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Flow Visualization and Numerical Simulation of a Two-Dimentional Fluid Flow Over a Foil

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Abstract This paper deals with a simple, fast and economical visualization method to validate two-dimensional Large Eddy Simulations (LES) of the flow over a foil. This technique exploits the optical properties of soap film and relies on the wake patterns and the frequency at which these are shed at the trailing edge of the foil.

Keywords Large Eddy Simulation · Flow Visualization · Soap Film Tunnel

1 Introduction

Developing accurate numerical models for wake structures behind bluff bodies is of primary importance for many applications in wind and aerospace industries. These wake structures, which include circulation bubbles and trailing vortices, shed at the trailing edge of an airfoil strongly influencing the aerodynamic performances and stability of aircrafts and wind turbines. The numerical simulation of these wake structures remains computationally challenging because of their sensitivity to the numerical details such as discretization scheme, grid resolution and time step. The validation of the numerical models is then of primarily importance. In the context of aerospace and wind turbine industries, flow measurements and visualizations are often conducted in wind tunnel

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using involved techniques such as Particle Image Velocimetry (PIV) or Laser Doppler Velocimetry (LDV).

In this paper we present a simple and economical method for a validation of two-dimensional (2D) numerical simulations of the wake structures shed at the trailing edge of a symmetric foil, placed in soap tunnel. This method relies on the optical properties of the soap film, which can make visible wakes behind various bluff bodies placed in flowing soap film with the aid of a low pressure sodium lamp[1].

2 Numerical and experimental setup

2.1 Experimental setup

The experimental setup is a soap film tunnel, which consists of a vertical gravity-driven flowing soap film; see Fig. 1. The soap film was made of a 1.5 % solution of a commercial brand of dishwashing liquid soap (Dawn) in water, which was supplied through a nozzle from a reservoir. The planar soap film was produced by guiding the soapy water via two taut nylon threads (1 mm in diameter) spreading out to the desired width (10 cm). The flow rate was adjusted through a gear pump. The wake vortex structures behind the airfoil, placed in the soap film, become visible under a low pressure sodium lamp (590 nm) light source, thanks to the optical properties of the soap film. These wake structures were imaged using a high-speed pco.1200hs camera at a frame rate of 800 frames per seconds.

In steady conditions the fluid height in the reservoir is maintained constant. This ensures a constant pressure head at the nozzle, quasi-constant flow speed and relatively homogeneous film thickness at the test section. The reservoir serves also to inhibit the flow perturbations. The size of the soap film channel is of 2.5 m by 10 cm and the flows speed is between 2.70 m/s to 6.50 m/s. The foil was located sufficiently far downstream, approximately at 1 m distance, from the nozzle. At this location the balance between the main forces at work (inertial, elastic, gravitational, and drag forces) should have been reached. Also, at this location the flow and soap film should have reached asymptotically its terminal velocity and constant thickness, respectively[2,3]. The flow velocity is estimated by tracking the very small air bubbles present in the soap film[4].

The soap film viscosity, needed for the numerical simulation is estimated using the empirical relation between the Strouhal and Reynolds numbers for 3D von Karman vortices shed behind a circular cylinder[8]. This relation is valid for 2D von Karman vortices[5]. In the range of the flow velocities considered in our experiments and the dimensions of our experimental setup, the kinematic viscosity of the film was found to vary from 20 to 30 times the viscosity of the water.

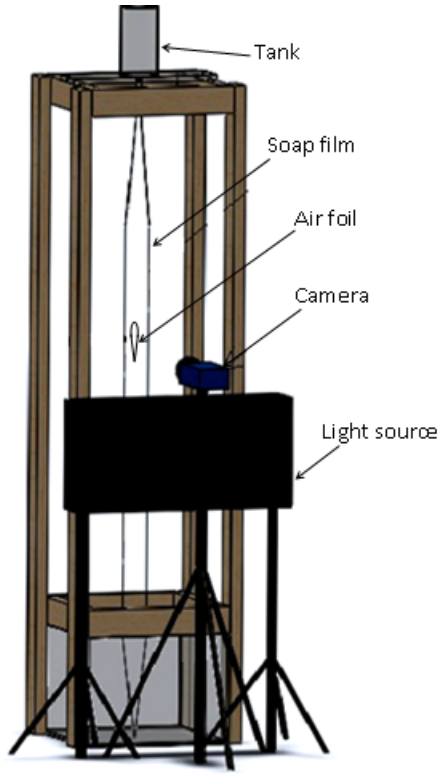

Fig. 1 Schematic of the experimental setup

2.2 Numerical modeling

The numerical simulations of the two-dimensional unsteady turbulent flow of the experiments were performed using the Large Eddy Simulation (LES) model implemented in ANSYS FLUENT. The SIMPLE algorithm was used for pressure-velocity coupling[7]. In these simulations eddies, whose scales are smaller than the filter width or grid spacing used in the computations, were filtered out. We started first the simulations with a large time step to reach a steady solution. After that the time step is reduced and a small perturbation is imposed to the steady velocity field in order to produce unsteadiness. The time step in our simulations is around 2×10^{-4} seconds; it corresponds approximately to 1/50 of the period at which the vortices were shed from the trailing edge of the foil in the experiments. This time step ensures the convergence of the model. The mesh that includes the flow domain and the object geometry, was generated in GAMBIT. We used structured grids (120,000 cells). Near the foil walls the mesh was refined to capture the near-wall turbulent regions. We have considered the flow conditions of the experiments with no-slip boundary conditions at the rigid boundaries. The domain size is 12 cm in the stream wise

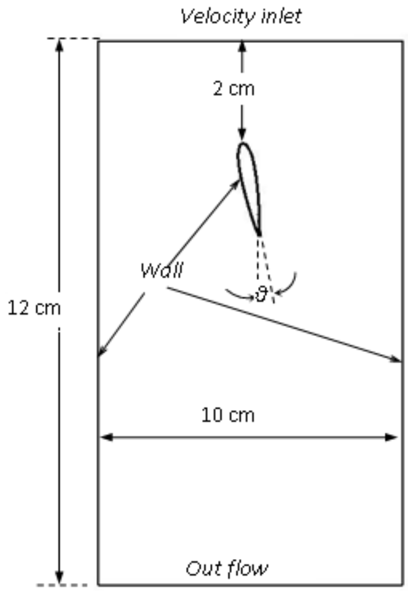

Fig. 2 Computational domain.

and 10 cm span wise directions, respectively. The foil is located at a distance 2 cm from the inlet section. The foil size is 1.9 cm long and 0.5 cm wide. The flow domain and the used boundary conditions are shown in Fig. 2.

2.3 Results and discussion

The comparison between the experimental observations and the numerical simulations is shown in Fig. 3. This figure shows that numerical simulations reproduce qualitatively the wake structures observed in the experiments. The agreement is fairly good for three different flow velocities and angles of attack.

The agreement between the simulations and experiments is also obtained at the quantitative level. The frequencies of the vortex shedding behind the foil are similar both in the experiments and numerical simulations. To determine the frequency of the vortex shedding from the numerical simulations we used Fast Fourier Transformation (FFT) of the lift coefficient variation. For instance, Fig. 4 shows a sample variation of the lift coefficient Cl with time. The FFT of this time series is shown in Fig. 5, which indicates that the fundamental frequency of the lift variation is approximately 166 Hz. The oscillations of the lift coefficient is due to the vortex shedding at the trailing edge of the foil.

Alternatively, from the experiment the vortex shedding frequency is determined by counting the number of vortices shed during a fixed period of time using series of images such as those shown in Fig. 5.

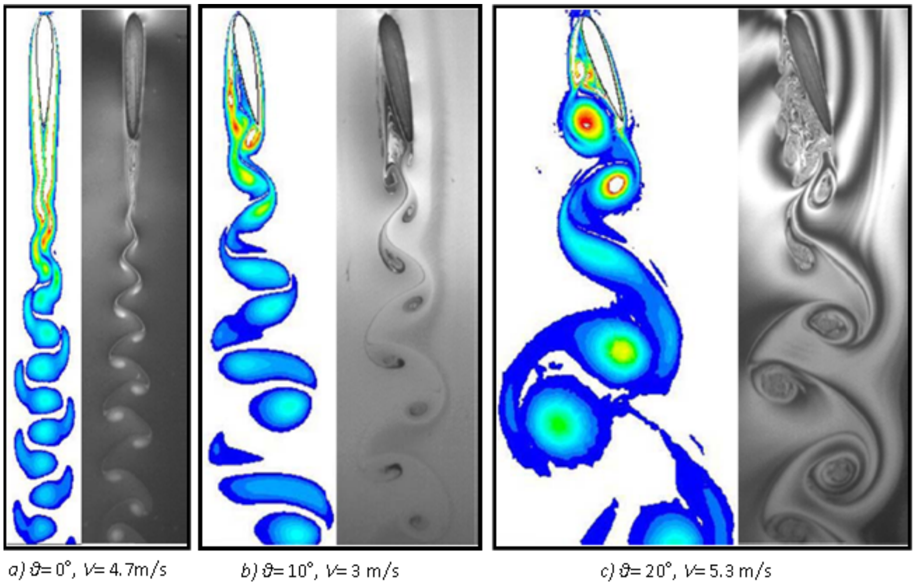

Fig. 3 Comparison between numerical vorticity isobars (left) and experimental pictures (right) for three different flow conditions.

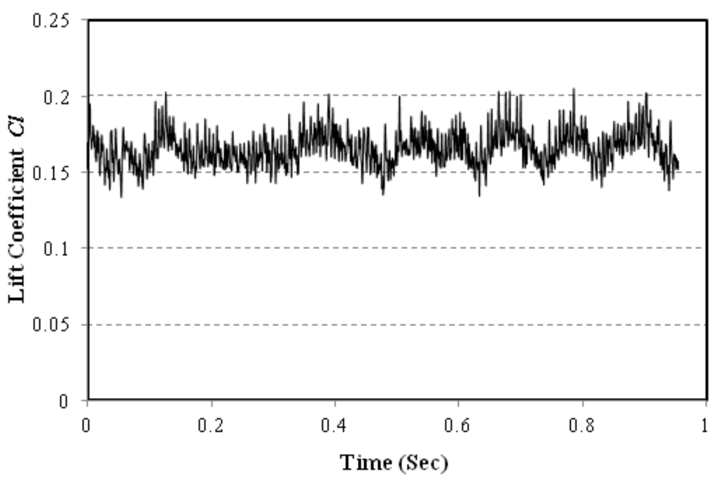

Fig. 4 Time evolution of the lift coefficient Cl.

3 Conclusion

Exploring the optical properties of soap film we show that a soap film tunnel can serve to validate 2-D LES simulation of the flow over a foil. This simple, fast and economical visualization method relies on the comparison of the visualization of the wake structures at the trailing edge of the foil as well as on the frequency at which the vortices are shed.

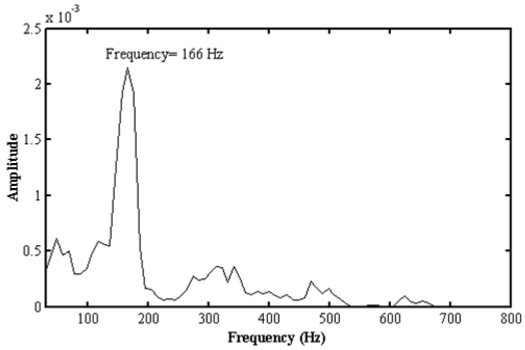

Fig. 5 Fast Fourier Transform of the lift time series.

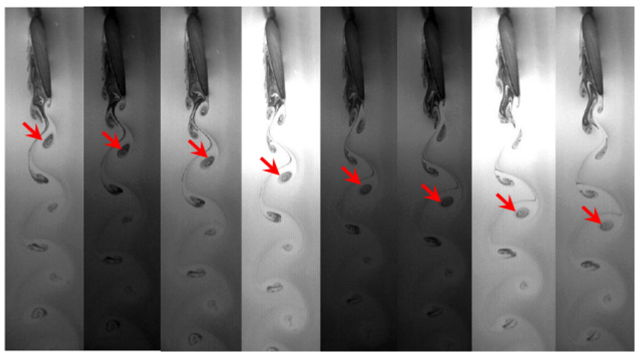

Fig. 6 A sequence of images with a (1/800) seconds interval. (θ =10 and V = 3 m/s). The arrow follows one of the vortices.

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