Preface

The interactions between fluid and flexible structures exist in nature, everyday life, and various industry applications. Birds and insects fly freely in the air. Their wings can be considered as flexible plates. Fish and aquatic mammals propel themselves in water. Their elongated flat bodies can be considered as flexible plates too. Flapping flags and falling leaves are also flexible flat structures moving with the wind. In biomedicine, snoring and heart valve opening and closing are the motion of the flexible flat human organs. In industry applications, such as papermaking, printing, and blown film producing, there also exist flapping phenomena of flexible plates.

The interaction between flexible plates and ambient fluids is a branch of the fluid structure interaction topic. From a physical viewpoint, this problem is the interaction between the flow field of the fluid and the stress field of the flexible plate. Two fields interact with each other on their interface, transferring momentum and energy. As a classical mechanism topic, the study of fluid structure interaction has a long history. With the development of science and technology, the study of the interaction between flexible plates and fluid has become a multidisciplinary research topic. By investigating this problem, we can reveal the mechanism of flow induced vibration of flexible bodies, understand the process of energy exchange between fluid and flexible bodies, and learn the ways flexible bodies interact with each other in flowing fluid. The study on the interactions between flexible bodies and fluid can not only make us understand nature better, but also help us invent new machines and improve existing devices to harvest clean energy from nature.

Based on experiments, together with theory modelling and numerical calculation, this thesis discusses the mechanism of the interactions between flexible plates and ambient fluids. Experiments were carried out in soap film tunnels. Flexible filaments were employed as flexible plates. Soap film tunnels, which are ideal tools to provide two-dimensional flow, were used in many experiments to investigate two-dimensional flow structure in past studies. A filament has a large aspect ratio, thus it can be considered as a one-dimensional structure. The uniform linear density and bending stiffness of a filament make it the best choice in simulating a flexible plate in two-dimensional flow. In our studies, we employed two types of soap film tunnels, vertical soap film tunnel and horizontal soap film tunnel. They provided different ranges of soap film flow speed. The soap film was illuminated by a sodium lamp. The thickness of the film was close to the wavelength of the light emitted from the sodium lamp. As a result the light rays reflected from the two liquid–air interfaces of the soap film interfered with each other and formed colour fringes. These colour fringes visualized the thickness variation of the soap film, which represented the flow field inside the film. They were recorded by high speed cameras. In this thesis, we also introduce the measurement of the physical properties of soap film and the filaments.

The main problems discussed in this thesis are: 1. Flow-induced vibration of a single flexible filament in a uniform flow. 2. Coupling between two parallel flexible filaments in a uniform flow. 3. Interaction between two tandem flexible filaments in the flow. 4. Flapping of a flexible filament in periodic flow.

The study of a single flexible plate in a uniform flow is the basis of this thesis. The experimental devices, data processing, theoretical analysis and calculation methods involved in this problem make a basis for studies of more complex phenomena. In the experiment, two connection methods are adopted to support the filaments in the flowing soap film. In the first method, the leading edge of the filament is fixed using a casing perpendicular to the film, which keeps the leading edge of the filament fixed in the stream. In the second method, the leading edge of filament is fastened to a silk fibre, which allows the filament to hold its position in streamwise direction while keeping its leading edge free transversely. A single filament in a uniform flow starts flapping once the flow speed and the filament's length exceed critical values. A shear layer is shed from the filament‘s trailing edge and becomes unstable with successive small Kelvin–Helmholtz eddies along it. Concentrated vortices in the wake with opposite signs are alternately distributed, which forms a vortex street. The filament information in the images recorded in the experiments is extracted by our developed program. By using the program, the motions of filament in the experiment are described in vector data. For further analysis, the filament locomotions are fitted into equation. Substituting the undulation equation into the kinetic and potential energies equations, we calculated the force imposed on the filament and the energies stored in the filament. In the last section of this part, a temporal linear instability analysis is employed to analyse the stability of the filament's flapping. The stability boundary is given and compared with experimental results and previous studies. The scope of the theoretical model is discussed.

The coupling between two parallel flexible plates in a uniform flow is one of the common interface coupling phenomena. A theoretical model of the interaction between two parallel flexible filaments in a uniform flow is proposed. The mechanism of the coupling modes between two filaments is explored in terms of linear instability analysis. Two control parameters are identified, the density ratio of solid filament to fluid S, and the square root ratio of fluid kinetic energy to solid elastic potential energy U. According to the temporal linear instability analysis, a ω–k dispersion relationship that predicts the distribution of flapping modes is established. Two special cases of flapping coupling, i.e. two identical filaments of the same length and two filaments of different lengths, are studied in detail. In the case of two identical filaments, the theoretical analysis predicts four coupling modes, i.e. the stretched straight mode, the anti-symmetrical in-phase mode, the symmetrical out-of-phase mode and the indefinite mode. The predictions are in qualitative accordance with the experiments. The causes of difference between theoretical predictions and experimental results are discussed. In the case of two filaments of different lengths, four modes similar to those in the former case are identified theoretically. In the experiments, two filaments are set top aligned and bottom aligned layouts separately. The coupling modes of two filaments in the two alignments are described and the differences are analysed.

The interaction between two tandem flexible plates in flow is an important problem concerned in bio-propulsion. In the interaction of two tandem plates in flow, the upstream plate flaps passively due to flow-induced vibration. Its movement alters the flow field and flow energy distribution. The redistributed energy passes to downstream along the wake of the upstream object. The downstream plate suffers a dynamic force to vibrate. Two tandem plates interact with each other by fluid. The experiment of two tandem filaments in flowing soap film shows that the upstream filament is influenced little in flow, whereas the downstream filament flaps at the same frequency as that of the upstream one, but with larger amplitude. The wake shedding from the upstream filament forms vortex street. The downstream filament travels zigzag in the vortex street. The statistical result from the experiment shows that the Strouhal number (*St*) of the upstream filament is almost equal to that of a single filament, whereas the *St* of the downstream filament is much larger than that of the upstream one. Data analysis shows the downstream filament extracts energy from the vortex street and receives greater force than the upstream one or a single filament in a uniform flow.

Flow-induced vibrations are observed in many engineering applications. A flexible body located in the wake of an obstacle is usually forced to vibrate by the periodic vortices shedding from the obstacle. Here we focus on the response of a flexible plate in the wake. A cylinder is plugged perpendicularly into the film and a filament is set in the wake of the cylinder. We design two methods to measure the force imposed on the filament. The static force measurement method is used to identify the average level of the force. The dynamic force measurement method measures the dynamics force by a precise optical route. Three response modes that depend on the distance between the cylinder and the filament are observed in the experiment. They are the Propulsion mode in which the filament produces enough thrust to balance the drag, Swing mode in which the filament slaloms between the vortex cores shedding from the cylinder, and Rock mode in which the filament flaps in the flowing soap film while rocking in the streamwise direction. A preliminary explanation of these modes is given in terms of the waving plate theory.

In summary, we investigate the interactions between flexible plates and fluids based on experiments using filaments in flowing soap film tunnels, together with theory modelling and numerical calculations. The studies yield a series of results. For the first time, we set up a theory model to describe the interaction between parallel flexible plates in uniform flow, give out the coupling modes and their distribution by linear instability analysis. In the study of two tandem plates in flow, we first report that the downstream plate performs a zigzag motion between these vortices shedding from the upstream one. As a result the downstream plate flaps at the same frequency as the upstream one, but with greater amplitude. A theoretical model shows that the downstream flag receives extra energy from the vortices. In the study of a flexible plate in periodic flow, we first report three response modes of the plate in different distances from the cylinder and explain these modes by theory.

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http://www.springer.com/978-3-662-43674-5

The Interaction Between Flexible Plates and Fluid in Two-dimensional Flow
Jia, L.
2014, XVII, 103 p. 57 illus., 23 illus. in color., Hardcover
ISBN: 978-3-662-43674-5