ME301 Project 2024 GROUP 05

Email addresses:
[1]apolline.fabre@epfl.ch
[2]georgios.stefanidis@epfl.ch
[3]roy.turk@epfl.ch

Sciper numbers:
[1]341437
[2]325143
[3]345573

FABRE, Apolline[1]
STEFANIDIS, Georgios[2]
TURK, Roy[3]

Abstract

Our goal in this course is to study the deflection of a submerged structure under fluid flow. The motivation for this experiment stems from a mutual passion for fluid mechanics and structural deformation. Many real world applications under certain hypothesis can be simplified and modelled by a thin plate, which aids in the design of flexible structures in fields such as hemodynamics, biomedical engineering and structural dynamics. The experimental setup involves suspending rectangular thin plates within the channel, allowing water to flow over them at controlled velocities. We focus on three parameters: the material and dimensions of the thin plates, and the flow velocity imposed by the fan.
Control of the water flow and management of the experimental variables are one of many challenges we faced throughout this experiment. However, we hope to provide meaningful results that predict the behavior of such structures under fluid flow.

Introduction

In this report, we go through all the steps taken to design the experimental setup. We begin by enumerating all the required materials and the methods used. We then give a brief summary of the three physical quantities to be measured along with the varying parameters. The experimental protocol is also presented as it is a crucial part that guarantees the repeatability of our experiment. Finally, we reveal the results obtained and offer insights into their implications and avenues for potential enhancement.

Materials and methods

The setup involves a selection of carefully chosen components and configurations, designed to induce significant and observable deflections of the thin plates.

1. **Plates**
   Numerous plates are required with different materials and dimensions to investigate the influence of varying properties on the deflection behavior under fluid flow. This multiplate approach enables the exploration of a wide range of scenarios that enhance our experimental findings.

2. **Water channel, fan, fan support, power supply**
   The best way to create a fluid flow in a controlled environment is to use the provided water channel. It allows a one dimensional flow right before the plate that is adequate with our experiment. The flow is generated by supplying power to a fan [1] secured in position with our custom 3D-printed support.
3. **Load cell, HX711 amplifier, load cell support**
   A load cell [2] is mounted from the top of the water channel using a 3D-printed structure. Additional MDF boards maintain the plates in place and the setup was assembled rigidly thanks to M4 and M5 screws.
   The HX711 amplifier plays a crucial role in measurements taken with a load cell. It serves as an interface between the sensor and the Arduino micro-controller by amplifying the small electrical signals generated in response to applied force.
4. **Laser, laser support, polyamide particles**
   The velocity measurement requires a laser that illuminates a plane in the water channel to accurately track the polyamide particles. The laser must also be held from the top of the channel, which is facilitated by a support provided with the laser. The seeding particles need to be neutrally buoyant to ensure an accurate analysis of the flow.
5. **Camera, tripod, ruler**
   A camera is used [3] to measure the deflection of the plates, along with a tripod to maintain a consistent angle throughout the experiment. A ruler is also added in the camera frame to set the scale when estimating the pixel count.
6. **Arduino UNO**
   The Arduino micro-controller [4] plays a crucial role in the setup as it is responsible for data acquisition from the load cell, providing real-time monitoring of the force applied on the plate.

This experimental setup allows us to gather accurate data, control and manage the fluid flow, ensuring repeatability and reliability in our measurements. Additionally, it provides the flexibility to explore various flow conditions and parameters, enabling a comprehensive investigation into the behavior of thin plates under different scenarios.

The physical quantities are the following:

1. **Load cell for force measurement**
   In our experimental setup, we incorporate a load cell to measure the force exerted on the thin plates. The sensor offers precise readings with a resolution of 0.1 g, ensuring high accuracy. To ensure the reliability of our data acquisition process, we begin the experiment by calibrating the load cell using a known weight. This gives us the opportunity to investigate the correlation between the plates' dimensions and materials and the flow velocity.
2. **Camera for deflection measurement**
   We simultaneously recorded the plate with the force measurement to get the deflection. A tripod allows us to stabilize the recording and ensure consistent results. The video has a resolution of 1920×1080 pixels and a rate of 30 fps. A ruler is also placed in the frame to set the scale with a resolution of 1 mm, which corresponds to 14 pixels. We deduce an overall resolution of 0.071 mm/pixel. We can further divide this result by the length of the plates and get a normalized resolution that corresponds to 0.089% the total length.

3. **Particle image velocimetry for velocity measurement**
   The velocity measurement is done using particle image velocimetry (PIV), an optical measurement technique used to visualize and analyze fluid flow. It involves seeding the fluid with tracer particles that follow the flow dynamics. A laser sheet illuminates these particles, and a high-speed camera captures their movement over time. The velocity vectors of the fluid can be calculated by analyzing the displacement of the particles between consecutive images. The camera recorded the flow with a resolution of 1920×1080 and a rate of 240 fps. Equivalent to the deflection measurement, a ruler is added for calibration.

The three parameters of interest are the following:

1. **Plate material**
   Given the potential influence of the material on plate deflection, we examined two Mylar plates alongside a PET plate. The red Mylar plates are thinner and therefore more flexible than the blue ones, and the PET corresponds to the transparent plates. The properties are summarized in Tab. 1.
2. **Plate dimensions**
   Another aspect worth investigating is the surface area in contact with the fluid flow. We expect a different behavior for bigger areas since the water will have less space to go around the plate, potentially leading to a large deflection in highly flexible materials. We tested the following small and large dimensions: 90 mm $\times$ 40 mm and 90 mm $\times$ 80 mm.
3. **Flow velocity**
   Ultimately, we regulate the flow velocity by adjusting the voltage supplied to the fan, resulting in stronger flows for higher voltages. The tests are conducted under three different voltage values: 16, 20, and 24 V.

	PET	**Mylar (blue)**	**Mylar (red)**
Young's Modulus [GPa]	2.02	5.24	5.24
Thickness [mm]	1.0	0.75	0.35

Table 1. Properties of the plates at our disposal. The different thicknesses of the Mylar give us the possibility of comparing the impact of flexibility for the same material.

Arduino code

Arduino code serves as a digital language that enables the functionality of micro-controller boards, such as the Arduino UNO. It is a versatile open-source board, offering an accessible platform for electronics projects.

The code developed for load cell data acquisition can be summarized in two steps. Firstly, we ensure the calibration of the load cell with a known weight to get the calibration factor. A loop enables the collection of incoming values from the load cell with a delay of 100 ms. The values are printed on the serial monitor in a format compatible with a MATLAB vector.

MATLAB code

After the acquisition of the raw data from the load cell via the Arduino, we use MATLAB for further analysis of the results. The initial phase is preprocessing the data, which involves removing unnecessary zero values from the beginning of the output, before turning on the power supply. We decide to keep the first 14 seconds of each measurement to have the same vector length.

We also use MATLAB to perform the velocity field analysis using the application PIVlab [5]. The area around the plate is defined as the region of interest across all frames, and the FFT window deformation algorithm is applied to analyze each frame. We used two interrogation areas with sizes 124 px and 62 px with step sizes of 62 px and 31 px respectively. Validation of the results is also necessary, which is why we apply a standard deviation filter with a threshold of 8σ, and a low contrast filter with a threshold suggested by the application. Finally, we interpolate some missing values to complete our analysis.

Experimental protocol

Two distinct experimental sessions were conducted as part of this project.

During the first session, we obtain two sets of measurements simultaneously. The first set captures the force applied on the plate using the load cell, while the second set captures the plate deflection via camera recordings. The experiment requires the coordination of three people: one responsible for managing the camera and power supply, another for handling the code and receiving the data, and a third for holding the "clapperboards" and providing overall supervision. Below is the experimental protocol for this session:

1. Prepare labeled papers to serve as "clapperboards" for easy video navigation later.
2. Prepare the Arduino code for data acquisition and calibrate the load cell.
3. Position the camera perpendicular to the flow, focusing it on the hanging plate profile. Ensure a vertically placed ruler in the water channel is visible on the camera screen for accurate scaling.
4. Once the "clapperboards" are ready, hold one in front of the camera.
5. Plug the Arduino and run the code.
6. Start recording then remove the "clapperboard".
7. Turn on the power supply.
8. Record for an approximate time of 20 s.
9. Power off the supply, then the camera.
10. Stop the Arduino code and transfer the gathered data to MATLAB.
11. Repeat steps 4 through 10 three times for each plate and fan voltage setting.

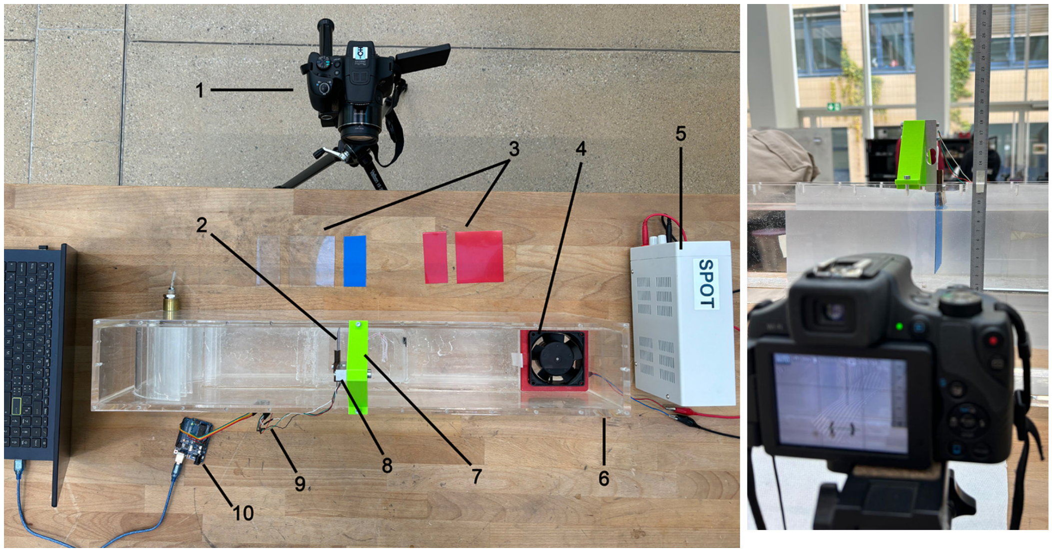

Figure 1. Experimental setup for force and deflection measurement. 1. Camera, 2. Submerged plate, 3. Next plates, 4. Fan, 5. Power supply, 6. Water channel, 7. Load cell support, 8. Load cell, 9. HX711 amplifier, 10. Arduino UNO

The second experiment is dedicated to the velocity measurement using PIV:

1. Prepare the PIV setup.
2. Mix a small amount of polyamide particles with water in a cup, then add the mixture in the water channel.
3. Position the camera perpendicular to the water motion, focusing it on the ruler to ensure correct recording.
4. Turn off ambient lighting and activate the laser for optimal visualization of particles.
5. Start recording and turn on the power supply.
6. Record for an approximate time of 20 s.
7. Power off the supply, then the camera.
8. Replace the current plate with another.
9. (Optional) Repeat steps 4 through 8 three times for each fan voltage setting.
10. Upon completion, transfer the acquired videos to a computer for later analysis on PIVlab.

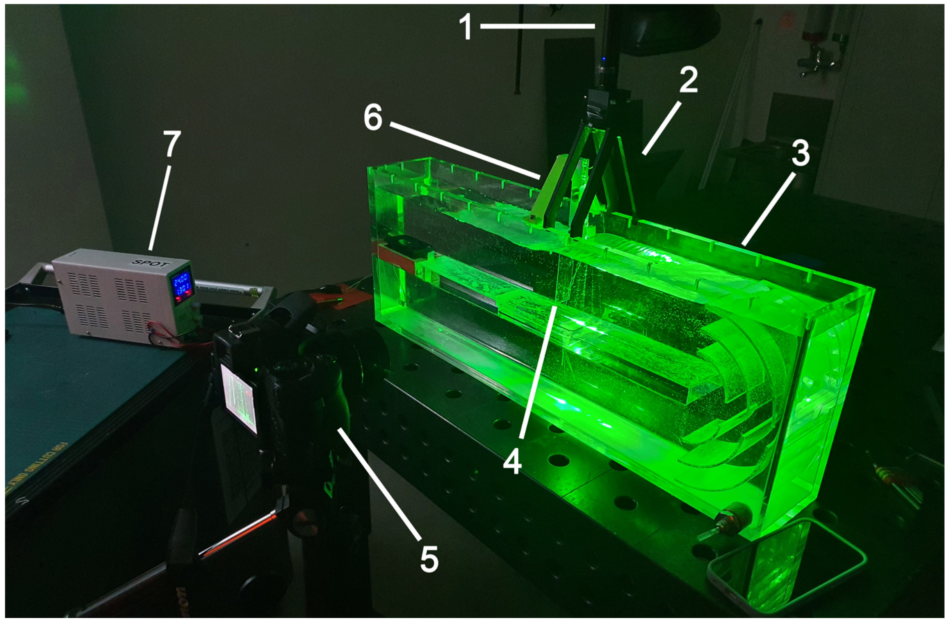

Figure 2. Experimental setup for PIV. 1. Laser, 2. Laser support, 3. Water channel, 4. Plate, 5. Camera, 6. Load cell support, 7. Power supply

Results

We can effectively analyze the behavior of each plate dimension and material by plotting the force F as a function of time for each voltage setting.

The general tendency and behavior for each plate can be summarized in two regions: the transient state and the steady-state. In the former region, there is an overshoot which corresponds to the initial pressure exerted by the water as it starts moving. Steady-state is then reached after a certain time t_s (Fig. 3).

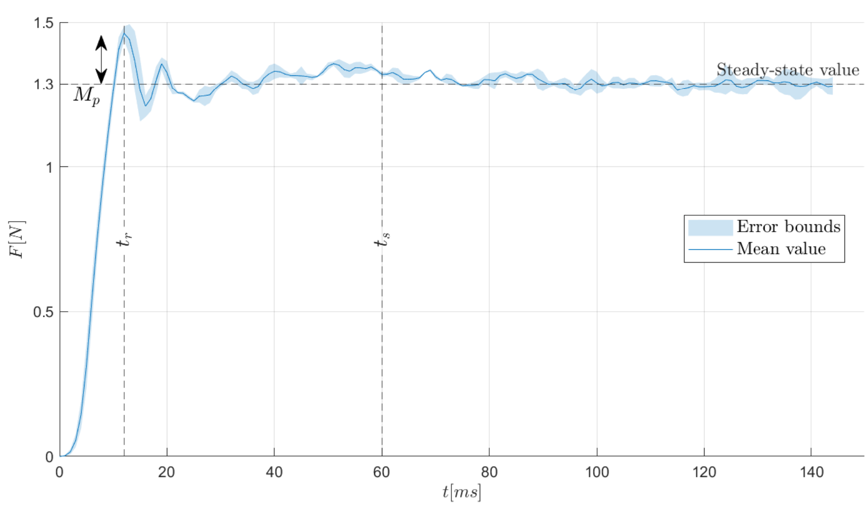

Figure 3. General behavior of a force measurement on the large PET plate at 24 V. The rise time t_r, settling time t_s, and overshoot M_p are shown.

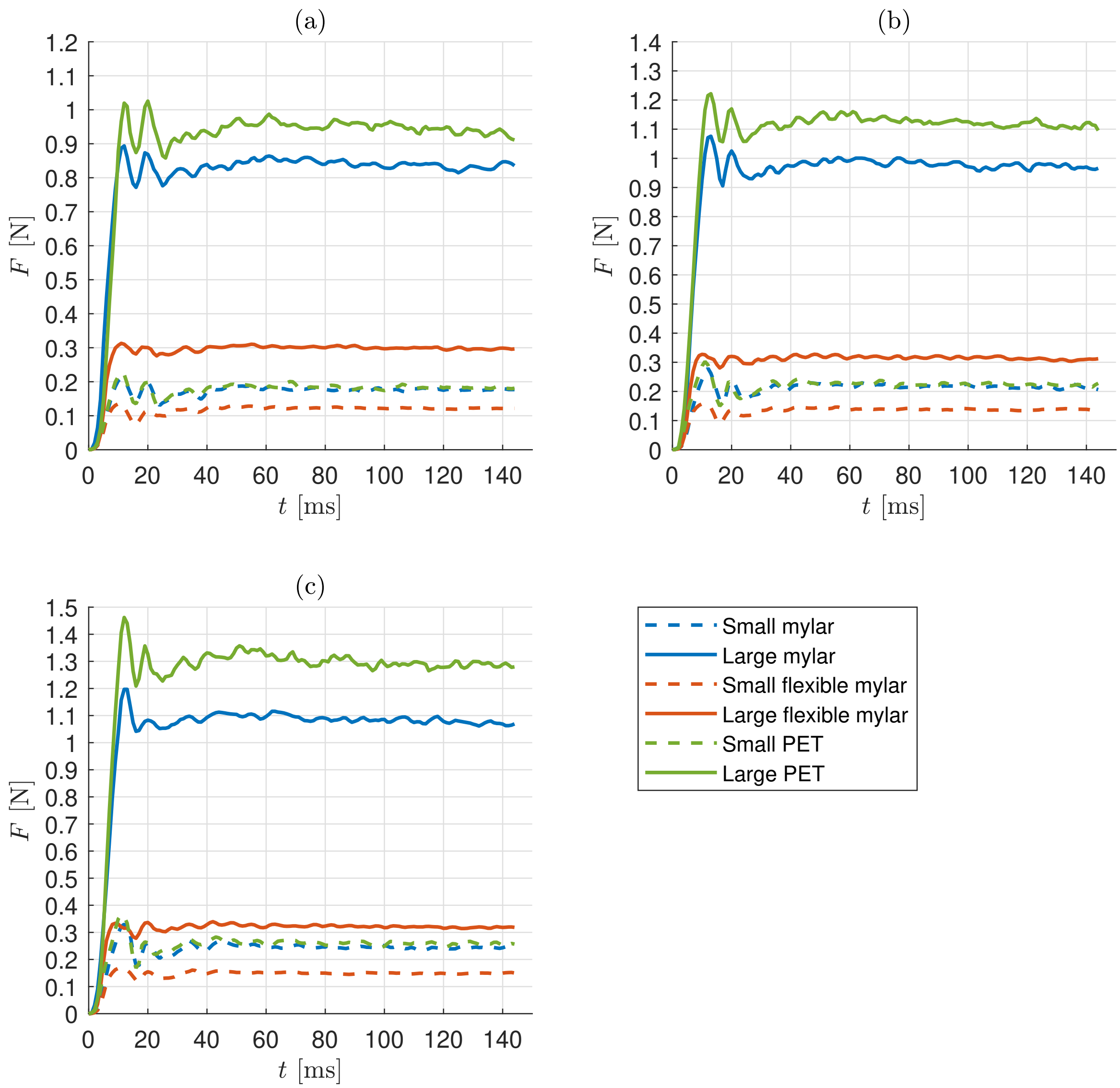

Figure 4. Results for the load cell force measurement. The plots (a), (b), and (c) represent the force as a function of time for each of the voltages 16, 20, and 24 V respectively. The different plots are distinguished by the plate dimension and material. The error range is not displayed for the sake of readability.

As for the plate dimensions, a larger surface area results in a greater force applied to the plates. Additionally, the force difference between the small and large flexible Mylar plates (red) is less pronounced compared to the other plates, where a bigger force difference is observed when going from small to large. For flexible materials, plate dimensions have a smaller impact on the exerted force. In contrast, for rigid materials, dimensions significantly influence the applied force.

Subsequent to that, we might anticipate a larger force on the thicker Mylar plate (blue) since its Young's modulus is double that of PET. However, this is not the case, the large PET plate has more force on it than the Mylar plate. This is due to the difference in thickness between both plates. It is an additional parameter that influences the force exerted on the plate.

For the deflection measurement, our focus is on the behaviour of the plates at steady-state. We plot the acquired deflection values δ corresponding to each voltage setting U and evaluate the value of the force applied on the plate at steady-state to explore potential correlations between these two parameters.

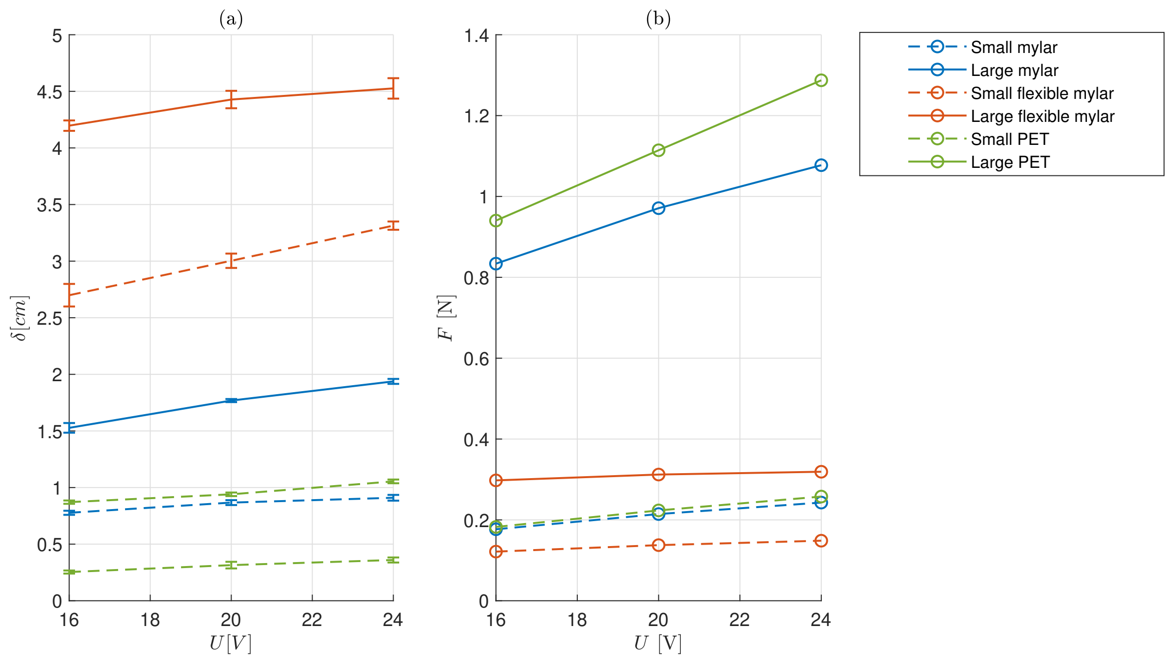

Figure 5. Results at steady-state. The plots show the deflection (a) and force (b) for each plate at each of the three voltage settings 16, 20, and 24 V.

Higher voltages lead to larger deflections and forces. As the flow becomes stronger, we expect the plates to bend more.

The thickness of the plates plays a more important role on the deflection than the surface area, as seen when comparing both types of Mylar.

Moreover, the plate exhibiting greater deflection experiences a smaller force, while the plate with lesser deflection undergoes a higher force, confirming an inverse relationship between both quantities. There is also no significant change in the quantities across all the voltages for the small plates. The force on these plates stays almost constant.

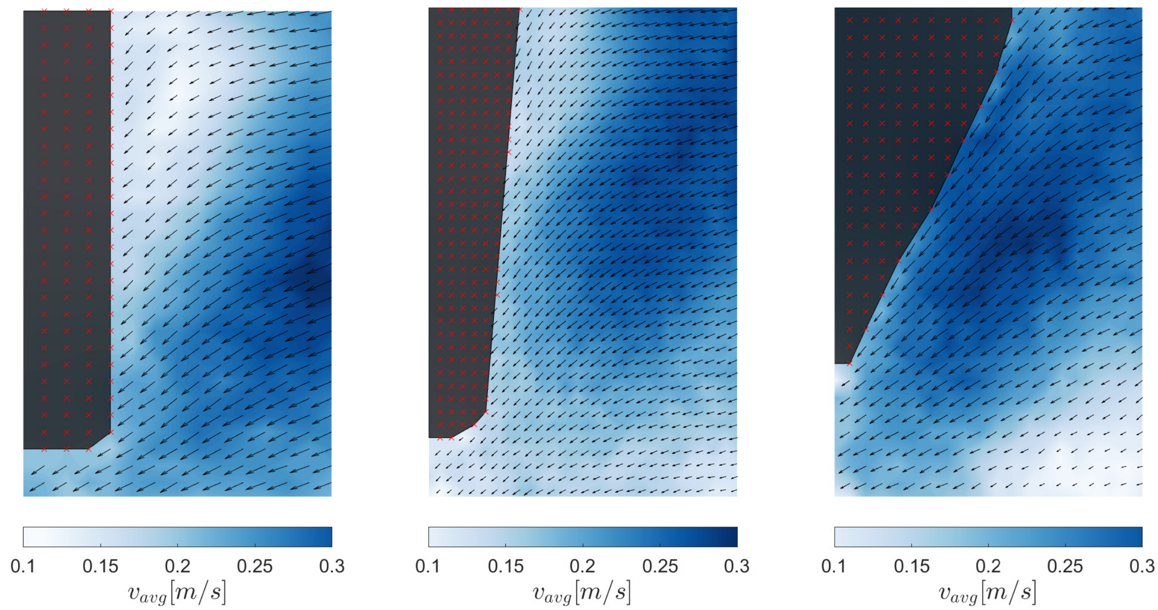

Figure 6. PIV results. The plot shows the mean velocity distribution for the PET, blue and red Mylar from left to right respectively. The black area masks the profile of each plate and the region behind it. These are areas that are out of our interest for the analysis.

The PIV analysis gives us access to the mean velocity v_{avg} distribution upstream of the plate. The difference among the plates is the stagnation of velocities at the upper surface. The more abrupt the flow deceleration, the greater the force transferred to to the plate. For the flexible Mylar plate (red), there is no discernible decrease in velocity, unlike the other two plates.

Conclusion

Our experiments show interesting relationships between force, deflection, and flow velocity.

In very flexible structures, the relationship between deflection and force deviates from linearity. These structures are subject to considerable deflection which restrains us from using the theory of small deformations from structural mechanics. Additionally, thickness emerges as a critical factor compared to other material properties, exerting the most significant influence on deflection and force measurement. Furthermore, our PIV results provide insights into how velocity stagnation occurs on the upper surface of the plates and its consequent impact on the force transmitted to the load cell.

Despite the insights gained, our experimental setup could be refined to ensure more accurate results. The extensive use of the fan in the water channel by other groups throughout the semester may have affected the consistency of measurements taken weeks apart, potentially influencing the observed relationships. Moreover, the absence of a high-speed camera hindered our ability to visualize the flow behind the plate and analyze turbulence patterns effectively.

If given the opportunity to conduct the experiments again, we would implement more precise methods to measure deflection, such as tracking the deflection over time for the entire plate rather than just the tip. The use of colored plates against a white background would facilitate the observation of shape deformation as the fan is activated.

Due to resource limitations, our selection of materials, sizes, and velocities was restricted. Particularly, our control over plate thicknesses was limited to what was available during the semester.

Author contributions

Every team member played an indispensable role in the project. Through close collaboration and regular meetings, we collectively constructed the experimental setup and conducted the measurements. During both experiments, specific responsibilities were delegated among team members. As for the data treatment, each one of us was responsible for the analysis of one of the three physical quantities.

Acknowledgement

We would like to present our deepest gratitude and consideration to the coaches of the SKILL and SPOT, as well as the teaching assistants, for their continuous support and guidance throughout the project.

References

[1] *Dc fan 3314nnu*, ebmpapst. [Online]. Available: https://www.mouser.ch/ProductDetail/ebm-papst/3314NNU?qs=h6Piwd%2Fnvzme66%252B0uGLHQA%3D%3D (cit. on p. 2).

[2] *Sen-14728*, SparkFun Electronics. [Online]. Available: https://www.digikey.ch/de/products/detail/sparkfun-electronics/SEN-14728/9555602 (cit. on p. 2).

[3] *Canon powershot sx60 hs*, Canon. [Online]. Available: https://fr.canon.ch/for_home/product_finder/cameras/digital_camera/powershot/powershot_sx60_hs/ (cit. on p. 2).

[4] *Uno basic starter kit*, ELEGOO. [Online]. Available: https://www.elegoo.com/products/elegoo-uno-basic-starter-kit (cit. on p. 2).

[5] *Pivlab - particle image velocimetry (piv) tool with gui*, William Thielicke. [Online]. Available: https://ch.mathworks.com/matlabcentral/fileexchange/27659-pivlab-particle-image-velocimetry-piv-tool-with-gui (cit. on p. 4).