibration, several parameters, such as the structural properties, flow speed, turbulence intensity, and the vibration of the membrane should be measured and investigated. The measurement is conducted in a quiet mini wind tunnel in which the noise of the fan driving the closed-loop flow is mostly absorbed by the acoustic linings. The schematic of the set-up is given in Fig. 1.

The working section of the wind tunnel is 100 mm by 100 mm in cross section and 1.8 m in length. This length is very long compared with normal wind tunnel designs and it is deliberately chosen for the duct

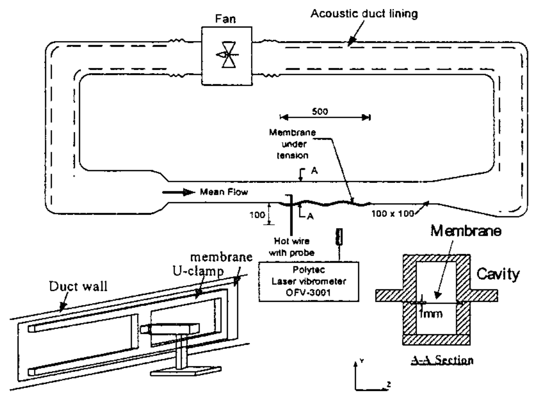


Fig. 1. The set-up of the measurement system using the four-microphone, two-source positions method. The hotwire measures the flow speed and the laser vibrometer measures the vibration. Both data acquisition and the generation of the incident noise are controlled by the computer equipped with A/D and D/A cards, and a Labview code.

acoustics testing. The flow velocity inside the tunnel is measured by a hotwire calibrated by a Pitot-static tube connected to a Furness electronic micromanometer. To ensure the uniformity of the flow, the turbulence intensity and the flow velocity are checked by traversing the hotwire across the working section with an interval of 5 mm. The turbulence intensity is less than 1% on average. The length of the membrane and cavity is L=500 mm and the mass per unit area of the membrane is m=0.17 kg/m^2. The duct and cavity height is h=100 mm. The duct wall is made of 15 mm thick acrylic, which is believed to be acoustically rigid. The first cut-on frequency of the duct is 1700 Hz. Two types of measurements are conducted simultaneously: the vibration velocity measurement of the membrane and the hot-wire measurement for the details of the boundary layer on the membrane.

2.1 Vibration measurement

As shown in the lower part of Fig. 1, a laser vibrometer (Polytec type with controller FV-3001 and sensor head OFV-303) picks up signals of membrane vibration through the transparent cavity walls installed outside the wind tunnel working section if the cavity is installed. The measurement point is located at about 200 mm from the leading edge of the membrane.

2.2 Flow measurement

A slot with a length of 500 mm and a width of 5mm was made on the tunnel wall opposite to the membrane. This allows the insertion and movement of the hotwire so that the boundary layer along the membrane can be measured. The axial distance between the measuring points was 100 mm. The flow velocity was measured by 1D 55P15 boundary layer hotwire probe (Dantec Dynamics A/S). The measure-ment covered the range of vertical distance of 0.05 mm to 50 mm from the surface of the membrane, 0.05 mm being the smallest distance before probe hit the membrane. Fine adjustment of the distance was determined by a calibrated video camera with a macro-lens of 70 X magnification and the distance resolution is 0.01 mm.

2.3 The procedure

First of all, the membrane is installed in two-dimensional configurations in the experiment as shown in Fig. 1 at section A-A. As explained in details in Huang and Choy (2003), a thin gap of less than about 0.5 mm was allowed between the lateral edge of the plate, which is parallel to the flow, and the side wall of the wind tunnel. The membrane was free to move along this edge while the acoustic leaking was minimized. This installation can simulate the two-dimensional theoretical model (Huang, 2002), in which the membrane width is infinite in the direction perpendicular to the flow.

First of all, the membrane without cavity is studied. In order to study the membrane response at a given flow speed when the flow is well established, a tailor-made U-shaped clamp is used to restrain the edges of the membrane from any motion until a certain flow speed is achieved in the wind tunnel. The clamp is then released such that the membrane is free to vibrate subject to the excitation of the aerodynamic pressure that prevails at the particular mean flow speed. The response of the membrane is measured by the laser vibrometer with the lens at the distance of about 200 mm. This procedure is carried out repeatedly at different flow speeds and tensions ranging from 20 N to 900 N. The tensile force of the membrane can also be measured by the strain gauge glued on the surface of the membrane. The dimension of the strain gauge sensor (TML FLA-3-11) is 3 mm and its attachment is believed to cause no noticeable influence on the dynamics of the stretched membrane. Since the surface of the strain gauge with the wire connection is on the outside surface, it will not influence of the fluid dynamic properties on the surface of the membrane.

3. Experimental results

3.1 Transient response of the membrane at different flow speeds

The time-trace of the membrane vibration velocity with the mass ratio of 1.3 under the tension of 800 N is shown in Fig. 2. Figure 2(a) shows the response of the membrane under the flow velocity of 5 m/s, which can be regarded as a stable condition. When the U-clamp contacts the surface of the membrane, the membrane shows no noticeable response with mag-nitude of velocity of about 0.04 mm/s.

When the clamp is released so that the membrane can vibrate freely, an impulse with the maximum vibration velocity in magnitude of 1mm/s can be observed in Fig. 2(a). The vibration of the membrane then damps down within 0.5 second of the impulse it maintains the magnitude of about 0.15 mm/s afterwards. Figures 2(b) to 2(e) show the growth of the membrane response with different aerodynamic forces in different flow speeds: 10 m/s, 12 m/s, 18 m/s and 20 m/s. The exponential growth with different growth rate is found for the response in Figs. 2(b) to 2(d). Linear growth is observed in Fig. 2(e) although there is small fluctuation of the amplitude beyond the saturated level.

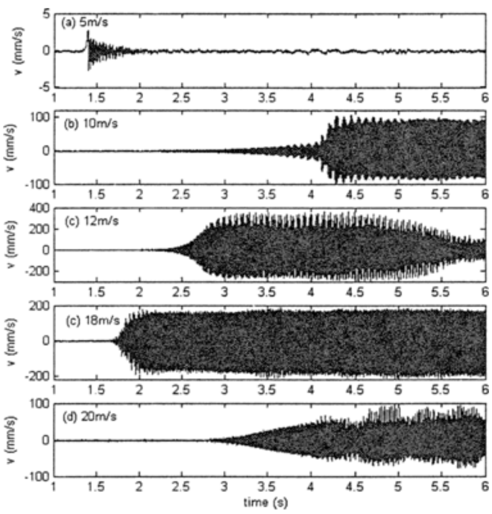


Fig. 2. Time-trace of the velocity of the membrane vibration under different flow speeds in the tunnel. (a) is the flow-induced vibration at the flow speed of 5 m/s (b), (c), (d) and (e) are flow-induced vibration at 10 m/s, 12 m/s, 18 m/s and 20 m/s, respectively.

3.2 Contours of the flow-induced vibration

When the membrane is stable, its response increases with respect to the general flow turbulence, but the increment is mild. When instability occurs, the sudden increase is obvious, cf. Figs. 2(a) and 2(b). Figure 3 shows the root mean square of the vibration velocity of the membrane under different tensions at different flow speeds. In Fig. 3(a), the response of the membrane is shown as a function of flow speed for three different tension levels of 0, 100 and 200 N.

Figures 3(b) and 3(c) show the variation of the response under the tensions from 300 N to 500 N and from 600 N to 900 N, respectively. As shown in Fig. 3(a), the vibration velocity of the membrane increases monotonically with the flow speed when the membrane is under low tensions. The increase of the response is not linear. It is noted that, when the tension is further increased to about 200 N, the root mean square vibration velocity is suddenly increased to an extremely high level at the flow speed of 5 m/s. The magnitude is about 400 times its immediate neighbourhood. However, such vigorous vibration only occurs in a small range of airflow speed. The range of the air flow speed at which such vibration occurs becomes wider with the increase of the tension.

Beyond this region of vigorous vibration, the response of the membrane seems to turn back to the original vibration velocity. Figure 4 shows a contour map of tension against the flow speed. The horizontal line indicates the existence of serious vibration. The circle represents the starting and terminating flow speeds for the flow-induced vibration. The region of the air flow speed for the flow-induced vibration is wider for higher tensions of the membrane.

There are several possible physical mechanisms for the observed flow induced vibration on the membrane. These are studied separately below.

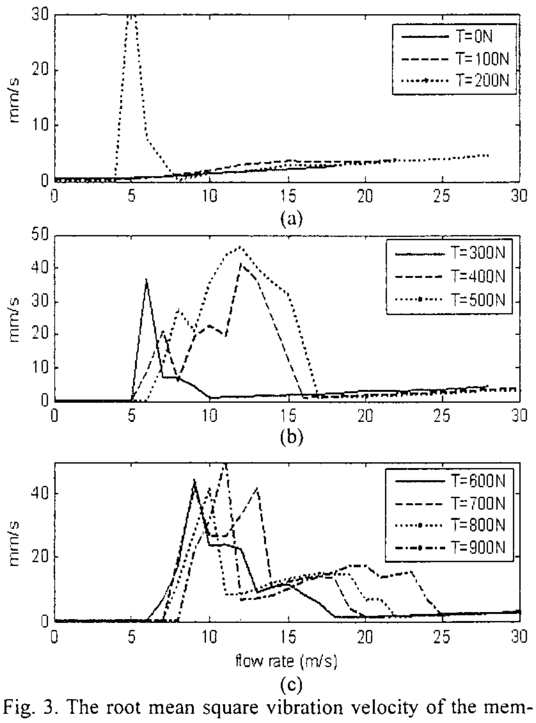


Fig. 3. The root mean square vibration velocity of the membrane with different air flow speeds under the tensions of (a) 0 to 200 N, (b) 300 N to 500 N, and (c) 600 N to 900 N.

3.3 Studies of the boundary layer behaviour

Figures 5(1a), 5(1b) and 5(1c) show the boundary layer velocity profile (U^*) in the form of velocity distribution normalized by the mean flow velocity. The conditions under which the data are taken is given in each sub-figure. The mean flow velocity ranges from 4 m/s to 26 m/s.

Figures 5(2a), 5(2b) and 5(2c) depict the turbulence intensity at three flow speeds corresponding to those in the first row. The effect of the membrane on the time-averaged boundary layer behaviour is examined by comparing the results under the hard wall condition with that under the flexible wall. No obvious difference is found when the mean flow velocity is 12.6m/s and 26m/s as shown in Figs. 5(1b) and 5(1c). In terms of the turbulence intensity, about 3% difference is observed, which is insignificant.

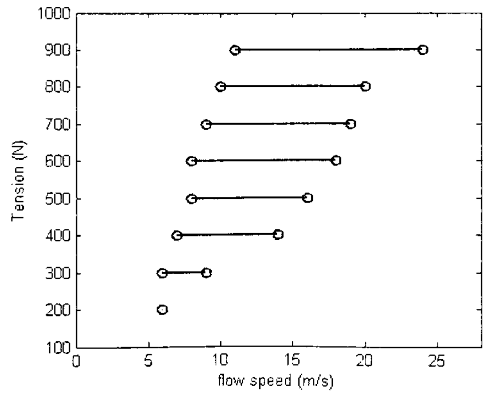
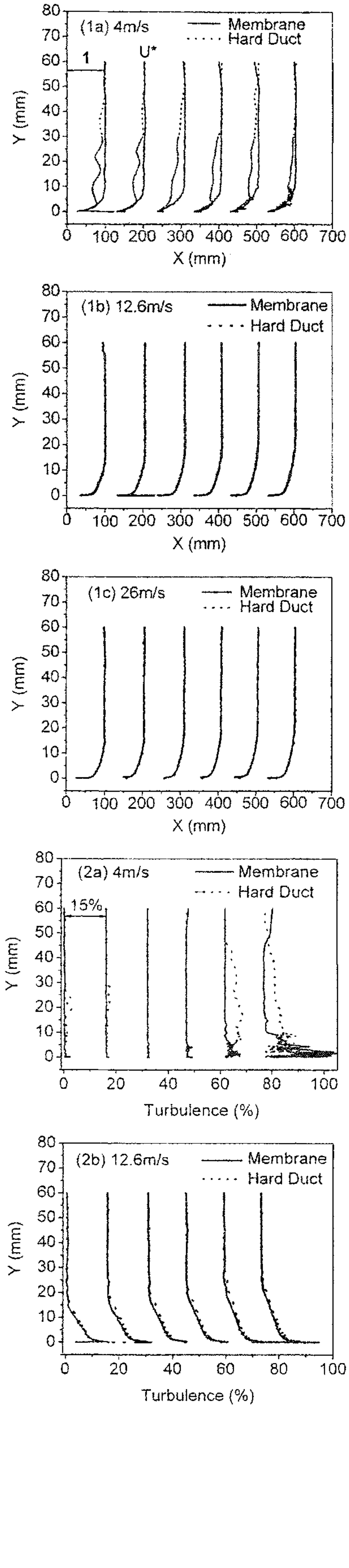


Fig. 4. Region of instability in the space of tension and flow speed.



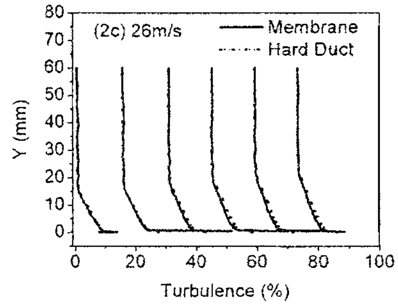


Fig. 5. The normalized velocity distribution (1a), (1b), (1c) and turbulence intensity (2a), (2b), (2c) along the region of the membrane in the channel.

3.4 Effect of cylinder-produced vortex shedding

In order to test the possibility of resonance induced vibration, a circular cylinder is used to cause vortex shedding at a frequency close to that found in the flow induced vibration on the membrane without such vortex shedding excitation. A cylinder rod of diameter 11mm is installed at the distance of about 250mm from the leading edge of the membrane and 4mm from the surface of the membrane. The diameter-based Reynolds number is $Re_d=7.96\times10^4$, but note that the flow differs from that past an isolated cylinder. The vortex shedding frequency at the flow speed of 11m/s is about 169Hz, which is the 'natural' frequency of the membrane exposed to this mean flow. This natural frequency can be observed by the random noise excitation and the mean flow without installing the rod. Figure 6 shows the power spectrum density of the response of the membrane with the excitation of the vortex. Figures 6(1a) and 6(1b) show the spectrum of the data taken from the hotwire probe and the response of the membrane when there is no rod.

The random noise signal in the small scale of turbulence along the surface of the membrane is observed in Fig. 6(1a). The corresponding frequency for the flow-induced vibration of the membrane is 169Hz. When the rod of 11mm diameter is installed, the vortex shedding frequency of about 169 Hz is measured by the hotwire and the spectrum is shown in Fig. 6(2a), the corresponding response of the membrane at different frequency is shown in Fig. 6(2b). The spectral density at 169 Hz appears to be lower although the flow-induced vibration still occurs. The vortex induced by the cylinder in the middle part of the channel with almost the same frequency is found to be unable to bring about a resonance-type

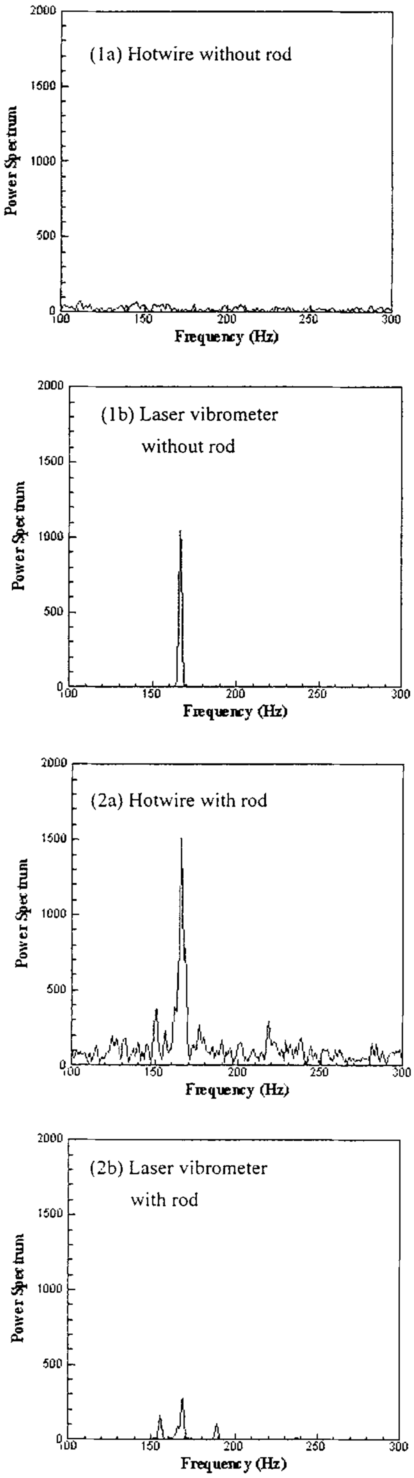


Fig. 6. The power spectrum of the hotwire and the response of the membrane measured by the laser vibrometer without rod (1a), (1b) and with rod (2a), (2b).

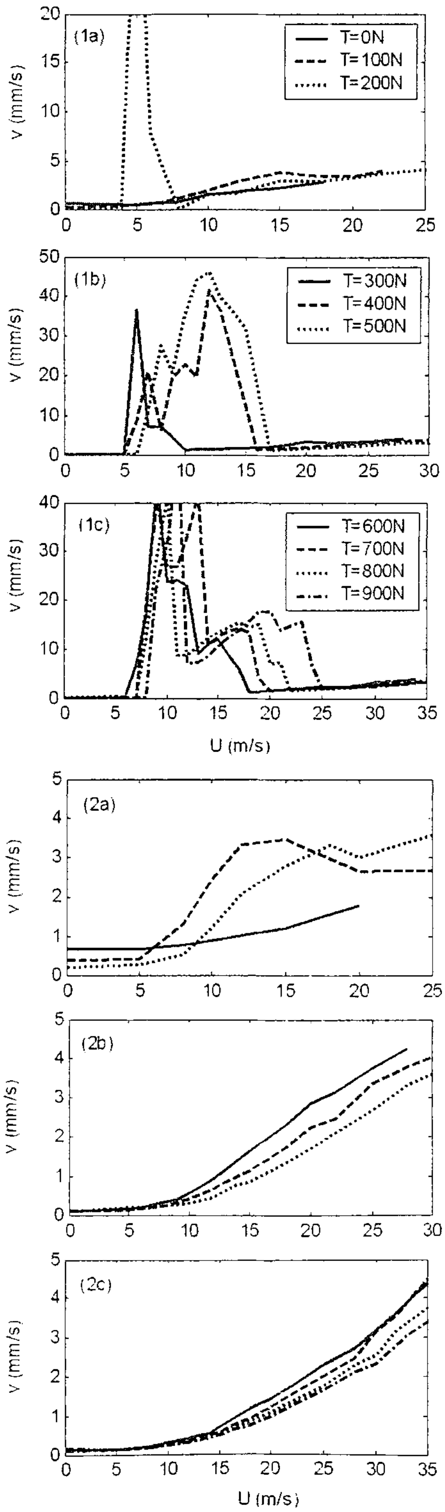


Fig. 7. The comparison of the root mean square vibration velocity of the membrane at different flow speed with free (1a), (1b), (1c) and fixed (2a), (2b), (2c) lateral edges.

response on the membrane. At this point, it is not lear whether this will change if the region affected by the vortex shedding from the rod is increased.

3.5 Effects of structural boundary conditions

The effect of the structural boundary is investigated by altering the lateral edges of the membrane. Figure 7 shows the comparison between the response of the membrane with four edges fixed (second column) and that with two lateral edges free (first column). The first row is for the low tensions ranging from zero to 200 N, the second row is for the medium tensions from 300 N to 500 N, and the last row shows the higher tensile forces from 600 N to 900 N. Figure 7(2a) shows that there is an increase of vibration velocity from zero tension to 100 N and beyond 100 N, the response becomes lower. The response is increased with the flow speed up to 15m/s and beyond, the response decreases and then increases again at higher flow speeds. The response of the membrane with the tension of 200 N has the similar tendency but its overall amplitude is less than that with 100 N. Figures 7(2b) and 7(2c) depict the response with higher tensions and the overall response becomes weaker when the tension is increased if the flow speed is beyond 6 m/s. Below the flow speed of 6 m/s, they have similar responses because of very low aero-dynamic force excitation. All the curves have similar trends, namely the response is monotonically increa-sing with the flow speed.

When a cavity is added beneath the membrane,

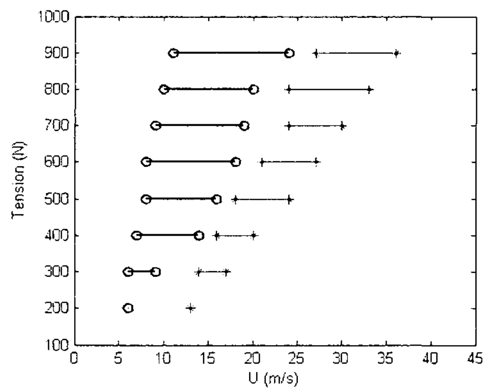


Fig. 8. Map of the flow-induced vibration of the membrane with cavity (—*—) and without cavity (— —). The lateral edges of the membrane are free to move in both configurations.

additional acoustic impedance is introduced due to the air incompressibility at low frequencies. The response should be affected because this membrane is sufficiently light and highly coupled with the acoustic field. Figure 8 shows the comparison of the contour map of the flow-induced vibration between the membrane without cavity and that with a cavity of depth equal to the duct height. The asterisks with the solid lines represent the range of the flow speed in which instability occurs when there is a cavity, while the circles with the solid lines represent the region of instability without the cavity. The cavity is found to shift the entire region of instability towards higher flow speeds. The cavity is therefore a powerful factor controlling the flow induced vibration.

4. Conclusions

Experimental studies have been carried out to investigate the effects of various physical mechanisms on the flow-induced vibration of the two dimensional membranes lining part of the duct walls. Several conclusions are drawn.

Tension is the main controlling parameter for the flow-induced vibration on the membrane. A v-shape region of instability is found in the parameter space of tension against flow speed. There is no flow-induced vibration when the tension is very low, but no vibration occurs either when the tension is too high.

The dynamic response of the membrane is greatly affected by its structural boundaries. The configuration in which all membrane edges are fixed is found to be more stable than the one in which the two lateral edges are free to move. The latter configuration is nevertheless used in the design of wave reflection as it is more effective.

A rigid-walled cavity beneath the membrane outside the duct also significantly influences the flow-induced vibration. The air stiffness inside the cavity is found to stabilize the membrane and the entire region of instability is shifted towards higher flow speeds for any given tension.

Vortex shedding from a cylinder is introduced to examine the possibility of resonance-type instability. The vortex shedding introduced peaks at the frequency of the membrane vibration in the absence of the cylinder. However, no resonance is observed.

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