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Experimentelle Untersuchung der Reaktion einer flexiblen Klappe in Wechselwirkung mit einer Fluidströmung

An experimental study to investigate the response of a flexible flap interacting with a fluid flow

Tayyaba Bano, Johannes Burkert, Rüdiger Schwarze

Institute of Mechanics and Fluid Dynamics (imfd), TU Bergakademie Freiberg, Lampadiusstr. 4, 09599 Freiberg, Germany; Tayyaba.Bano@extern.tu-freiberg.de

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Flexible flap, Fluid-structure interaction, Particle Image Velocimetry

Abstract

In this study, a new experimental set-up is designed to examine the fluid-structure interaction (FSI) effects on thin flexible flaps submerged in an open water channel. Investigations are performed to analyze the flow conditions for medium to high Reynolds number ranging from $700 < Re < 7000$. A rectangular flap with one end free, made of silicon is subjected to deform in a cross-flow direction. The measurements signify the mutual interaction of flexible flap and fluid and therefore the flap response and fluid flow around the flap are investigated. The flow field is observed by performing the planer 2-dimensional (2D) Particle Image Velocimetry (PIV) measurements. Flow behavior in terms of vortex shedding frequency and velocity field is considered and wake structure is observed by time resolved (TR) PIV images. The existing experiments also aim to validate the recent numerical method developed for turbulent flow conditions to investigate FSI. The influence of dimensionless parameter Reynolds number, *Re*, across the flap is focused in the measurements. The outcomes of this research provide a better insight and an improved understanding of a thin structure in liquid applications where the dynamic response of structure is influenced by fluid interaction.

Introduction

FSI arises in an extensive engineering application such as electric, mechanical and biological systems. Examinations of lighter and flexible objects entails a rapid development in experiments and new simulation models that illustrate the mutual interaction of flexible bodies and the fluid. A summary of recent literature on flexible structures, in terms of: structure dimensions, material, and flow type are expressed in Table 1.

The dynamic motion of flexible arrangements plays a significant part in natural streams mixing such as agriculture and marine canopies as well as in fluid control devices. The flapping behavior is explained by performing a digital particle image velocimetry (DPIV) across rectangular rigid and flexible plates of low aspect ratio (AR). The phenomenon of vortex formation and hydrodynamic forces are described for each polycarbonate plate design having AR of 3.75 and for the *Re* of 2000 (KIM and GHARIB, 2011) . Furthermore, the motion of the flexible blades is experimentally investigated, and the flow field is evaluated by PIV. Blades made of silicon foam and high-density polyethylene (HDPE) are tested during the investigations and the velocity field with respect to different blade movements using PIV is presented, moreover the influence of Cauchy number, *Ca*, and effective length, L_e, is suggested for the vegetation motion (Luhar and Nepf, 2011, 2016). Similarly, the oscillations of flexible plates in a tandem engagement are experimentally examined by means of the planer PIV with a normal plane according with the center of plates to observe the flow field corresponding upstream and downstream of the plates. Tip positions of the plates with respect to the *Ca* are explained by varying the spacing between the adjacent plates. Besides, a mathematical model is derived to support the experimental investigations (Jin *et al.*, 2018) . In addition, to observe the waving motion of the nearby flaps and across the flap tips, experimental as well as numerical studies are conducted for the silicon rubber flaps arranged in a row. PIV is implemented to investigate the velocity field by means of continuous laser beam. The effect of flaps mass ratio is investigated to observe the flow conduct and structure fluid dynamics (Favier *et al.*, 2017; Revell *et al.*, 2017). Furthermore, the measurements are performed to study the influence of hairy flaps on the wake of a bluff body. The study is presented in terms of shedding frequency, length of separation bubble and velocity field with respect to a plain body. PIV is implemented to measure the filament motion and flow dynamics. The author summarized by stating that such kind of passive control strategies can lead to a flow control approach for thin shear layers involving FSI (Kunze and Brücker, 2012; Pinelli *et al.*, 2017). Likewise, to observe the waving instabilities for a larger arrangement, a numerical approach is implemented by (O'Connor and Revell, 2019) to an oscillating flow condition presented in (Favier *et al.*, 2017) with 128 wall-mounted flexible flaps. The relation between the travelling wave and the vortex structure generated at the flap tips with respect to the array length is explored further (O'Connor and Revell, 2021) by varying the number of flaps from 6 to 20 once again for the experimental case (Favier *et al.*, 2017). It is concluded that for a smaller array configuration only a single defined wave is present, whereas for larger arrangement, a waving behavior is induced due to the generation of secondary vortices at the flap tips. The flap deflection is also affected by such secondary vortices and a decreased deflection is observed showing an important suggestion for the flow phenomena.

In this research work, an experimental data is offered with the aim of explaining the complex physical FSI problems. The literature survey shows the benefits of flexible objects for an extensive range of practical applications. Despite the recent significant research, the transient dynamics of flapping structures need still more to be discovered. Therefore, the current study explores and helps to improve further the concept of FSI for flexible flaps intended for three-dimensional (3D) problems as well as presents the wake development and effect of flap bend on flow behavior. Therefore, to explain the 3D flow fields, planer-2D PIV in two different plane directions are implemented and the measurements are concluded for several inflow conditions.

Table 1. Summary of literature review involving flexible structures: type of the flow, structure material and length;[1]Experimental study; [2]Numerical study

Author	Structure density ρ^s, *kg/m³*	Structure length *L, cm*	Reynolds number *Re*	Number and type of structure
Luhar (Luhar and Nepf, 2016)[1]	670, 950	5, 10, 15, 20	n/a	8, 2D- flexible blade
Jin et al. (Jin *et al.*, 2018)[1]	1200	4	2200,5000	2, 2D-flexible plates
Favier et al. (Favier *et al.*, 2017)[1,2]	1200	2	120	10, 2D-flexible flaps
Connor (O'Connor and Revell, 2019)[2]	1200	2	80	128, 2D-flexible flaps
Connor (O'Connor and Revell, 2021)[2]	1200	2	120	6 – 20, 2D-flexible flaps

Experimental set-up

Experiments for the presented study are conducted in an open water channel at the Chair of Fluid Dynamics and Turbomachinery, TU Bergakademie Freiberg (TUBAF). The tests are organized for a flexible flap profile as depicted in Figure 1a. The water channel has a total length of 5 m, height of 0.405 m and a width of 0.309 m, with a transparent test section. For the present measurements, the water level, *H*, remains constant at 0.250 m for a given flow rate in the channel. The flap is mounted normal to the flow direction and is designed with an aspect ratio (AR) of L/w = 5:1 and is made up of silicon rubber (Elastosil RT 601, Wacker Chemie, Germany).

The dynamics of structure and fluid is studied for the incoming flow rates of $Q \in [10{,}100]\ m^3/hr$ every $\Delta Q = 10\ m^3/hr$, which corresponds to the flow velocity of $v \in [0.0359{,}0.359]\ m/sec$. The *Re* is defined based on constant flow velocity,v, and flap width,w, as $Re = vw/\text{v} \in [700{,}7000]$. For the investigated range of *Re*, the flap experienced definite deformation, the corresponding bending definitions are shown in Figure 1b. Whereas, Table 2 presents the properties of the flap and the fluid respectively. The coordinate system used in the current investigation is specified as the x-axis is in the direction of flow, the y-axis is in the vertical direction and z-axis is set towards the width of the water channel.

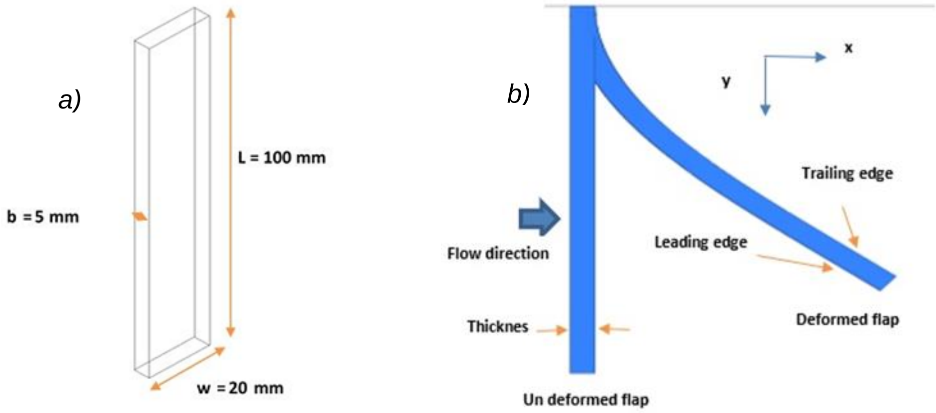


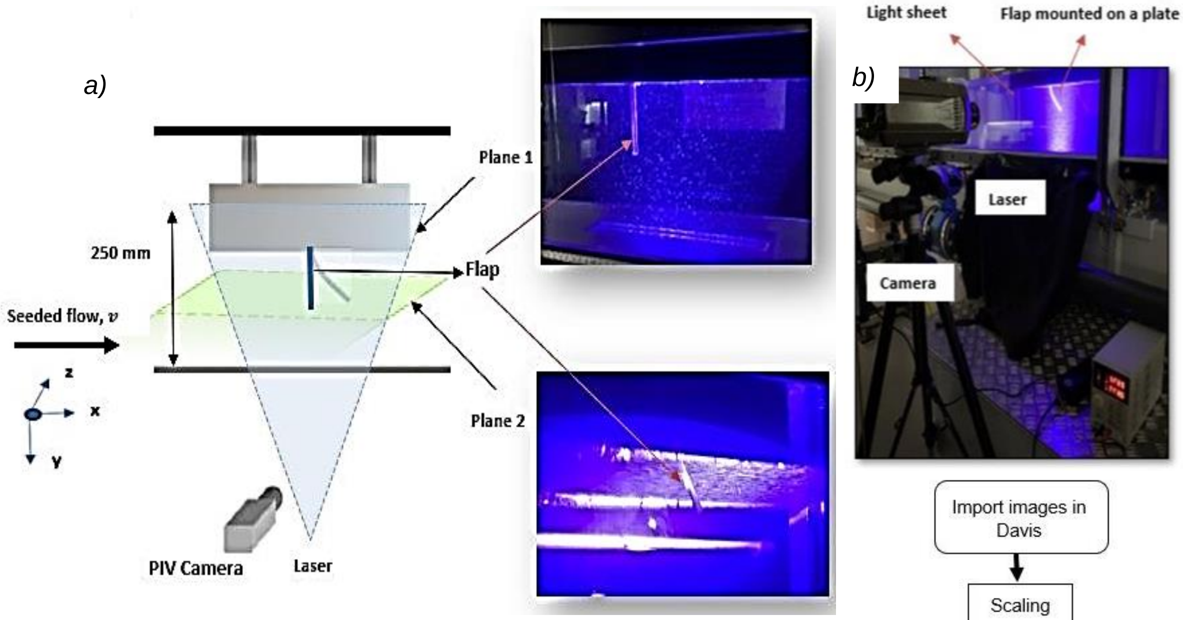
***Figure 1** a) Flap geometry b) Flap bending definitions*

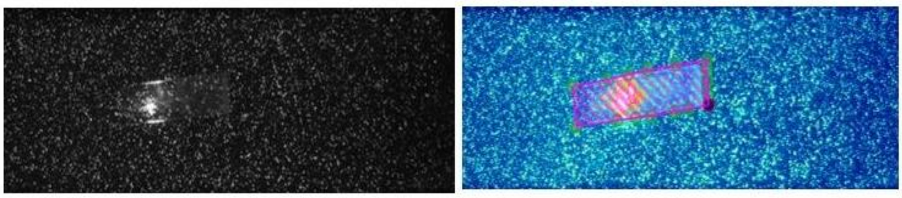
Table 2. Material properties and dimensions

Fluid-Water	Density, ρ^f	998.2 *kg/m³*
	Dynamic viscosity, μ	0.001003 *kg/m-sec*
	Velocity range, v,	0.0359 – 0.359 *m/sec*
	Flow Reynolds number, *Re*	700-7000
	Current fluid height, *H*	0.250 *m*
	Averaged particle size, d^p	100 *µm*
Structure-Flap	Length, *L*	100 *mm*
	Width, *w*	20 *mm*
	Thickness, *b*	5 *mm*
	Density, ρ^s	1020 *kg/m³*
	Young's modulus,E	1.23 *MPa*
	Poison's ratio, v	0.3
	Shear modulus, *G*	0.473 *MPa*

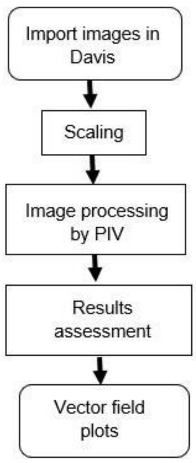
The flow field in the surroundings of the flap is described by 2D planer PIV by establishing a vertical plane: plane 1 at the center of z-axis (xy plane) and the flap respectively. The other plane is set horizontally, plane 2 positioned in y-axis (xz plane). The PIV camera is positioned in the front of measurement section and the water channel is sowed with the white particles of the averaged diameter, d^p, 100 μm. A basic schematic of an experimental set-up is shown in the Figure 2 (a). Initially the measurements are recorded for plane 1 by adjusting a blue laser diode (Osram PLPT9 450LB_E, P_{max} = 5*W*, λ = 440 – 450 *nm*) of continuous light under the water channel which covers the observation section so that the side-view of flap can be seen from the camera, as shown in the Figure 2(b). For the subsequent horizontal plane measurements, the laser is adjusted in the front of water channel and mounted above the PIV camera, also a mirror is placed under the channel to reflect the light sheet illustrating the bottom-view of the flap. The measurements are taken for each flow case by setting the plane 2 at various positions i.e., in the center of the bended flap and at flap-tip by varying the distance of the laser diode. Besides, the investigations are performed for the flow conditions without immersing the flap in the water channel for both planer orientations and hence the velocity flow field with and without the flap is attained for a varied range of *Re.*

Images are recorded by a computer to synchronize the PIV camera and the laser. Illustrations are captured using a high speed (HS) camera *Phanton V12* having the maximum resolution of 1280 *pixels* × 800 *pixels* with lens type of *Nikon* 50 *mm f 1.8*. The field of view (FOV) of the maximum resolution is illuminated for the varying incoming flow rates and the subsequent images are interrogated and processed by a PIV software *DaVis 10*. The TR velocity vectors of particles are observed, and the averaged velocity magnitude is examined for the defined range of *Re* representing the size of the final vector window covering 250 *mm* × 200 *mm* for side-view of the flap. Similarly, the recorded images for the bottom-view of the flap are processed to observe the flow in the other view direction depicting the final FOV of 250 *mm* × 80 *mm*. The corresponding image post processing is shown in Figure 2(c).





c) Raw image and masking of the flap (plane 2)



Flow chart of the DaVis 10 post processing

Figure 2 *a) A schematic of experimental set-up, b) Experimental arrangement for plane 1, c) Image processing by Davis 10*

Results:

In this section, the distinctive flow dynamics is characterized across the flexible flap in terms of *Re* and the corresponding bending behavior of the flap is discussed. For all the investigated cases, the flap bending is observed to be increased with increase in *Re* as the larger inertial forces would affect the flap to bend more. To investigate the bend pattern of the flap, the bending motion is examined only at the leading edge of the flap. The maximum xy-directional deflection of the flap is presented in the Figure 3 with respect to the undeformed flap position.

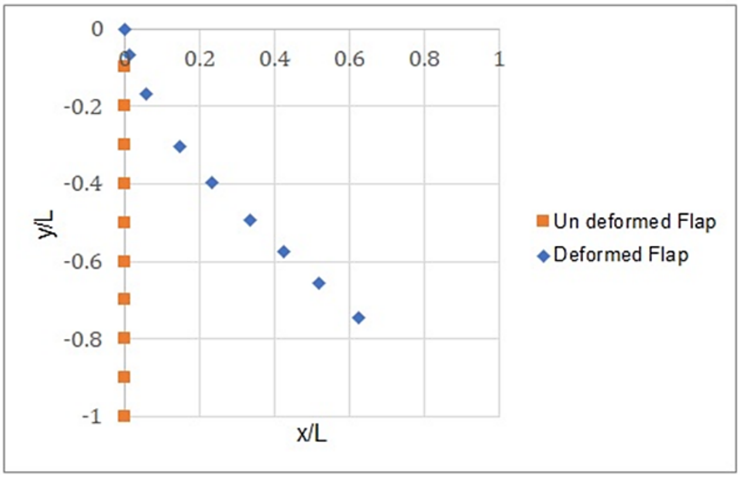


Figure 3 *Flap bend, un deformed Vs deformed (Re = 7000)*

In order to establish the relationship between the flap dynamics and the flow structures, velocity distribution in the flap surrounding is assessed and the resulting averaged as well as the TR velocity vectors are evaluated as shown in the Figure 4. The snapshots of velocity field are obtained from a vertical (plane 1) and as well as horizontal plane (plane 2) located nearly at the middle of bended flap. To assess the flow for least and highly deformed flap, velocity contours around the flap-tip as obtained by plane 1 are presented in Figure 4a for the maximum and the minimum *Re* conditions. The PIV findings indicate that the flow is signified by the separation of the uniform upstream flow past the flap which leads to the development of the wake region downstream. Initially at *Re* = *700*, the flow is visibly separating from the flap-tip (side-view), creating a smaller velocity region in the flap wake (Figure 4a). The temporal variation in the flap curvature and the resulting bending motion for the highest velocity influences the contraction in the wake region, as well the wake zone grows to be narrower. This entails that the flap bended positions play an influenced part in enhancing the wake pattern and flow formation in the flap vicinity. The flow dynamics in the wake of a structure is influenced by the velocity fluctuations and the stiffness of the structure, therefore the increase in *Re* leads to the wake contractions. The corresponding TR visualization of the bottom-view indicate that the vortices shed consecutively from the edges of flap and the flow begins to oscillate in an alternate manner (Figure 4b).

The periodic nature of the flow is estimated by the vortex shedding frequency, f_s, and is assessed by taking different probe locations in the flap wake to observe the temporal variation of velocity component in the flow direction ($x -$ component, u) and hence the frequency. Fast Fourier transform (FFT) function in MATLAB is used to extract the frequency pattern, the dominant peak in the resulting frequency spectrum is spotted at 3.89 *Hz.* Moreover, based on the shedding frequency, Strouhal number, $S_t = f_s\, w/v,$ is found out to be 0.217. The value can be comparable with the literature (Lorentzon and Revstedt, 2014, 2020) for the cantilever applications. The distribution of velocity fluctuation and a sample of frequency analysis is shown in the Figure 5 respectively.

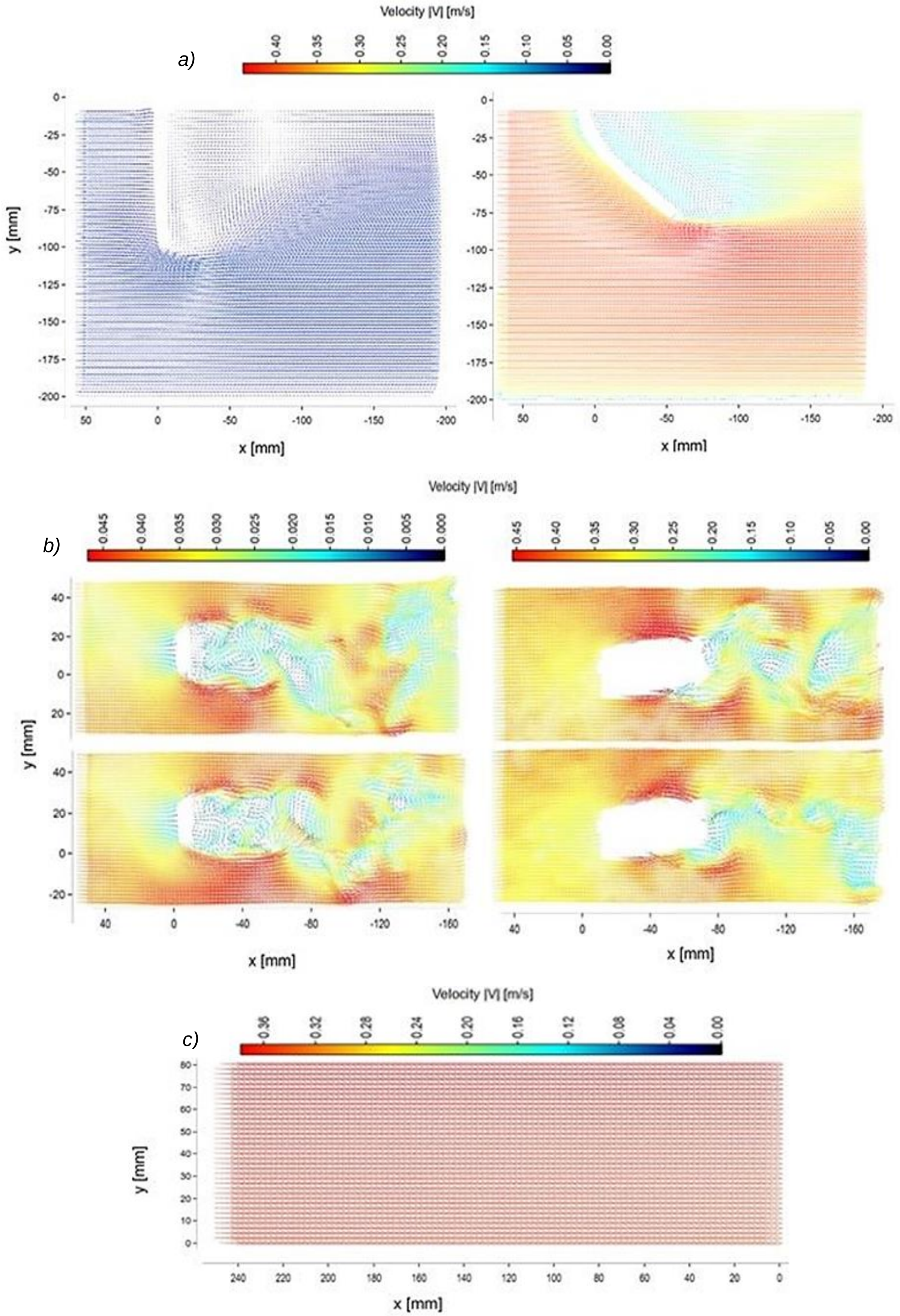
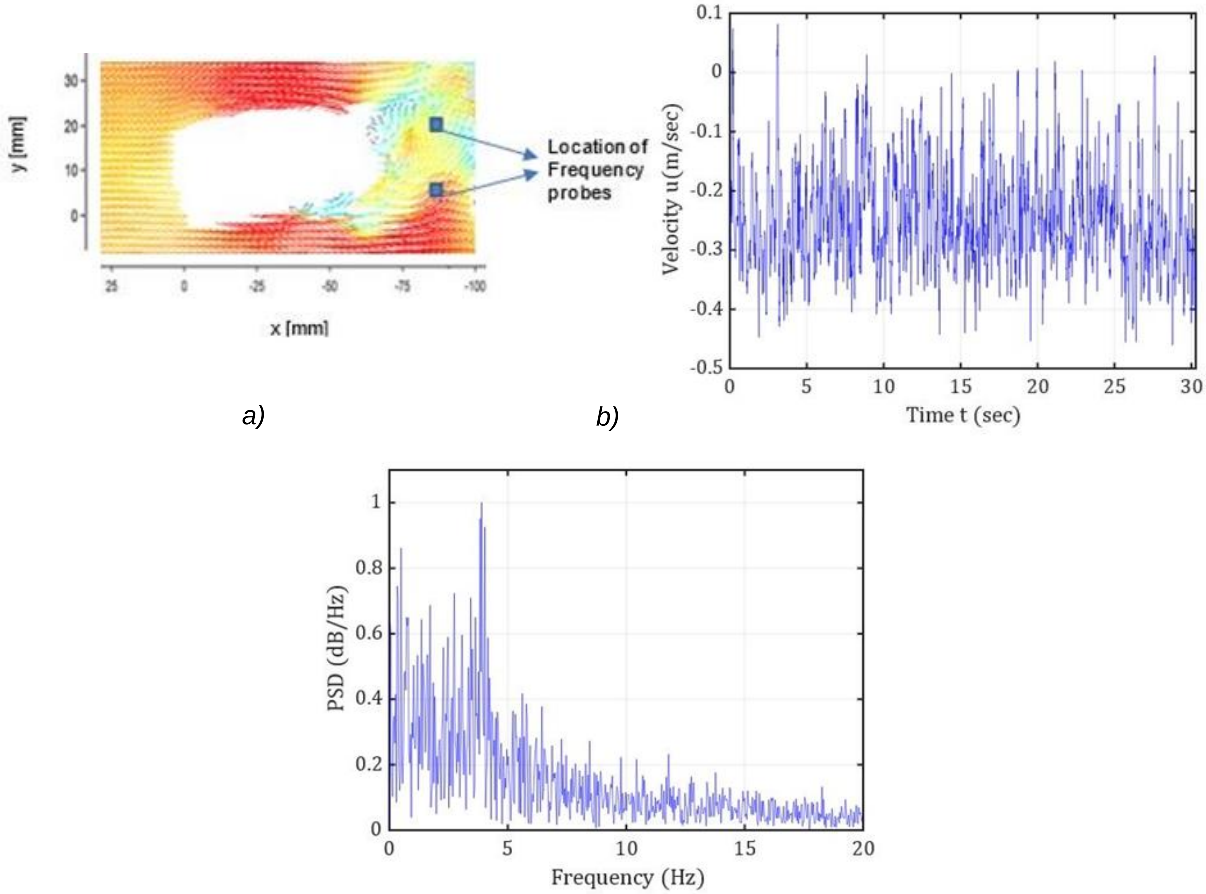


Figure 4 *a) PIV averaged velocity flow field, Re = 700 (left) and Re = 7000 (right) plane 1, b) TR visualization of bottom-view, Re = 700 (left) and Re = 7000 (right), c) velocity field without flap (bottom-view), Re = 7000*



a) b) c)

__Figure 5__ Frequency analysis, Re = 7000 a) location of frequency probes in the flap wake, b) velocity variation verses time, c) Frequency spectrum

Conclusion

In the present study, the behaviour of a rectangular shaped flexible flap is investigated, and the corresponding flow field is observed by performing the PIV measurements. The observations are attained for two different plane orientations to perceive the flow from various directions. The results show that vortices are generated in the flap wake and alternatively shed in the downstream. The velocity field is visualized in the flap surroundings for different *Re* indicating the intensity of flow recirculation. Relative to the less deformed flap, additional tip deflection for higher *Re* indicates the higher bend of stream in the flap wake. Therefore, the offered visualizations appear to explain the flow physics around the elastic structures. For the current research purpose, a simple deforming structure is chosen to demonstrate the motion of thin objects and surrounding flow, though the flapping performance of natural creatures are very complex and have varied shapes. The presented experimental data can also be used for the comparison of FSI simulations. Besides, a more detailed inspection of the flap motion and FSI would be done in the future.

Acknowledgement

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