Harvesting Energy from a Flexible Flapping Membrane in a Uniform Flow

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Summary: The flapping dynamics and strain energy distribution of a flexible membrane immersed in a uniform flow is numerically studied. The system is controlled by two main parameters, i.e.the structure-fluid mass ratio (M^*) and the reduced flow velocity (U^*). Simulation results demonstrate that the membrane exhibits a periodic oscillation with one dominant frequency for a certain range of non-dimensional velocity. Within this range, flapping amplitude increases with U^*, and non-uniform strain energy distribution is generated along the membrane. In addition, the maximum available strain energy shows an upward trend with an increasing of U^*.

Introduction

With the increasing demand of clean and eco-friendly energy, flow-induced instabilities as one of the potential mechanisms to generate small amount of electric power from flows have received renewed attentions [1]. Such instabilities which originate from the competition between the fluid force and structure's rigidity are able to induce a self-sustained oscillation of a flexible body. A canonical example is a flexible membrane, or plate, immersed in a uniform flow, which has been extensively studied in both experimental and numerical ways due to its rich flapping dynamics [2].When the membrane is made of piezoelectric materials, the fluid energy, which is continuously pumped into the membrane, can be extracted and transferred into electricity. This novel power generator has attracted many researchers' interest. Some experiments and numerical simulations have been conducted to study its flapping dynamics and conversion efficiency [3-5]. In the present work, we simulated an energy-harvesting membrane immersed in a uniform flow by solving the *Navier-Stokes equations* and the structural motions were obtained using a modal analysis approach. We first validated the numerical method developed with experimental results, and then studied the variation of total strain energy at various reduced velocities.

Methods

The coupled fluid-structure interaction is solved using our in-house code on a HPC facility, where a parallel computing using MPI for the information exchange between different processors is used. The unsteady Navier-Stokes equations are solved on structured multi-block grids with a cell-centred Finite Volume Method. The convective flux is discretized using a central differencing scheme with artificial dissipation. Implicit backward-difference scheme of second-order accuracy and dual-time stepping algorithm are adopted to ensure a strongly coupled solution in the time-domain. The linear structural equations are solved using a modal analysis method and the structural modes are obtained by the classical Euler-Bernoulli beam theory.

Results

We first compared our simulation results with the experimental results of Chen et al [6]. Fig. 1 and Fig. 2 demonstrate the variations of dimensionless amplitude A^* and frequency f^* as a function of reduced velocity, respectively. The reduced velocity U^* under investigation covers a range from 7 to 9 with corresponding Reynolds number from 4.5×10^4 to 5.7×10^4. The experimental results shown in Fig. 1 indicate that as the reduced velocity U^*increases, more flow energy is harvested by the membrane, resulting in the increase of flapping amplitude, which is well captured by the present simulation. However, with further increase of U^*, the incoming flow tends to supress the membrane's vibration due to a stronger fluid-structure interaction. Our simulation fails to replicate this nonlinear feature due to the linear structural model we adopted. With regards to the flapping frequency plotted in Fig. 2, we found that within the present reduced velocity range, the membrane always exhibits a periodic motion associated with a second order structural dynamic mode. The instantaneous deformation of membrane at $U^*=9$ is illustrated in Fig. 3. A closer inspection of this figure reveals that the vortex is formed at the leading edge and grows as it travels along the membrane and further shed into the wake in the vicinity of trailing edge. This periodical vortex shedding, responsible for large deformation of the structure, further strengthens the fluid and structure interaction between the membrane and wake vortices. To estimate the available power generated by the vibration of elastic membrane, the mean square of strain energy is computed from the deformation of membrane, more precisely, the curvature radius and membrane thickness (Techet et al [1]). Fig. 4 shows the mean square strain energy distribution along the membrane at various reduced velocities.

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It can be readily observed that the mean strain distribution is highly non-uniform along the membrane's length, which is similar to earlier studies [1] [5]. The higher strain is available near the leading and central part of membrane while diminishes near the tail edge. This is mainly because the membrane is vibrating at its second order structural mode with no bending deformation near the tail of the membrane, which can also be clearly observed from Fig. 3. The instantaneous membrane strain energy at different reduced velocity is represented in Fig. 5. It is clear that the maximum available strain energy grows linearly with the increase of reduced velocity resulting from the formation of strong vortices and the increase of flapping amplitude.

Conclusions

The energy-harvesting features of a flexible membrane immersed in a uniform flow are numerically studied in this paper. The simulation reveals that the flapping amplitude of the membrane grows with the increase of U^* at the beginning, but showing a downward tendency as a further increase of U^*due to the suppression of incoming flow. On the contrary, an opposite variation is observed on the flapping frequency. The strain energy distribution along the membrane is non-uniform, presenting the peaks at the leading and central part of membrane. More strain energy can be harvested by increase incoming stream velocity.

References

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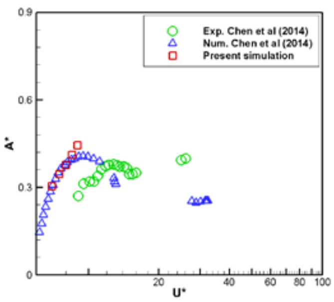

Figure 1. Dimensionless amplitude A^*vs. reduced velocity U^*

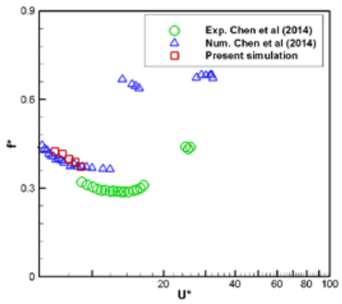

Figure 2. Dimensionless frequency f^* vs. reduced velocity U^*

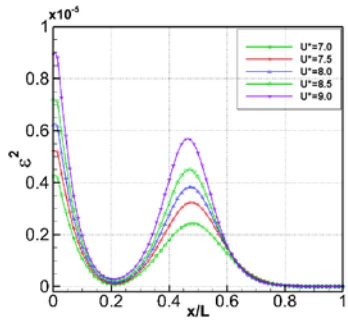

Figure 4. Square of strain over the membrane length at various U^*.

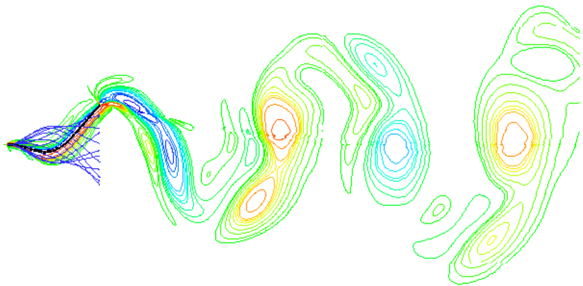

Figure 3. Snapshot of the periodic flapping membrane and vorticity contour at U^*=9.

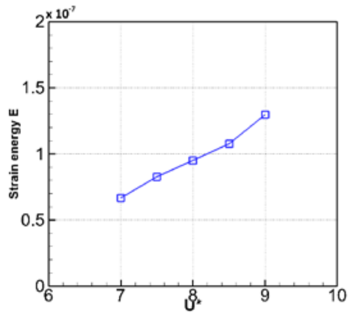

Figure 5. Strain energy E vs. reduced velocity U^*