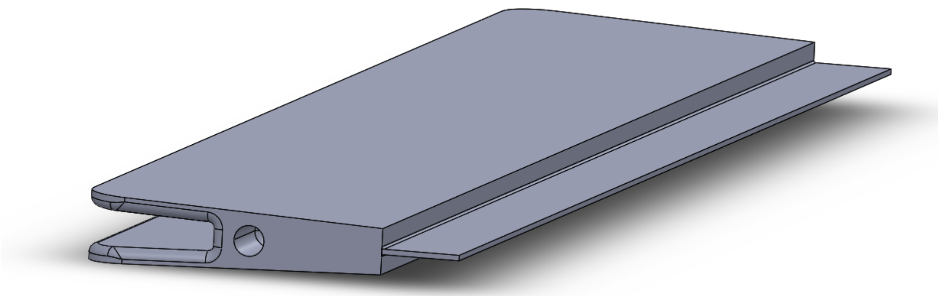
Project thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Carsten Cleve-Hansen

Splitter plates effect on trailing edge vortex shedding and fluid structure interaction

Trondheim, 12 2019



NTNU – Trondheim
Norwegian University of Science and Technology

Summary

Denne prosjektoppgaven er en planlegging av et eksperimentielt studie, hvor splitter platers effekt for reduksjon av virvelavløsning bak en hydrofoil skal undersøkes ved bruk av PIV. Reduksjon av virvelavløsning er essensielt for å kunne redusere vibrasjoner i hydrofoilen som følge av disse, og ved å redusere vibrasjoner vil man øke levetiden til en hydrofoil som brukes i ulike deler av en vannkraft turbin. Studiet er en del av en større forskningskampanje rundt virvelavløsning og fluid struktur interaksjoner, som gjennomføres på Vannkraftlaberatoriet ved Norges Teknisk- Naturviteskaplige Universitet (NTNU). Denne oppgaven tar for seg et litteraturstudie, hvor bruk av splitter plate for kontrollering av virvelavløsning blir studert. Et forslag til design av splitter plater som skal brukes i studiet legges fram, og hvordan disse skal festes til hydrofoilen i testriggen. Det eksperimentelle oppsettet blir presantert, og mulige systematiske feil blir diskutert ut i fra valgte testparametere. Eksperimentet som planlegges i denne oppgaven vil bli gjennomført som en del av en master oppgave som skal gjøres våren 2020.

Abstract

This project thesis is a design of an experiment, where the use of splitter plates on a hydrofoil to mitigate vortex shedding shall be investigated. The reduction of vortex shedding is the key to reducing vortex induced vibrations, which can cause early fatigue of the hydrofoil. The project is a part of a ongoing investigation into the mitigation of vortex shedding at the Waterpower laboratory at the Norwegian University of Science and Technology (NTNU). The measurement campaign that is planned will be carried out using the particle image velocimetry (PIV) technique to calculate the velocity fields, and a laser doppler vibrometer (LD-V) to measure the vibrations together with strain gauges. The project is built up by six chapters. The first chapter is an introduction, the second chapter is a description of the basic theory that lays behind the project, then there is a literature review on splitter plates as a passive control device, a design proposal of the splitter plate and trailing edge of the hydrofoil, and an explanation of the experimental set up and discussion of possible bias errors in the experiments. Finally there is a conclusion/discussion of the proposed design. The experiment that is planned in this project thesis will be executed as a part of a masters thesis the spring of 2020.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

Hydro power is a sustainable source of electricity, that does little impact to the nature. In a time where the focus on climate changes due to human pollutants and emissions are higher than ever, it is important to invest in renewable energy sources like hydro power. In Norway, hydro power is already the main energy source, and the research regarding it have been going on for a long time. The Waterpower laboratory at the Norwegian University of Science and Technology have been studying different aspects of hydro power in over 100 years. These days, most of the studies on hydro power is on modifications that can extend the life time of different components, and it is here this study comes in. In hydro machinery there are several components that are shaped as hydrofoils to exploit the kinematics of the water that runs through it.

Hydrofoils are being used in hydro machinery as guide vanes, stay vanes and runner blades. If the frequency of the vortex shedding from these are overlapping the natural frequency of the hydrofoil, there will be resonance and the hydrofoil will come to a stage called lock-in. This can cause unnecessary fatigue and failure of components. Therefore it is an interesting topic of study to be able to reduce the vortex shedding, and keep the shedding frequency off the resonance area in range of operation. In this project thesis a measurement campaign is planned, where PIV will be used to investigate how splitter plates can affect the vortex shedding and fluid structure interactions in a flow over a hydrofoil. Splitter plates have shown good results as a passive control device when used in cylinder flow, and it is therefore reason to believe that they can work in flow over a hydrofoil as well.

Since this project is a design of experiments, there will not be presented any results. The project contains of a design proposal that is based on a literature study of similar cases. A production plan of the different components are also included, where the pros and cons of different manufacturing methods are discussed. Finally a explanation of the experimental set up are presented, together with a discussion of important testing parameters that must be chosen correctly to avoid inaccurate results. The results from the future measurement will be compared to a reference study that was conducted by Sagmo et al. (2019). In this study the shedding frequency and natural frequencies of a hydrofoil is investigated to see which inlet velocity leads to the lock-in state. The idea is that the use of splitter plates can mitigate the vortex shedding and fluid structure interactions, and by that avoid resonance at the range of operations for hydro machinery.

Chapter 2

Basic Theory

2.1 Vortex Shedding and Vortex Induced Vibrations

Von Kármán vortex street, or vortex shedding, are one of the most known coherent structures in turbulence. Vortex shedding are large scale motions that appears in a flow over a bluff body as a result of separation at trailing edge. The motions can be described as oscillating vortices that develops downstream of the bluff body. Flow separation on the body surface at low Reynolds number will not cause any instabilities, but if the Reynolds number increases above its critical value, there will be unsteady wake motion down stream, i.e. vortex shedding. The critical Reynolds number is about $Re = 40$, according to Baker (2016). The none dimensional number describing this flow behaviour is the Strouhal number (equation 2.1). This number is a result of experiments on vortex shedding, done by the Czech physicist Vincenc Strouhal, in 1878.

$$f_s = St\frac{U_\infty}{L} \tag{2.1}$$

Here f_s is the vortex shedding frequency, St is the Strouhal number, U_∞ is the free stream velocity and L is the characteristic length. This non-dimensional relationship can help us predict a theoretical shedding frequency, by setting the other values based on former experiments and the geometry of the bluff body. For a smooth cylinder, the Strouhal number is about 0.20 (Sarpkaya, 1979).

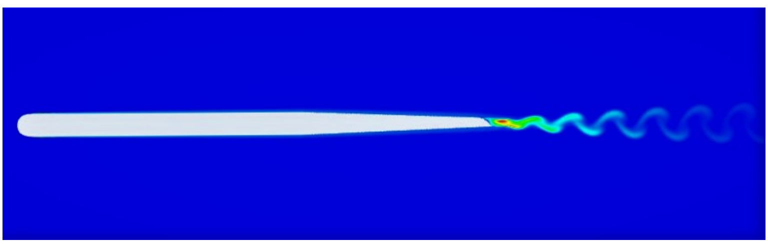


Figure 2.1: Contour of turbulent kinetic energy of a hydrofoil that is experiencing vortex shedding

These alternating vortices will again cause vibrations on the bluff body, due to oscillating lift force acting on the aft section of the body. The oscillating lift forces comes from pressure differences that are experienced at the separation pints on the body, i.e. the pressure that is acting on the body is no longer symmetrical. If the body that are undergoing these asymmetrical pressure forces is free to move, it will start to oscillate. If the body is fixed it will start to vibrate. If these vibrations reaches the same frequency as the natural frequency of the bluff body, you will reach the lock-in state. This phenomena is called vortex induced vibrations or VIV for short, and is a highly investigated topic. It is relevant in many engineering applications, such as bridges, offshore installations, aviation, drilling and production risers in petroleum production and, as the topic of this thesis, in hydro power plants, to name a few. The ultimate objective of the research is the understanding and prevention of VIVs, preferably without drag increase (Sarpkaya, 2004).

The guide vanes in hydraulic turbines will experience VIVs. By mitigating these vibrations, one could avoid unnecessary fatigue and risk of failure. Sagmo et al. (2019) did PIV measurements and CFD simulations of a hydrofoil at lock-in conditions to investigate the shedding frequency and vibration caused by the vortex shedding. The most critical situation is when the shedding frequency overlaps the natural frequency of the hydrofoil, causing strong vibrations and high risk of fatigue. By knowing at which inlet conditions these frequencies overlap, it can be easier to avoid that happening. Using trailing edge modifications to mitigate the VIVs through the interference region with the natural frequency can also be a solution, and in this thesis the use of splitter plates at trailing edge will be investigated.

2.2 Splitter Plates

Splitter plates are a passive control device used to reduce the strength of the vortex shedding, and hence reduce VIV and drag forces. Splitter plates are thin plates that is either attached to the trailing edge of a bluff body, shown in figure 2.2, or placed some length downstream of the body. The geometry of the splitter plates varies, and different length and thickness will give different results. The idea is that the plate shall split up the vortex motions down stream so that they decay. Studies have showed that if the splitter plate is long enough, the vortex shedding will be canceled out in scale with the bluff body. There will always be shedding on scale with the plate thickness, but the forces are obviously a lot weaker since this is a much smaller scale. Studies have showed that splitter plates is very effective when used on cylinders, and some of the studies are reviewed in section 3.1.

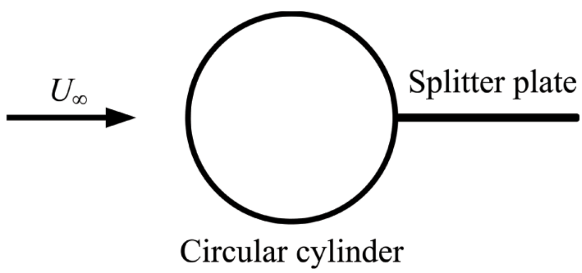


Figure 2.2: Splitter plate attached to cylinder

2.3 Particle Image Velocimetry

Particle Image Velocimetry (PIV) is a method of measuring the velocity field of a flow, and will give instantaneous velocity measurements in the cross-section of a flow. The technique works by sending flow following particles in the flow, and their motion are used to estimate the local fluid kinematics. The particles are chosen to be neutrally buoyant and efficiently scatter light. To measure the motion of the particles a shed of light is used, and a the particles are recorded with a camera. By knowing the time between every picture of the flow, the velocities of the particles can be obtained, and hence the velocity field of the flow. The recording parameters must be chosen so they give good spatial separation of the images, to ensure accurate results. The light shed that illuminates the flow is usually provided by a laser. The laser beam is shaped in to a planar sheet with using lenses. Other methods can also be used to provide the illumination, but lasers are the most common according to Grant (1997). The reason why laser is convenient for use in PIV, is because many laser have the advantage of a pulsed output with a duration and repetition rate that can be coordinated with the closing time of the camera lens. An example of an experimental setup for PIV are shown in figure 2.3.

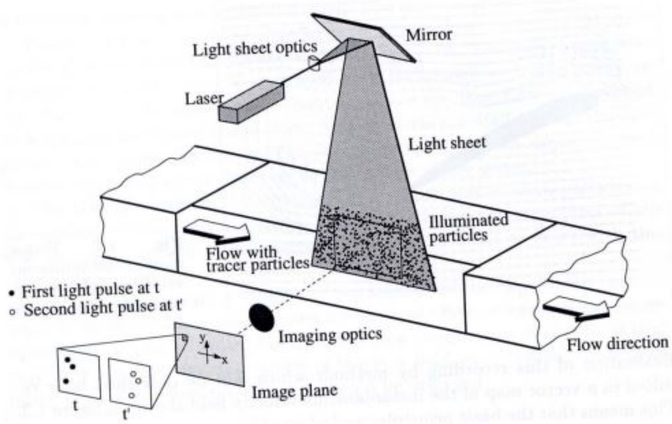


Figure 2.3: Example of experimental arrangement for planar 2D PIV in a wind tunnel (Raffel et al., 2018).

PIV have shown to be a very effective way of obtaining velocity fields in experiments. However, it is important to know how to calibrate the system correctly and how to avoid systematic errors, some important parameters will be described in the following sections.

2.3.1 Tracer Particles

The tracer particles are supposed to follow the flow perfectly, without changing the flow pattern in any way. Therefore these particles must be small, but they must also be big enough so they are possible to visualize. They must scatter the light from the illumination source efficiently. The density of the particles are chosen so they behave naturally buoyant, which mean that the density of the tracer particle must be close to the density of the fluid of interest.

2.3.2 Interrogation Area

To analyse the recorded images they must be split up in smaller areas, shown in figure 2.4. These areas are called interrogation areas (IA). The interrogation areas must be large enough, so that most of the particles stays within the same area during one sampling. If the IA is to small, important information will be lost as the particles passes through the area without being recorded. Another concern that is important to take in to account when choosing the IA is that it must fit several tracer particles. A rule of thumb is that the IA should include 10-25 tracer particles (https://www.dantecdynamics.com/). The size of the IA is chosen after doing a test of the set-up.

To avoid that information from particles at the edges of the interrogation area is lost, the areas must overlap. Overlapping of IAs are shown in figure 2.4. The normal overlapping of interrogation areas are 50%, but here it is important to be aware of oversampling. Oversampling is a bias error source, which occur when velocity data are measured from the same particle.

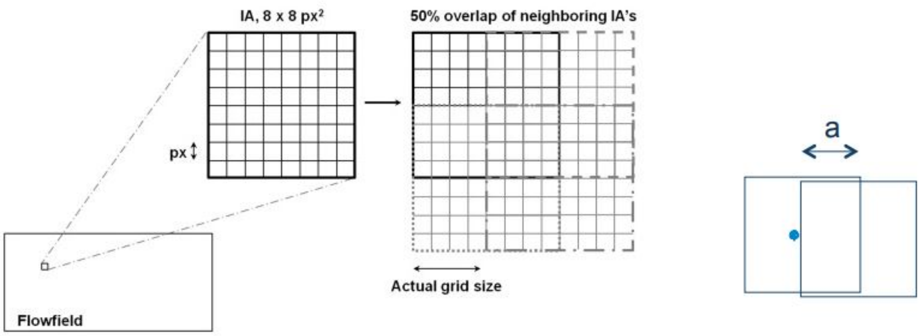


Figure 2.4: Left: Example of how the flow field is divided in interrogation area (Vergine and Maddalena, 2014). Right: Overlapping of two IAs.

2.3.3 Image Analysing Methods

In PIV there are several different methods for analysing the imagines. Young's fringe analysis method is a way of following "Young's fringes" to see their direction, and hence obtain velocity. The fringes can be found by illuminating image pairs so that they act as interfering point sources, and the transmitted light is then forming Young's fringes. Correlation methods are another way of analysing PIV imagines. Different correlation methods are *auto-correlation* and *cross-correlation*.

An auto-correlation equation, obtained from Fourier transform of the fringe pattern, produces three peaks that gives the displacement of particles between imagines. There is one peak at the origin, which is zero-order (self-correlation), and two first-order displacement peaks of plus and minus the displacements between particles (Grant, 1997). The velocity can then be measured from the distance between the center of the first- and second-order peaks. This gives a volume average of the velocity in the examined cell. Cross-correlation can be used in analysing single-famed, double- or multiple-exposure PIV imagines. By cross-correlating two images of the same area with a small time interval, the velocity field is obtained from the displacement of the illuminated particles.

2.3.4 Recording Methods and Camera Sensor

PIV recording methods are usually divided in two categories. The first is methods that capture the illuminated particles at multiple times in a single frame (single-frame/double- or milti-exposure), and the second is methods that provide a single image of the illuminated particles for each time of illumination (multi- or double-frame/single-exposure).

The most common camera sensors are CCD and CMOS, where CMOS are the state of the art design and is therefore the most reliable. CMOS sensors are able to produce much higher read-out rate which makes it a better choose, especially when it comes to high speed PIV.

2.3.5 Peak Locking

Peak-locking, also known as pixel-locking, is a well known bias error source when using PIV. To avoid significant errors due to this phenomena it is important to have a particle image diameter of minimum two pixels (Raffel et al., 2018). If the particle image diameter is to small, for example less than one pixel, the measurements will only be able to track particle movement from one pixel to another. This results in errors because all the particle displacements will fall under an integer amount of pixels, instead of the exact displacement. t

Chapter 3

Literature Review

3.1 Passive Flow Control with Splitter Plates

Kwon and Choi (1996) investigated the effect of using splitter plates in a flow over a cylinder at $Re = 80 - 160$. The study is comparing the results with splitter plates of different lengths, and a cylinder without a splitter plate. The vortex shedding to disappears when the length of the plate is above its critical length, l_c. This length, for example, was shown to be $l_c = 3d$ at $Re = 100$ and $l_c = 5d$ at $Re = 160$, where d is the diameter of the cylinder. Also the Strouhal number is decreasing with increasing plate length, with a local maximum at about $l/d = 2$. See **Fig. 3.1**. For cylinders, the characteristic length, L, in equation 2.1 is the diameter, d.

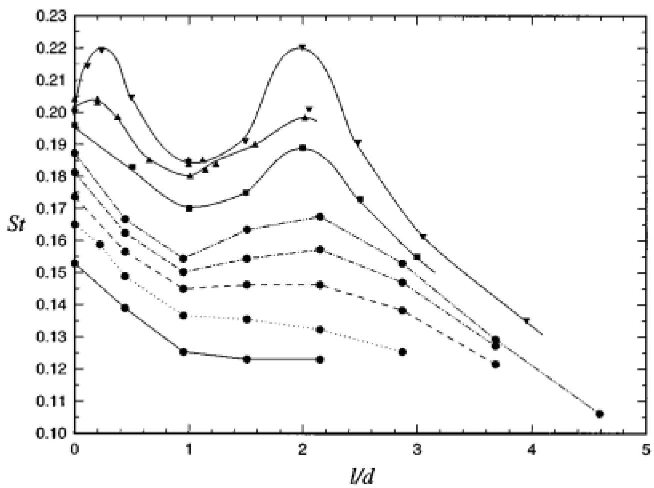


Figure 3.1: Variation of the Strouhal number with the length of the splitter plate: —, Re=80; ●●● , Re=100; —, Re=120; –●–, Re=140; -●●-, Re=160. (Kwon and Choi, 1996)

The splitter plate also had an effect on the drag forces acting on the cylinder. With increasing plate length, the time-averaged drag coefficient, $C_d = 2D/\rho u_\infty^2 d$, decreased. The skin friction drag reached its minimum when $l/d \approx 4.5$ (Kwon and Choi, 1996).

In another study carried out by Boisaubert and Texier (1998), the effect of using a splitter plate in the flow over a semi-circular cylinder, with flat side down stream, was investigated. The results in the experiment were obtained by using PIV measurements.

They used a semi-circular cylinder of dimensions $D = 8cm$ and $A = 5.20$, and tested with splitter plate positioned at different gaps ($g = 0.0D, 0.5D, 1D$), to precisely identify the near-wake modifications induced by the splitter plate. The splitter plate used was of length $L_{sp} = 1D$, and thickness of $0.5cm$. At Reynolds number $Re = 200$, they observed that the plate position of $g = 0.5D$ was best suited for near wake stabilization. For the attached splitter plate, the shedding takes place at $t^* = 8$, where t^* is a non-dimensional time unit. This is a delay of 100% compared to the semi-circular cylinder alone, where the shedding is taking place after $t^* = 4$. For $Re = 400$, the results show that the optimal positioning for the splitter plate is $g = 1D$. During the observation time, which was $t^* = 10$, no shedding occurred at this configuration, opposed to the other configurations where vortex shedding were observed at around $t^* = 8$. The study concludes that using splitter plates as passive control device on semi-circular cylinders have a good effect on delaying vortex shedding down stream. However the optimal position of the splitter plate is not the same for the different Reynolds numbers that were tested. It seems that as the flow regime increases, it is more sufficient to position the splitter plate further down stream.

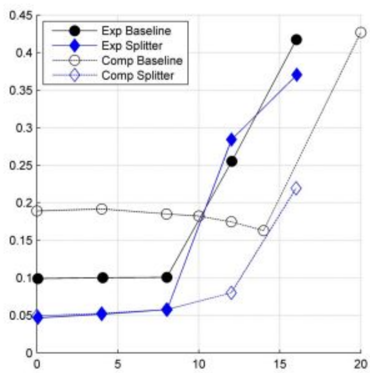
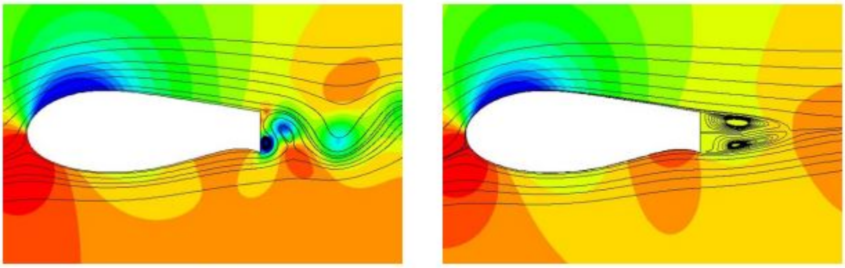


Figure 3.2: Comparison of drag for experiment and RANS computations, FB-3500- 1750 airfoil at Re = 666,000. (Baker and van Dam, 2008)

The effect of using splitter plates for drag reduction on a blunt trailing-edge airfoil was investigated in a study by Baker and van Dam (2008). Different edge treatments on the splitter plates were tested, at a chord based Reynolds number of 666,000. The Aeronautical Wind Tunnel (AWT) at the University of California were used as test rig, and the results were compared computational methods. The turbulence closure of the Reynolds-Averaged Navier-Stokes equations was provided by two equation $k - \omega$ SST model. For the case with splitter plate, the experimental and computational results matched very well in both lift and drag forces, but the baseline airfoil the drag forces does not agree very well when comparing experimental and computational. According to Baker and van Dam (2008), this is likely because of over-predicted strength from the vortices due to the artificial restriction of the flow to two-dimensions in the computational results. Looking away from the computational results of the baseline airfoil, both the experimental and computational results with slitter plate show a 50% reduction in drag, compared to the experimental results of the baseline airfoil, this is shown in **Fig. 3.2**. The drag reduction is likely to come from absence of the vortex shedding once the splitter plate is added to the airfoil, shown in **Fig. 3.3**.



(a) (b)

Figure 3.3: Calculated pressure contours with instantaneous streamlines for the FB-3500-1750 airfoil at Re = 666,000 with (a) no modifications, and (b) single splitter (Baker and van Dam, 2008)

Different types of splitter plates fitted on a blunt trailing edge airfoil have also been studied by Tanner (1975). Five different splitter plates were tested, and reduction of base drag was the goal of the research. The lengths of the splitter plates varied from $l/h = 1.05$ to $l/h = 2.38$, the thin plates had a thickness of $h_1/h = 0.14$ and the thicker ones had thickness of $h_1/h = 0.31$, where h is the trailing edge thickness of the airfoil, and l and h_1 are the lengths en thickness' of the splitter plates respectively. The best case was a splitter plate of length 2.38 and thickness 0.31, with a sharp trailing edge. Compared to the blunt trailing edge airfoil without splitter plate, this case had only about 24% of the base drag, at zero angle of attack. The thin and short splitter plate ($l/h = 0.5, h_1/h = 0.14$) also shown good results with base drag of 42% of the base section. Comparison of blunt and sharp trailing edged splitter plates shows that profiling of the trailing edge can give even better results.

More recently, other trailing edge modifications have been researched. When looking in to noise reduction on airfoils, trailing edge brushes have been tested. This could also have some value when looking in to reduction of vortex induced vibrations and vortex shedding, as two of four main noise source mechanisms for lifting airfoils comes from vortex shedding (Herr and Dobrzynski, 2005). Herr and Dobrzynski (2005) did experiments with trailing edge brushes in Aeroacoustic Wind Tunnel Braunschweig, which is an open-jet anechoic test facility. A flat plate model with a solid and thin trailing edge was used as reference, when a NACA 0012 was tested with brushes. The brush extensions at the trailing edge showed to be a promising device for trailing edge noise reduction, with a potential of 2 to 14 dB of edge noise reduction within a wide range of frequencies. The hypothesis for the reason of the noise reduction is that the brushes is damping turbulent flow pressure amplitudes. Jacob et al. (2010) did a similar study on a cambered NACA 62(12)-10 airfoil, in a small anechoic wind tunell facility at Ecole Centrale de Lyon (ECL). They could also detect a noise reduction due to the trailing edge brushes, for this type of airfoil. The noise reduction is explained by disorganization of turbulent structures before they radiate sound. A coherence study showed that the brush is reducing spanwise coherent structures, i.e. a reduction of turbulence production. Based on these two studies, it is reason to believe that using similar brushes at trailing edge will dampen the strength of the vortex shedding as well.

Most of the studies carried out on splitter plates uses relatively low Reynolds number, at least compared to the Reynolds number that is going to be used in the studies of this thesis. However, in a recent study by Dai et al. (2018), prediction of vortex shedding suppression from circular cylinders at high Reynolds number using base splitter plates was investigated with using three dimensional CFD calculations with OpenFoam software. The validation of the study was done by comparison with experimental data. The Reynolds number used in the numerical experiment was $Re = 1.8 * 10^5$, with splitter plate lengths between $0 < l/D < 1.25$, where l and D are plate length and cylinder diameter respectively. Looking at the different forces acting on the cylinder, one can determine if the vortex shedding is mitigated. Hence, when fluctuating lift and drag forces are reduced, the explanation is that the vortex shedding is suppressed. This study found that the ideal splitter plate length to cylinder diameter ratio was 0.66. At this length the fluctuating lift coefficient reached its minimum, yielding a reduction of 30%, compared to the reference case without splitter plate.

As seen above, splitter plates and other trailing edge modifications have shown to give promising results in drag reduction for flows over different types of bluff bodies. It is evident that most of the drag reduction comes from the reduction of vortex shedding down stream. All of the papers that have been reviewed in this section are using air as the ambient fluid and most of them are also using fairly low Reynolds numbers. In this thesis the ambient fluid will be liquid water, and the chord based Reynolds number is going to be much higher compared to most of these studies. Therefore it is difficult to know how well the splitter plates will work in this project, but it is none the less an interesting topic.

Chapter 4

Design Proposal of Experiment

4.1 Trailing Edge Designs

Based on literature studies, a design proposal of the hydrofoil fitted with splitter plate must be conducted. There are different approaches that can be used to make a ”qualified guess” of a design that will give good results. With looking at results from previous studies of similar cases, and how the design can be made efficient for testing different parameters of the splitter plate, e.g. various lengths. A design that makes it possible to change only the splitter plate, while the hydrofoil is in the test rig would be ideal and will possibly save a lot of time.

The test hydrofoil contains of a foil body, and a trailing edge tip that can be removed. The trailing edge tip is the one that can be modified and changed. To change the trailing edge, the whole foil needs to be removed from the test rig, and the trailing edge must be removed and a new one needs to be attached with glue. This whole process takes about 4-6 days, and to save time it would be best to find a solution for changing only the splitter plate without taking the trailing edge part off. Figure 4.1 shows a exploded view of the trailing edge tip with splitter plate, and the foil body.

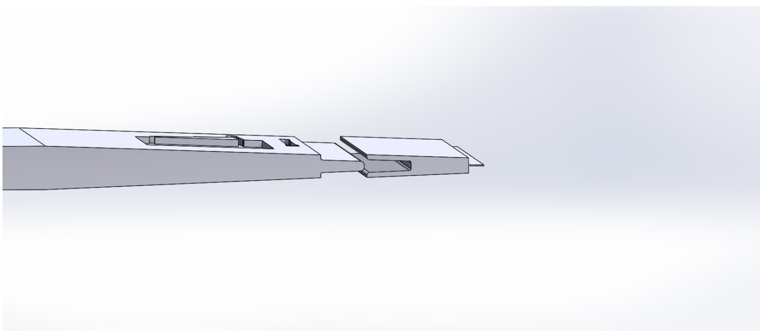


Figure 4.1: Exploded view of foil body and trailing edge tip with splitter plate

The solution to this can be to make the trailing edge part with a slit, where the splitter plates can be attached in and removed from without having to remove the whole trailing edge tip. Figure 4.2 shows a proposed design of how this trailing edge tip would look. The idea with this design is that the splitter plate is attached to the slit by using glue. The glue that will be used is a type that loosens when heated above a certain temperature. In this way, different types of splitter plates can be tested without having to remove the whole test section from its set-up.

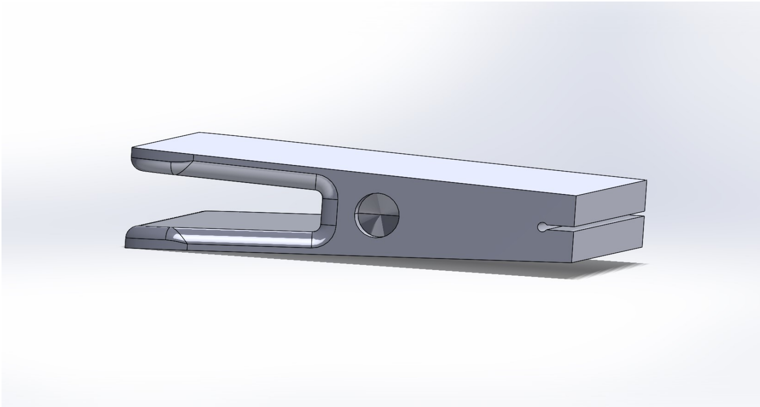


Figure 4.2: Trailing edge tip with slit to attach splitter plates

The reason for the circular section at the end of the slit is to have the possibility to attach splitter plates of softer material without the use of glue. By creating an interference fit between the slit and the splitter plate, changing splitter plates of soft material would be even faster.

4.2 Splitter Plate Design

Given that the trailing edge with slit works, there will be time to test several different splitter plates. The plan is to test a stiff splitter made in either aluminum or a rigid polymer. The plate shall have a rectangular shape, and a thickness of $t = 0.5mm$. The length of the splitter is the parameter that is going to be changed to see the effect. Splitter plate length will be described as the ratio of plate length l_s and the trailing edge thickness t_e. The trailing edge thickness for the hydrofoil that is investigated is $t_e = 4.2mm$.

From section 3.1, the study by Dai et al. (2018) resulted in a best case result with plate length of $l_s/D = 0.66$. This is the study with operating Reynolds number closest to what is going to be the case for this thesis, and therefore it would be interesting to see if this plate length will be effective for a hydrofoil as well. Using the trailing edge thickness instead of diameter will then give splitter plate length $l_s/t_e = 0.66$ which gives $l_s = 2.772mm$.

Tanner (1975) tested splitter plates on blunt trailing edge airfoils, which is similar to the case of this thesis, only that the fluid here is water. Anyways, the results should be transferable, and the best case of that study was with a plate length of $l_s/t_e = 2.38$. Therefor this length would also be interesting to investigate.

In the study by Kwon and Choi (1996), it was found that a plate length of five diameters fully suppressed the vortex shedding on cylinder scale (there will still be shedding on scale of splitter plate thickness) at a Reynolds number of 160. Even though the Reynolds number

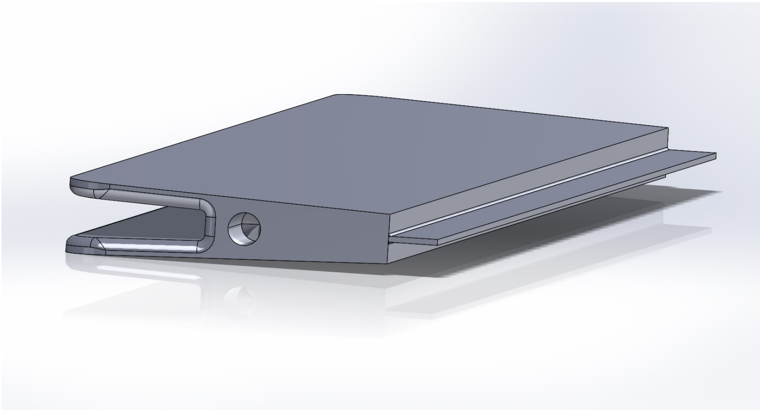


Figure 4.3: Trailing edge tip with splitter plate of length $l_s/t_e = 1$

for this experiment will be much higher, it is attractive to test the same plate length (i.e $l_s/t_e = 5$) to see if the shedding would be fully suppressed on t_e - scale.

As a reference case, a splitter plate of length $l_s/t_e = 1$ will be used. A model of the trailing edge tip with this splitter plate is shown in figure 4.3

The different designs described above are all planned to be fixed and rigid, made in either steel or aluminium. With a stiff splitter plate like this, there can be some problems when using on guide vanes in hydro machinery. The reason for that is because the guide vanes should be able to fully close off the water flow through the turbine (figure 4.4), and the splitter plate would may prevent that. Therefore it is interesting to test out how a more flexible material would work, and if that could give the same results. A more flexible material, like rubber, would not prevent the guide vanes from closing off the water flow and for that reason it would be more suitable for use in hydro machinery.

As mentioned in section 4.1, the use of rubber plates are also an advantage when doing the experiments. Making a interference pass between the slit in the trailing edge tip and the rubber plate will make it possible to change splitter plates without using glue to make it stick. This can save valuable time in a testing process that can be time consuming. It is hard to say how well a flexible splitter like this would work, since there are not a lot of literature on it. But for the reasons described above, it is something that should be tested out.

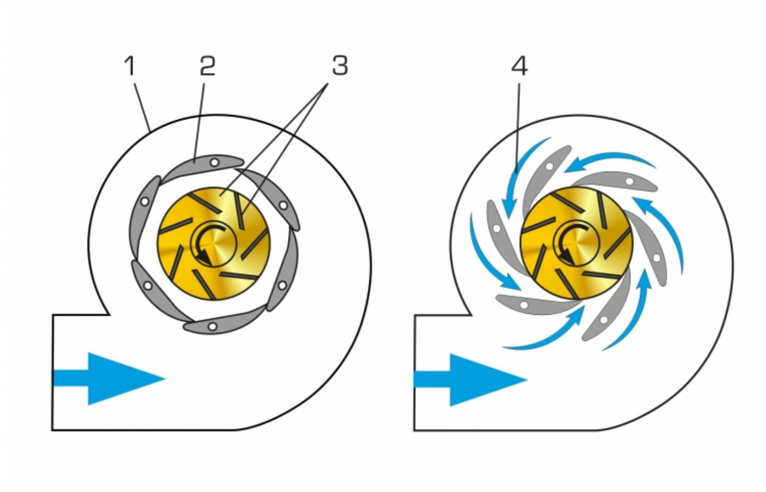


Figure 4.4: Illustration of open and closed guide vanes (2) in a Francis turbine. Right: closed, left: open. (https://www.gunt.de/)

4.2.1 Splitter Plate Thickness

The thickness of the splitter plate should be significantly less than the thickness of the trailing edge of the hydrofoil to be able to reduce the VIV. If the splitter plate is to thick, the vortex shedding induced from the trailing edge of it will be similar to what the hydrofoil would experience without the plate. Then the splitter plate would work only as an extension of the hydrofoil. But on the other hand, the splitter plate must be strong enough to resist the forces that are acting on it. To calculate the forces that the splitter plate will experience is a very complicated matter, since there are many factors involved. Therefore it is only done calculations on how much force the splitter plate will tolerate, and then assumed that the forces from the flow will not surpass this.

To make a rough estimate on how much forces the splitter plate can resist, some simplified calculations are conducted. Say the plate is a cantilever beam in two dimensions (i.e with width of $b = 1mm$), using the yield strength of the used aluminium alloy $\sigma_y \approx 440MPa$. This gives a bending moment of $M_y = 1833.33Nmm$ when using a thickness of $h = 5mm$, from equation 4.1. The moment of the inertia in two dimensions is $I_y = 10.42mm^4$ and the modulus of elasticity is $E = 72GPa$, so for a splitter plate of length $l_s/t_e = 1$, the deflection (w) that leads to yield in the material is $w_{max} = 0.015mm$, using equation 4.2. The deflection is not very large, but this is a very strong aluminum alloy, and it would require a lot of vibration forces to reach the yielding momentum. It is therefore unlikely that the splitter plate will break with a thickness of $t = 5mm$.

$$M_y = \frac{1}{6}bh^2 * \sigma_y \tag{4.1}$$

$$w_{max} = \frac{M_y L^2}{3EI} \tag{4.2}$$

Equation 4.2 comes from the Euler-Bernoulli beam theory, and the equation 4.1 that gives the bending moment is derived from internal equilibrium in the beam. The properties used in the calculations are obtained from https://gleich.de/en/products/certal-spc/, and applies for the aluminum alloy that will be used in the experiments. The calculations preformed above gives a very rough estimate, but it gives an idea of the forces the splitter plate are able to sustain.

4.3 Manufacturing

The trailing edge tip with splitter plate must be manufactured in order to do experiments with them. The plan is to produce a trailing edge tip with slit, showed in figure 4.2, and then produce splitter plates of different lengths and material that can be mounted directly in the slit. To produce the parts for the experiments, there are two options, they can either be 3D printed or machined. Both methods have their strengths and weaknesses, and these will be discussed in the following two sections.

4.3.1 Machining

The first option is to machine the parts in solid aluminum. The foil body and the reference hydrofoil tested by Sagmo et al. (2019) are produced this way, and therefore this would be the ideal method when comparing the results. This is because the natural frequency will be more or less the same as in the reference case, which will make it easier to see how the splitter plate is affecting the vibrations in the hydro foil.

On the other hand, if the trailing edge tip is to be machined, this is a job that has to be done by a company independent of the university. This job is quite costly in terms of time and money, and will therefore limit how many different splitter plates that can be made. Another thing that can make it challenging to machine the trailing edge tip is the geometry. There are two options, either make several different parts with different plate lengths, or to make one part with a slit. As described earlier, the preferable way to do it is to make one part with a slit. The circular section at the end of the slit (see figure 4.2) are advanced to machine, since it can not be done with milling.

Yet, there is an optional way to do this without involving an independent company in the machining process. Since there are an available unmodified trailing edge tip (like the one showed in figure 4.2 only without the slit) that can be used. By making the slit strictly rectangular, which means it can be milled out with a thin milling tool, it can be done at the workshop in the Waterpower laboratory. This will reduce cost and there will be less uncertainties about when the part will be finished, since it can be done locally. The inconvenience of this practice is that all the different splitter plate types needs to be glued in place, and therefore it will take a bit more time when testing the rubber plates.

Machining the trailing edge tip and the splitter plate as one part is also an approach that can be used. Anyways, this is a challenging one since the plate is supposed to be quite thin ($0.5mm$). When milling out the plate, it is a risk that it can start to vibrate. To avoid vibration when milling the plate, it must be affixed properly. This is possible to do, but can sure be difficult.

To do the experiments with the trailing edge in aluminium is the best practice when comparing the results to the reference case of Sagmo et al. (2019), but it can be somewhat challenging to machine. The other approach is 3D printing, which will be discussed in the following section.

4.3.2 3D Printing

To produce the trailing edge part with a 3D printer is the most efficient way of doing it. This can be done with a 3D-printer at the university, and can possibly save some time. This means that it is possible to make more different parts, and the effect of changing plate lengths can be detected in the experiments. The ability to make the slit as in figure 4.2 more precisely will make changing between plates go more seamlessly, when using rubber plates.

The downside of using 3D-printing is that the trailing edge will then be made in a material of different characteristics than aluminum. As mentioned earlier, this will probably affect the natural frequency, and this can make the experiments hard to validate.

A possible way of solving the validation problem when basing the experiments on 3D printed trailing edge parts is to make one part in aluminum to compare the natural frequency. For example machining one part with a splitter of length $l_s/t_e = 1$, and run the experiment with this. After that the results can be compared to an experiment done with the 3D printed trailing edge with a splitter of same length, and see how much the natural frequency is affected. The results from this can then be used as guidance and validation when running tests on 3D printed trailing edge with different splitter plate lengths.

4.3.3 Conclusion of manufacturing process

After weighing pros and cons of the different manufacturing options against each other, the one that seems like a best choose is to mill a rectangular slit in the trailing edge tip that is available at the laboratory already. It is also confirmed that they have small enough tools to mill out a slit of correct size at the work shop. The milling process will be a challenge since the tool is very small, and aluminium is a soft material that can stick to the tool so it breaks. To avoid this, the milling process must be done with ease.

The plates that will be used must be ordered. The material of the plates will be either aluminium or stainless steal, and rubber. The preferred material of stainless steal and aluminium are aluminium when considering what will give the best test results. This is again a matter of keeping the whole test section in the same material, to avoid influencing the natural frequency. The advantage of using steel is that steel is a stronger material, so it will be easier to handle without breaking it when doing the experiments. The different materials needs to be ordered in sheets or plates of the correct thickness, i.e. 0.5 mm. Then these plates are to be cut in the dimensions that the different splitter plates shall have. This can be done in different ways, but the method that will give best accuracy will be to use a laser cutter.

Since there will be no option to make the slit with a circular section, both the aluminium and rubber plates needs to be glued in place. This makes the process a bit slower, but the natural frequency will not be affected as it would with a 3D printed trailing edge tip. In other words, it is considered more important to sustain the natural frequency of the hydrofoil at similar level as the reference case in order to get more comparable results, than it is to save some time. Figure 4.5 shows an exploded view of the different trailing edge parts that will be used. As one can see, the only thing on this design that needs to be changed to get different test parameters is the splitter plate, fig. 4.5 c).

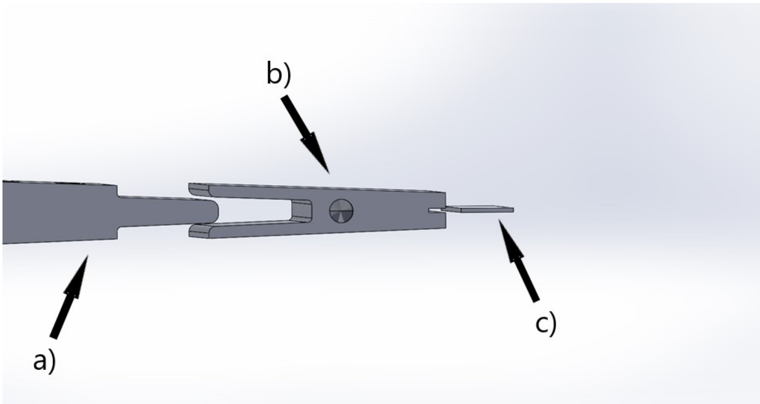


Figure 4.5: Illustration of different parts at trailing edge showing a) foil body, b) trailing edge tip with rectangular slit, and c) splitter plate

Chapter 5

Measurement Activities

The measurement campaign that is to be completed in the master thesis following this project thesis is going to done by using PIV (explained in section 2.3). The vibrations in the hydrofoil will be detected by a strain-gauge. Depending on how much time the experimental measurements will consume, there may also be conducted numerical studies of the case using CFD. If the CFD calculations are successful, they can be used as validation of the experimental results.

5.1 Experimental Setup

The PIV and frequency measurement setup will be similar to what was used by Sagmo et al. (2019). An illustration of the layout of the experiment can be found in figure 5.1. The hydrofoil in the test section will be aligned with the incoming flow, giving zero degrees angle of attack. An ABB electromagnetic flow-meter placed down stream of the test section will measure the volumetric flow rate.

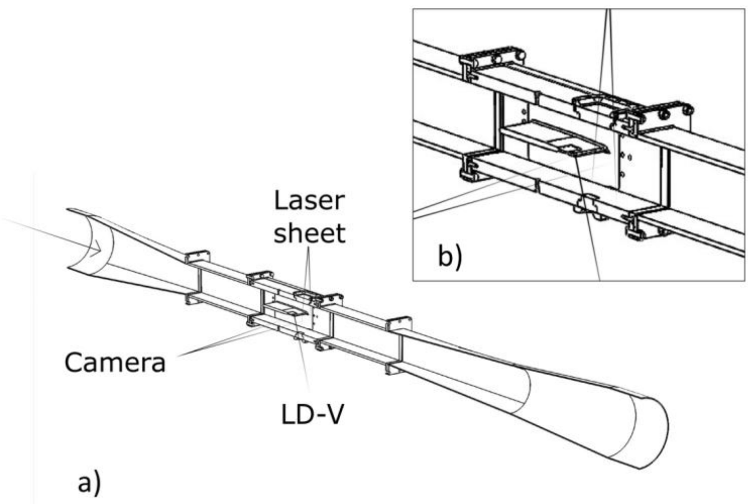


Figure 5.1: Section view of the experimental test setup. b) gives an enlarged view of the rectangular test section and positioning of the hydrofoil. (Sagmo et al., 2019)

The velocity field will be calculated in 2D using PIV measurements with a high speed system that is provided by LaVision GmbH. The system consist of a laser that provides illumination of the flow through a laser sheet, a camera that records the flow and a software used to calculate the flow field from the recorded pictures. The optimal positioning of the laser in a 2D PIV system is so that the laser sheet is parallel to the biggest velocity component of the observed flow field (V_{max} is in-plane). Then the camera is placed so the viewing direction is perpendicular to the laser sheet. This is important to keep systematic errors in the measurements as small as possible.

Table 5.1: PIV recording parameters for the hydrofoil wake flow measurements (Sagmo et al., 2019)

Field of view (FOV) / Area of interest	21.1 mm x 16.9 mm / 1280 px x 1024 px (x-y)
Interrogation volume / Interrogation area	1.06 mm x 1.06 mm x 0.5 mm / 64 px x 64 px (x-y)
Experimental velocity range	(8 - 14) m/s
Observation distance & Lens F-number	215 mm & 5.4
Recording method & Camera sensor	Double frame/Double exposure & CMOS
Exposure time & image acquisition rate	250 μs & 2.4 kHz
Image processing mode	cross-correlation
Mean tracer particle diameter d_p	13 μm
Tracer particle density δ_p	$1.1g/cm^3$
Illumination source	Nd:YFL dual cavity laser, 527 nm wavelength

Table 5.1 shows the different recording parameters of the hydrofoil wake flow measurements in the experiment by Sagmo et al. (2019). This is from the same test rig which will be used when doing the PIV measurements of the hydrofoil with splitter plate as well, and the recording parameters will be similar. There may be some small changes in in some of the parameters, e.g. field of view or observation distance.

On the hydrofoil surface, near the trailing edge at approximately mid-span, there will be a strain gauge that will measure vibration frequencies and amplitudes together with a laser doppler vibrometer (LD-V) pointing trailing edge.

5.1.1 Discussion of Experimental Setup

The density of the tracer particles is $\delta_p = 1.1g/cm^3$, which will make them naturally buoyant in water. The size of the particles are chosen from different factors, but they must at least be big enough to reflect the illumination.

First of all the tracer particles must be big enough so that peak-locking is avoided. The recording parameters presented in table 5.1 gives a particle image diameter of about 2.4 pixels (Sagmo et al., 2019), which satisfy the condition of minimum two pixels (presented in section 2.3).

The interrogation area must also be set correctly in order to get good results. The IA is usually defined after doing tests of the set-up. The average number of particles in each interrogation area is 10 from the parameters in table 5.1, which satisfy the rule of thumb that are described in section 2.3. The interrogation areas must be overlapped so that particles on the edges are recorded. The commonly used overlap value is 50%, but Sagmo et al. (2019) used 75% in his studies. When overlapping is high, there is a risk of oversampling. Oversampling results in neighboring data to be biased in similar degree, because the velocity data are estimated from the same particle. But by using an advanced processing schemes oversampling can be avoided Raffel et al. (2018). Sagmo himself tested both with 50% overlap and 75% overlap, and noticed that there was no oversampling of significance.

The recording method is double frame/double exposure, which is when the illuminated particles are captured at two times and put in to two frames. Then the displacement in of the particles in the two frames from each time is cross-correlated to calculate the velocity. The camera sensor is CMOS, which is the state of the art sensor described in sec. 2.3.

5.1.2 Experiment Execution

The experiments that will be executed at the Waterpower laboratory described above, will be a time consuming process. Therefore it is important that the process is well planned, so that unexpected events are avoided as much as possible. The design is made to be as efficient as possible when testing plates of different parameters, while at the same time does not affect the experimental results. To obtain the full potential of the experiments, there are a couple of things that needs to be taken in to consideration. First of all, it is critical to be careful when changing between different splitter plates. Since the plates are supposed to be connected to the foil with using glue, it is essential that all left over glue from previous tests are removed before attaching the new splitter plate. If not, the old glue will make the slit uneven, so that the next splitter plate that are attached will not fit correctly and this will again affect the results. Another factor that is important to get good results is to make sure that the splitter plate are affixed so that is orthogonal to the trailing edge. With tiny parts this can be difficult, but if the slit is deep enough in to the trailing edge tip it should not be a problem. With a slit depth of $3mm$ this problem will be solved, without having difficulties removing the splitter plate after the test is done (if the slit is too deep, it can be hard to take the splitter of because of the glue).

All the equipment and and material that are needed for the experiment will have to be ordered well ahead of when the testing is planned to start, so that there are no delays caused by equipment or material that has not arrived. This must be communicated to the people that work at the work shop, so that they are able to order what is needed for the experiments.

Chapter 6

Conclusion and Further Work

6.1 Conclusion/ Discussion

In this project thesis, the measurement campaign using PIV of a flow over a hydrofoil fitted with a splitter plate have been planed. Based on literature studies and theory, a design proposal of the trailing edge tip and splitter plates have been presented. The factors that was considered most critical in the design proposal were the material, i.e. how the natural frequency is affected, and how to make it efficient when preforming the experiments. The Design that was found to be the best alternative is the one shown i figure 4.5, based on the criteria that was considered most demanding. The trailing edge tip will be manufactured without the slit, so the slit needs to be milled out at the local work shop at the Waterpower laboratory at NTNU. This is a delicate matter, since the slit is supposed to be only $0.5mm$ which requires a small tool. Milling in aluminum can be challenging, since the material is soft and can easily stick to the tool which will cause the tool of breaking. Therefore this process must be done by taking very small cuts at a time. There are uncertainties on weather this is doable or not, but hopefully it will go as planned, otherwise it has to be figured out another way to doing this. The material for the splitter plates will be ordered in correct thickness, so the remaining to get those ready are to cut out the correct shapes giving plates of different lengths. The aluminium plates that are to be used should ideally be of the same alloy as the rest of the hydrofoil so the natural frequency is unaffected. By having the same alloy of aluminium over the entire test section it is also easier to do CFD simulations, because then it is no need to specify different materials in the different parts of the assembly. Using aluminium of a different alloy is also fine, but then there are a bit more uncertainties on if or how much the frequency is changed. The rubber plates will obviously affect the natural frequency a bit, since it is not aluminum, but the results from experiments with them are still interesting in regards of use in hydro power (as described in section 4.2).

Another remark that needs to be made when comparing the proposed trailing edge design with the reference trailing edge design studied by Sagmo et al. (2019) is the curvature that can be seen at the reference trailing edge. Figure 6.1 shows a comparison of the two designs. It is reason to believe that the flow will behave differently when passing a curved trailing edge (fig. 6.1 a)) compared to a sharp one (fig. 6.1 b)). But the reason for using a sharp trailing edge is to be able to predict exactly where the separation point will be, which is more difficult when using a curved surface.

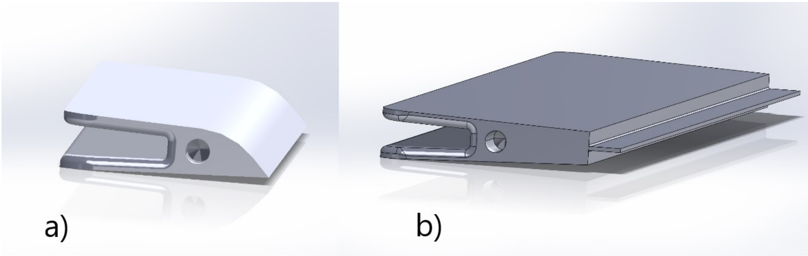


Figure 6.1: Comparison of trailing edge design where a) is the reference trailing edge design, and b) is the design with splitter plate

6.2 Further Work

Since this project work have been a design of experiment, the further work that will be done is evidently to carry out the experiments that are planned. The different parts of the design will hopefully be ready as soon as possible, so the testing and PIV measurements can start. As discussed earlier, this can be a time consuming process. So it is an advantage to get started as early as possible to be able to test several different splitter plate lengths. If the PIV measurements goes as planned, and there are available time it could also be interesting to do CFD simulations of the test section. The possibility of using CFD will be discussed in the following section.

6.2.1 CFD

CFD or computational fluid dynamics can be a useful tool as well in this project. Depending on how much time the experimental studies will take, it is possible that there will be done some CFD as well. If done correctly, this can be used as validation of the experimental results, and vice versa. Anyways, when using CFD it is important to know how the tool works, and the user needs to be critical of the obtained results. A CFD study of this case can be conducted in two dimensions, which means you can save a lot of computational time compared to a case where three dimensions needs to be included. To get accurate results, a mesh of high quality must be generated. At the trailing edge of the hydrofoil that is to be investigated, there are sharp corners that can make meshing in these sections difficult. Also, since the simulations needs to be transient, the time step needs to be taken in to consideration. With a fine mesh, there is need to have a fairly small time step, which again will result in high computational cost.

If CFD are to be used, it must be used sufficient to get reliable results. Therefore it is necessary to put a good amount of time and effort in to it, or else it will not benefit the study at all.

Bibliography

Baker, J.P., van Dam, C.P., 2008. Drag reduction of blunt trailing-edge airfoils, in: BBAA VI International Colloquium on: Bluff Bodies Aerodynamics & Applications, Milano, Italy.

Baker, R.C., 2016. Flow Measurement Handbook. Cambridge University Press.

Boisaubert, N., Texier, A., 1998. Effect of a splitter plate on the near-wake development of a semi-circular cylinder. Experimental Thermal and Fluid Science 16, 100–111.

Dai, S., Younis, B.A., Zhang, H., Guo, G., 2018. Prediction of vortex shedding suppression from circular cylinders at high reynolds number using base splitter plates. Journal of Wind Engineering & Industrial Aerodynamics 182, 115–127.

Grant, I., 1997. Particle image velocimetry: A review. Journal of Mechanical Engineering Science 211, 55–76.

Herr, M., Dobrzynski, W., 2005. Experimental investigations in low-noise trailing-edge design. AIAA Journal 43, 1167–1175.

https://gleich.de/en/products/certal-spc/, . datasheet central spc. `https://gleich.de/en/products/certal-spc/`. Accessed: 2019-12-17.

https://www.dantecdynamics.com/, . Measurement principles of piv. `https://www.dantecdynamics.com/solutions-applications/solutions/fluid-mechanics/particle-image-velocimetry-piv/measurement-principles-of-piv/`. Accessed: 2019-12-15.

https://www.gunt.de/, . Hm 150.20 operating principle of a francis turbine. `https://www.gunt.de/en/products/2e-energy/hydropower-and-ocean-energy/operating-principle-of-a-francis-turbine/070.15020/hm150-20/glct-1:pa-148:ca-671:pr-567`. Accessed: 2019-12-07.

Jacob, M.C., Finez, A., Jondeau, E., Roger, M., 2010. Broadband noise reduction with trailing edge brushes, in: 16th AIAA/CEAS Aeroacoustics Conference, Stockholm, Sweden.

Kwon, K., Choi, H., 1996. Control of laminar vortex shedding behind a circular cylinder using splitter plates. Physics of Fluids 8, 479–486.

Raffel, M., Willert, C.E., Fulivo, S., Kähler, C.J., Wereley, A.T., Kompenhans, J., 2018. Particle Image Velocimetry: A Practical Guide 3rd ed. Springer.

Sagmo, K.F., Tengs, E.O., Bergan, C.W., Storli, P.T., 2019. PIV measurements and CFD simulations of a hydrofoil at lock-in. IOP Conference Series: Earth and Environmental Science 240, 1755–1315.

Sarpkaya, T., 1979. Vortex-induced oscillations: A selective review. JOURNAL OF APPLIED MECHANICS 46, 241–258.

Sarpkaya, T., 2004. A critical review of the intrinsic nature of vortex-induced vibrations. Journal of Fluids and Structures 19, 389–447.

Tanner, M., 1975. Reduction of base drag. Progress in Aerospace Sciences 16, 369–384.

Vergine, F., Maddalena, L., 2014. Stereoscopic particle image velocimetry measurements of supersonic, turbulent, and interacting streamwise vortices: challenges and application. Progress in Aerospace Sciences 66, 1–16.

NTNU – Trondheim
Norwegian University of
Science and Technology