Wake-structure interactions: experiments on vertically flowing soap films

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We present an experimental study concerning the dynamic response of a structure embedded in a flow field, owing to the vortex induced forces. As a primary step, an experimental set-up has been developed so as to observe the vortex structures in the interacting wakes shed by two staggered cylinders on a gravity-driven vertically flowing soap film. Visualizations confirm the emergence of fully-developed complex wake patterns, formed through interactions between the wake vortices. The arrangement of the bluff bodies are done in such a way that a 2P mode wake, with two vortex pairs in each shedding cycle, is formed. This regime is one of the most commonly occurring bluff body wakes. Free oscillations under the 2P mode also correspond to a peak in the vibration amplitudes. Finally, an outline is laid out to theoretically calculate the vortex induced forces on the structure and on how that would compare with the obtained experimental results.

1 Introduction

Soap films have been frequently used as a tool to visualize wake structures behind a flow obstacle, since the pioneering work in (1) and are the closest one can get to measuring a truly two dimensional (2D) flow. A soap film consists of a micrometer thick sheet of water covered on each side by soap molecules. The soap surfactant keeps the thin film stable and the film width can be up to 10.5 times more than its thickness. The current work is motivated at: (a) understanding the fluid-structure interactions owing to the vortex wake generation in a flow system, and (b) comparing the dynamic response of the body, as seen in the experiments, with the corresponding theoretical predictions.

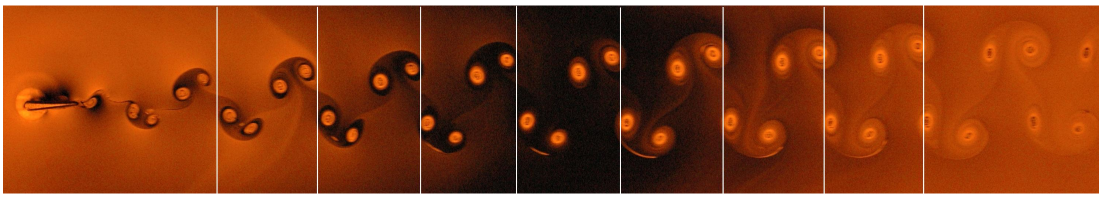

Figure 1: Typical 2P mode snapshot. A thin foil, which is imparted forced simple harmonic pitching oscillations, acts as the bluff body. The snapshot is from (2).

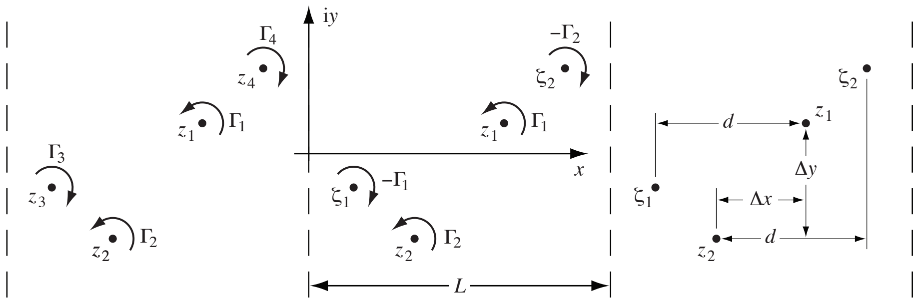

Figure 2: Model 2P configuration with two pairs of vortices vortices per period.

The wake structures are formed by introducing the circular cross-sectional faces of two staggered cylinders into the plane of the vertically flowing soap film. Transverse spacing and streamwise spacing between the bluff bodies are varied to obtain a wake arrangement that belongs to the 2P regime (wake with 2 pairs of vortices per cycle). The two standard von Kármán streets (2 vortices per period) shed by the individual cylinders interact downstream to generate the 2P regime (for illustrative examples on this mode, see Figures [1, 2]). Besides being one of the most commonly observable wake patterns behind oscillating bluff bodies (3), it has also been seen in literature (4; 5) that oscillation amplitudes attain a peak (for free vibrations of the bluff body) during this 2P regime. Hence, it is of utmost importance to explore more on the fluid-body interactions for this type of wakes. In the current work, we propose a technique to compare the dynamic response of the body obtained based on theoretical calculations (basic model proposed in (6), added work in (7)) with the performed experiments.

2 Experimental set-up

There are many ways to produce a soap film. Figure [3] from (8) demonstrates three examples: (a) a stationary soap film through which objects are dragged, (b) the horizontal soap film that draws fluid from a reservoir, and (c) a vertically falling soap film. In our experiments we have used a modified version of example (c).

A schematic diagram of our experimental set-up can be seen in Figure [4]. The upper reservoir was filled with water mixed with dish washing soap. A valve below the reservoir was used to control the flow rate of fluid and the speed of the soap film. Film speed can also be controlled by adjusting the width of the test section. A wider test section will flow slower compared to a thin test section. Flow velocity cannot exceed a certain rate, as then the film will become supersonic and unstable transverse oscillations will appear. We observed these oscillations when the injection nozzle was fully opened. Fishing line forms the soap film frame and two cylinders were placed in the film linear stages so as to adjust their positions. Finally, the soap water is collected in a reservoir at the bottom. Typical (2) background flow velocities range around 150 cm/s and the film thickness is approximately 1.5 μm. We were not able to measure the speed of our film flow, but this is traditionally done using hot wire

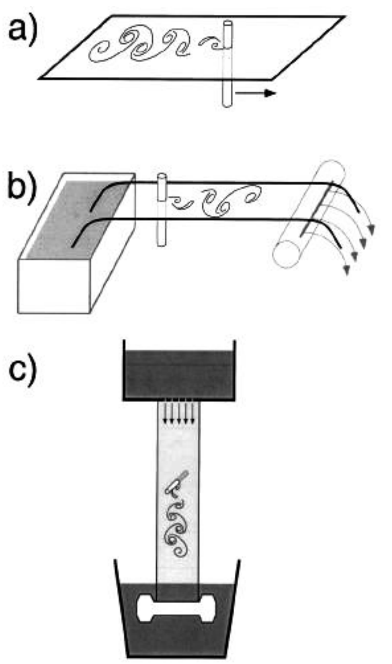

Figure 3: Employable methods of flow for soap film experiments (8).

anemometry or tracking small bubbles in the film. Our film produced no bubbles we could use to measure the speed.

The film must be started in a very particular way. All air drafts need to be minimized, the wires and soap water solution need to be free of debris, and the cylinders placed in the film must be pre-wetted to avoid bursting the film when placed in the flow. First the cylinders are moved out of the flow region, then the wires are released from the hooks holding them in place and are touched together along the entire soap film length. Next, using small metal hooks the fishing line is carefully pulled apart creating the soap film. The wires are made parallel to make sure that the flow is uniform. Once the film is created, the cylinders are carefully placed in the flow using a linear stage.

Figure 6: High contrast wake structures (8).

Vortices were visualized with a monochromatic light placed behind the film and a DSLR camera filming from the front. We used a 16 W light green monochromatic source. Visualization of the vortex patterns in the soap film relies on the optical interference fringes formed by the light being reflected from the two film surfaces. A quarter wavelength change traversing through the thickness of a water film (≈0.1 microns) will change the interference pattern from constructive to destructive. This creates light and dark fringes that are amplified when viewed under monochromatic light. As seen in Figure [5] from (8),

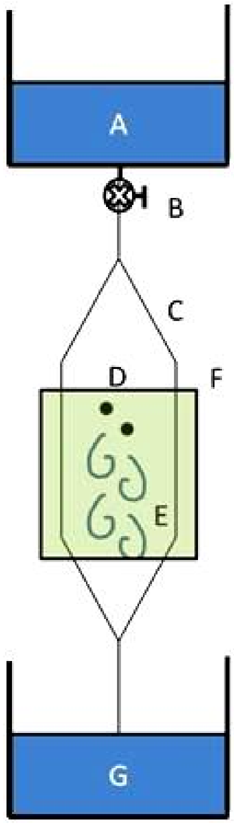

Figure 4: Conceptual diagram of the experiment setup. (A) Upper reservoir holding the soap water solution (B) Nozzle that controls the flow rate (C) Fishing line frame (D) 2 cylinders placed in the flow (E) Wake formation (F) Monochromatic light source (G) Lower collection reservoir.

these light and dark regions act as tracers in the flow. The interaction between the film and obstacles create small thickness changes and are then advected down the flowing film.

Stability of the film depended heavily on how large the soap film was and the minimization of external disturbances such as shaking and air drafts. Initially our film was very unstable lasting only 5-10 seconds and would frequently break when we placed an obstacle in the flow. By shortening the length of the test section, we were able to create much more stable films with some of them lasting up to 20 minutes.

We used two staggered and fixed cylinders to generate a 2P wake (see Figure [2]), comprising two pairs of vortices per shedding cycle.

3 Results

We were able to create soap films with flow obstructions that were stable up to 20–30 minutes. The flow structures from the interaction between one and two cylinders and the soap film were visualized with the incident monochromatic light and a DSLR

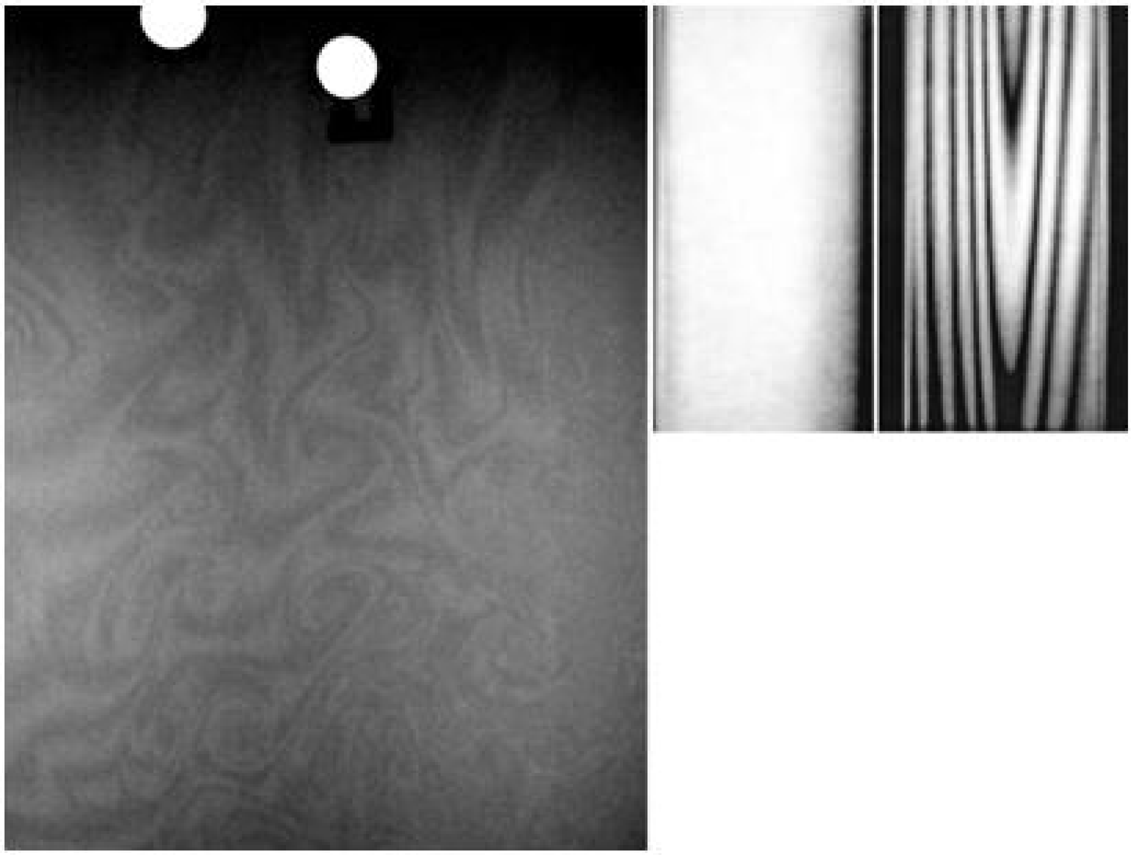

Figure 5: Wake visualizations. White circles highlight cylinder locations. Middle: Example of correct film thickness, Right: A film that is too thick (all the images are from (8)).

camera. Though visualization of structures was successful, flow structures were somewhat difficult to discern owing to the low power of the monochromatic light source. An example of flow structure visualization is seen in Figure [8]. The white circles highlight the location of the cylinders obstructing the flow. In this figure the flow structures are not easily seen. This also made it difficult for us to adjust the cylinders to find the particle wake mode (2P) that we were trying to see. Our film may also be too thick as there are many other structures forming on the edges of the flow. A film with the appropriate thickness will appear with no passive structures. The difference between light sources is very apparent when comparing our images with previous soap film experiments. This will be corrected by using a higher power (90 W) sodium lamp instead of using a 16 W lamp. The enhanced brightness of the monochromatic source will create more distinctly identifiable fringe patterns.

We were successful in creating the 2P regime for some wakes, even though our images do not have very high contrast. In Figures [8, 9], it is possible to identify several periods of symmetric 2P formations. Symmetric wakes are formed when the streamwise spacing between the staggered cylinders is approximately a half period length. Since only 3-4 periods are visible and the velocity of the film is unknown, comparing the experiments with the available theoretical tools can be challenging. However, use of

Figure 7: A snapshot of the ongoing experimental process (at the Basement Fluid Mechanics lab at Norris Hall, Virginia Tech).

Figure 8: Processed image from a typical snapshot taken during our experiments.

the new light source and smaller cylinders are expected to facilitate the comparison between theory and experiments.

4 Comparing the experiments with theoretical calculations

The prime motive is to compare the dynamic response exerted on a freely oscillating cylindrical bluff body with the corresponding experimental data. Using the point vortex model proposed in (6; 7), the amplitude response of the body should be potentially solvable. Thus, based on a particular generated wake arrangement, the corresponding oscillatory displacements of the body will be solved and that should ideally approximate half of the transverse separation between the two staggered cylinders in the concerned experiment. However for this, measurements of several experimental parameters like the background flow velocity and the frequency of vortex shedding will be essential. Another step-up would be the use of thin disk-like structures acting as bluff bodies embedded in the flow. Such an arrangement would ensure that the fluid forces are dominant on the structure and hence the free vibration data would be more reliable.

For the theoretical calculation of the dynamic effects of the bluff body owing to the wake vortices, a momentum conservation approach will be applied. Linear momentum

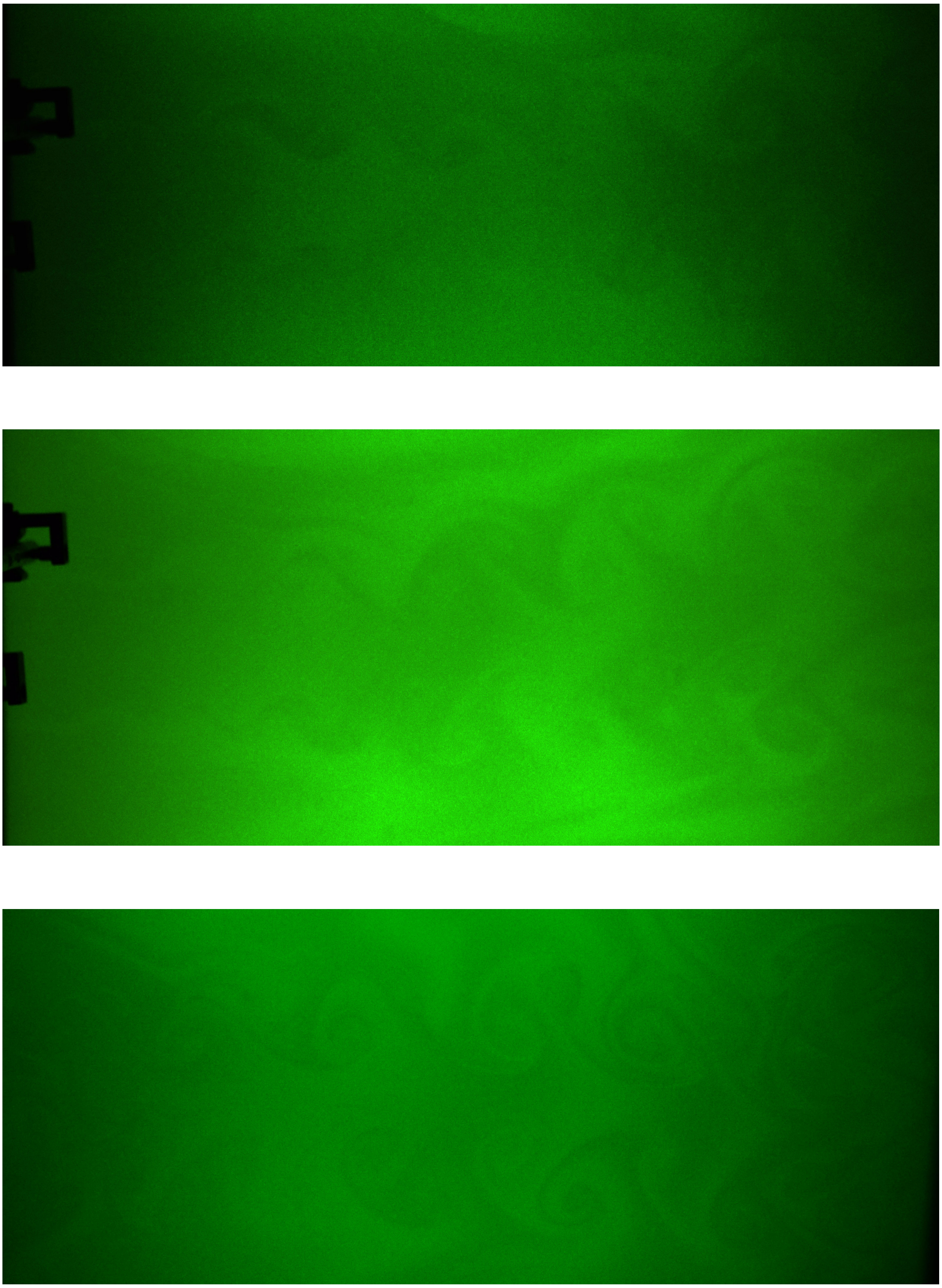

Figure 9: Sample snapshots of wake structures generated during our experiments. Two staggered cylinders operate as the bluff bodies. The test section has been illuminated by incident green monochromatic light from the rear. The central snapshot, for example, show the rough locations of the cylinders. They are held in place at the centers of the black projections.

conservation for a control volume (includes the shedding body) over a time increment during which a new pair of vortices are shed into the fuid, leads to the formulation for the wake-induced dynamic response of the structure (see (9) for an outline of a similar approach used to compute the wake-induced forces on the body for the regular von Kármán vortex street).

For relative equilibrium configurations (when the vortex configuration evolves downstream with invariant size and shape), the application of von Kármán's momentum approach will be quite straight-forward. The main points of distinction will be: (a) velocity field owing to the vortex street is different, and so is the translational velocity of the vortex system, and (b) different spatial arrangement of the wake vortices. However, for the time-evolving vortex patterns, the computation of the evolved locations of the individual vortices (non-equilibirum being the cause of the complexity) over a time increment and using the information for the momentum conservation analysis will be the primary challenge.

Additionally, some of the experimental wakes show two pairs of vortices arranged symmetrically about the wake centerline. These have been referred to in literature (10) as symmetric wakes. We plan to compare the point vortex model predictions for such wakes with the evolution of the experimental vortices. For this too, measurement of the above-mentioned experimental parameters will be imperative.

5 Conclusion

The results presented here represent wake structure formations by placing bluff bodies in gravity-driven vertically flowing soap films. Although preliminary in nature, the snapshots of the flow field exhibit distinct vortex structures. Improved visualization is expected using brighter lights (new experiments will be performed soon with better equipped lighting arrangements). The eventual target is to compare the experimental data on the dynamic response generated on a body by its shed wake with the corresponding predictions obtainable from the theoretical point vortex model.

Acknowledgements

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