

Experimental investigation of airship aerodynamics

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Abstract

The UCL iMMC-TFL group is involved in the Flywin project which the aim is to build a 15 [m] long demonstrator of a large cargo airship. Our thesis is to design an experimental setup in order to measure - in the small wind tunnel of the UCL iMMC-LEFT laboratory - the aerodynamic properties of a scaled down model of the demonstrator airship. The study is structured in several steps. The first one is to design a scaled down model and its attachments relative to the test section. The second is to perform tests on the model in wind tunnel for both small and large angles of attack and of side-slip. Tests on the fins aerodynamics will also be performed. Some of our results will be compared with aerodynamic models from the literature. Last step is to use Particle Image Velocymetry to visualise the flow around our model.

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Nomenclature

α	Angle of attack in pitch	$[\circ]$
$\bar{c}$	Mean chord	$[m]$
β	Angle of attack in yaw	$[\circ]$
η	Efficiency factor of the hull	$[-]$
μ	dynamic viscosity of the air	$[Pa.s]$
ρ	Density of the upstream flow	$[kg.m^{-3}]$
C_D	drag coefficient	$[-]$
C_F	Friction drag coefficient	$[-]$
C_L	Lift coefficient	$[-]$
C_p	Pressure coefficient	$[-]$
C_Q	Side force coefficient	$[-]$
D	drag force	$[N]$
L	lift force	$[N]$
l	Rolling moment	$[Nm]$
L_a	Length of the airship model	$[m]$
m	Pitching moment	$[Nm]$
n	Yawing moment	$[Nm]$
p_∞	Static pressure of the free stream	$[P_a]$
Q	Side force	$[N]$
q	dynamic flow pressure	$[P_a]$
$Re_{\bar{c}}$	Reynolds number based on mean chord $\bar{c}$	$[-]$
Re_D	Reynolds number based on diameter D	$[-]$
Re_{L_a}	Reynolds number based on L_a	$[-]$
Re_V	Reynolds number based on $V^{1/3}$	$[-]$
S	Reference surface	$[m^2]$
Str	dimensionless Strouhal number	$[-]$
u	Component of the local flow velocity in the x direction	$[m.s^{-1}]$
U_∞	Component of the upstream flow velocity in the x direction	$[m.s^{-1}]$
V	Volume of the airship (model)	$[m^3]$
v	Component of the local flow velocity in the y direction	$[m.s^{-1}]$
V_d	Volume of the airship (demonstrator)	$[m^3]$
w	Component of the local flow velocity in the z direction	$[m.s^{-1}]$

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Introduction

A brief history of the airship

A “lighter than air” airship is an aircraft, member of the aerostat family which has the essential characteristic of being of lower density than air. Its lift is assured by buoyancy according to the Archimedes’ principle. Airships are generally designed with an elongated aerodynamic shape. It has several appendices to allow its control, its propulsion as well as payload.

The idea of an airship was born directly after the creation of the first balloons in 1783 [15]. One of the major shortcomings of balloons is that they were unable to direct themselves. On December the 3rd the same year, Jean Baptiste Meusnier¹ presented to the French Academy a thesis called “Mémoire sur l’équilibre des machines aérostatiques” [16]. His thesis helped him to conceive a 80[m]-long elliptical balloon shown in figure 1. Unfortunately, the lack of funds and his premature death stopped the realization of his project.

Several concepts of airships have since been created, but the first man to manage to pilot an airship is Henri Giffard² in 1852. He used it during the racecourse between Paris and the city of Trappes for an equivalent distance of 27 [km]. Its 44 [m]-long airship presented in the figure 2, had a steam engine which operated a propeller positioned under the belly of the device. Henri Giffard reached a speed of 10 [km.h⁻¹], but could hardly fly with a sustained wind.

In 1872, Paul Haenlein³ piloted a semi-rigid-frame airship propelled by an internal combustion engine. However these engines were still too heavy, the lift was thus reduced and the range of the airship was limited. We have to wait until 1884 to get the first fully controlled free flight : “La France”. This airship is shown in the figure 3. The airship “La France” was constructed by Charles Renard and Arthur Krebs. Powered by electricity, “La France” carries out the first closed circuit course of about 7 [km].

In July 1900, the Luftschiff Zeppelin (abbreviated LZ1) designed by Fer-

¹ French mathematician and engineer. He is considered as one of the first inventor of the airship

² French researcher specialized in the field of air navigation

³ German engineer and flight pioneer

Ferdinand von Zeppelin⁴ made its first flight from a floating hangar on Lake Constance, near Friedrichshafen in southern Germany. This first Zeppelin LZ1 had a length of 128 [m] and was driven by two 14.2 horsepower Daimler engines. For its first trial, LZ1 carried five people, achieved an altitude of 410 [m] and crossed a distance of 6 [km] in 17 minutes. With many hardships, troubles and prototypes, Zeppelins began with civilian use in 1909 and before World War I a total of 21 Zeppelin airships had already been made. The German Army and Navy bought 14 Zeppelins and used them during World War I in support of fleet patrol to do some recognition and bombing operations. Under the direction of Paul Jaray, Zeppelins were also designed and built for commercial purposes, like the Hindenburg LZ129 or the Graf Zeppelin LZ127 (shown on figure 4) which made the first world tour in August 1929 including the first crossing of the Pacific: Tokyo-San Francisco non stop.

Several disasters will mark the history of the airships. These disasters were mainly due to the fact that the airship is sensitive to bad weather conditions, and that the gas used, hydrogen at the time, is highly flammable. Thus, in 1921, the semi-rigid “Roma” airship made in Italy and bought by the United States⁵ crashed during a test flight and was the last US airship to use hydrogen. In 1925, a rigid airship, the “Shenandoah” was the first one to use Helium instead of Hydrogen. It caught fire in flight and unfortunately caused fifteen deaths.

Becoming useless during the World War II, airships were replaced by planes at the end of the war. Those have therefore experienced considerable technical progress during this period, allowing the first commercial transatlantic flights in the 1950s, then the generalization of jetliners over long distances during the Glorious Thirty.

Since the 1990s, a new airship design has emerged : the hybrid airship. It combines the airship’s aerostatic lift from a “lighter than air”, with the “heavier than air” dynamic lift from the movement through the air. We can mention for example, the Lockheed Martin P-791 (figure 6), an hybrid airship which flew for the first time in 2006. It can easily travel to and from austere sites such as frigid Canadian mine sites, the Brazilian rain forest, Africa and China [17].

⁴ He was a German general and later aircraft manufacturer, who founded the famous Zeppelin airship company

⁵ United States also became interested in airships in the early 1920s

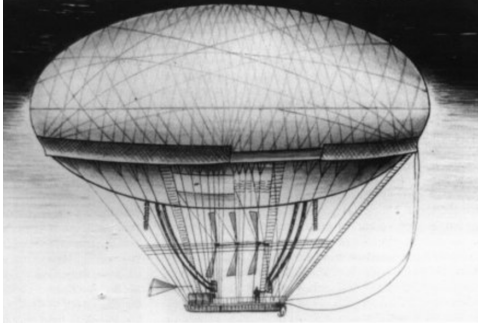


Figure 1: Meusnier's steerable hydrogen balloon-1783 [1]



Figure 2: Henri Giffard blimp-1852 [2]

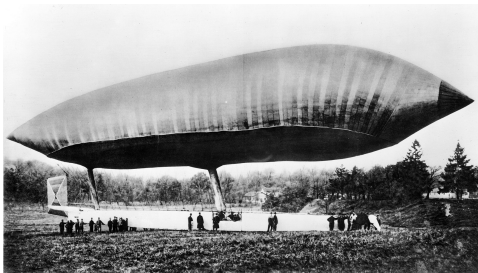


Figure 3: French dirigible "La France" - 1884 [3]



Figure 4: The giant German dirigible Graf Zeppelin, at Lakehurst, New Jersey - 1929 [3]



Figure 5: Zeppelin NT semi-rigid airship inflated with helium - 1997 [4]

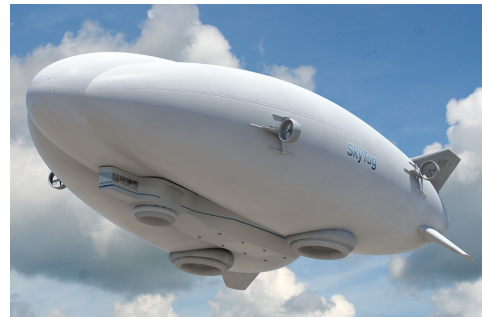


Figure 6: Lockheed Martin Hybrid Airship [5]

Motivation and goals of the study

Globalization has allowed man to travel and discover the world. This globalization is based on the speed of financial, informational or merchandises flows. The speed and the massification of these exchanges were facilitated by the modern civil aviation which opened our horizons.

The airplane is probably the most reliable, the fastest but also the most expensive mean of transport, its use remains mostly dependent on oil. Multiple issues such as climate change, rising energy prices, social equity, push us to

rethink our transportation lifestyle.

We are therefore facing a dead end: the speed of trade will only lead to the use of more resources and the pollution of our planet. Consequently, the dirigible balloon re-arouses the interest. New airship development projects emerge. It could allow freight and people to be transported putting less pressure on the planet resources than the jet. The airship offers the opportunity to use an energy mix of solar, hydrogen or hydrocarbons derivative such as the blue petroleum. It could be a serious alternative to protect the international exchanges. Modern technologies will hopefully make us forget the tragedies of its history.

In this context, the Flywin project aims to develop a semi-rigid airship drone for freight transportation. Associated to this research, the UCL iMMC-TFL group is responsible for the aerodynamic modelling and characterisation of a 15 m-long demonstrator of this cargo airship.

The task has been given to us to study the aerodynamics performances of the hull and the fins of this demonstrator. Therefore we have designed and conceived two main experimental setups allowing us to measure aerodynamic forces for the airship in different configurations.

The objective of our thesis is to experimentally measure in the small wind tunnel of the UCL iMMC-LEFT laboratory, the aerodynamic properties of a scaled down model of the demonstrator airship. Our experimentation has to be done for small and large angles of attack and of side slip; i.e. up to a fully lateral wind, conditions that the airship can encounter at very low speed or in hover situation. We measured separately the performances of the bare hull, of an isolated tail fins and of the hull with fins attached. Another key aspect of our thesis is to do a visualisation of the flow using Particle Image Velocimetry (PIV), a measurement tool which allows us to get CFD like pictures of the flow field.

Thesis outline

Chapter 1 The first chapter presents the theoretical foundations on which our work is based.

First of all, the conventions that we adopted throughout our work will be presented. The coordinate system will be defined and the characteristic variables of the problem will be presented in order to non-dimensionalize the results.

We will present the hypothesis that we made to conduct our experimentation. Furthermore, we will present the theoretical tools required to describe the problem. Starting by the aerodynamics derivatives and polar, stability consideration and explanation of physical phenomena such as vortex shedding or Kelvin-Helmholtz instability. We will finish with the ANOVA (analysis of

variance) theory we use to estimate the mean and standard deviation of our data.

Chapter 2 The second chapter will describe the state of the art. First we will present the different characteristics of a wind tunnel as well as the experimental measurement tools and hypothesis that we used during the experimental phase in order to obtain our data: measurement of the flow velocity in wind tunnel or measurement of the forces and moments with the aerodynamic balance. We will explain how the PIV works and we will finish by presenting different models for airship aerodynamics that we implemented to compare with our data.

Chapter 3 The third chapter will talk about the design of the experimental setup we used to carry out our experiments. We will start with the facility characteristics present in the iMMC-LEFT laboratory and then present airship design process.

Chapter 4 The fourth chapter will present the airship experiment, the method to calibrate the balance and torque meter. We will also present the experimental procedure. This chapter will end by the presentation and the analysis of our results.

Chapter 5 The fifth chapter will present the fin experiment part. It follows the same procedure as previously explained in the chapter 4: we will start by the experimental procedure, followed by the data acquisition and correction then we will finish by presenting our results and analysing them.

Chapter 6 In the sixth chapter we will compare our results to different models from the literature that we implemented.

Chapter 7 This last chapter will be about the flow visualization obtained through Particle Image Velocimetry measurements. We will present the PIV setup then the calibration process.

Finally, a conclusion will provide a summary of the key results that emerged from the investigation. We will discuss the results and evaluate the limitations of our work. At last, we will provide recommendations for any further work dedicated to a similar subject.

1. Theoretical tools, hypothesis and conventions

The analysis of the experimental results which will be made subsequently requires several theoretical concepts that we will discuss in this section.

1.1. Axis system

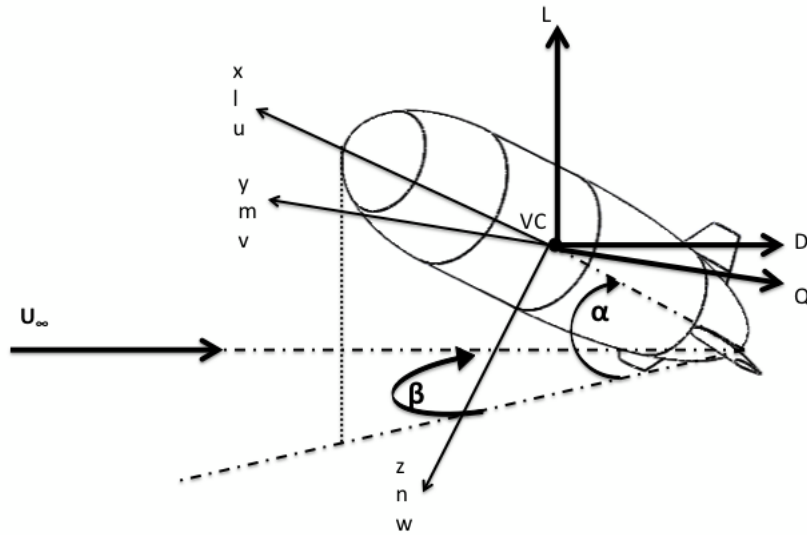


Figure 1.1: Reference coordinate system, aerodynamic angles, forces and moments.

We will use the same coordinate system as represented on figure 1.1. The origin of the coordinate system is placed on the volume center (VC) of the airship and the axis are aligned as follows:

Axis:

- x: the roll axis, longitudinal with respect to (w.r.t.) the airship.
- y: the pitch axis, lateral w.r.t the airship.
- z: the yaw axis orthogonal to the x,y plane and pointing downward.

Velocity:

- u: velocity component along x.
- v: velocity component along y.
- w: velocity component along z.

Moments:

- l: rolling moment (around x).
- m: pitching moment (around y).
- n: yawing moment (around z).

Angles: The angle formed between the longitudinal axis x and the upstream airflow direction can be projected in the x,z plane giving the angle of attack α . The sideslip angle β is the directional angle of attack between axis x and the oncoming airflow.

Aerodynamic forces: Aerodynamic forces exerted on the airship are decomposed in two components w.r.t. the airflow direction: lift force L is normal to upstream flow and drag force D is aligned with upstream flow.

1.2. Nondimensionalization

It is common in fluid mechanics and especially in aerodynamics to make physical quantities dimensionless. Therefore, characteristic quantities are used but their choice is not unique. However, it often involves upstream dynamic pressure: $q = \frac{1}{2}\rho U_\infty^2$ [Pa].

Reynolds number: $Re = \frac{U_\infty L}{\nu}$, in which characteristic length scale L_a is chosen according to the problem. It can be the mean chord $\bar{c}$ in the case of a flow past a wing or a fin. L_a is chosen to be the length of the hull in the case of an airship, some also use $Volume^{\frac{1}{3}}$ in this case. And for flow past a cylinder the characteristic length L_a is its diameter D.

The Reynolds number is the ratio between inertia forces and viscous forces and characterizes the nature of a flow. Two problems that share the same Reynolds number will also share the same flow regime: laminar, transitional or turbulent.

Later in our study we will use Reynolds number based on the length of the hull for problems involving the airship and Reynolds number based on the mean chord for the fin experiments.

Pressure coefficient: $C_p = \frac{p - p_\infty}{q}$, where p_∞ is static pressure of the free stream.

Lift and drag coefficient: Respectively, $C_L = \frac{L}{q \cdot S}$ and $C_D = \frac{D}{q \cdot S}$. Here stands another choice for nondimensionalization: which surface of reference S shall we choose? Usually for wings (and fins), the surface is the projected surface of the wing on the wing plane. In the case of an airship the

choice is less straightforward and the reference surface is often chosen as $S = (Volume)^{2/3}$. Giving in our case:

$$C_L = \frac{L}{\frac{1}{2}\rho U_\infty^2 V^{2/3}}$$

and

$$C_D = \frac{D}{\frac{1}{2}\rho U_\infty^2 V^{2/3}}$$

Lateral force coefficient: $C_Q = \frac{Q}{q \cdot S}$

Pitch and yaw moment coefficient: Respectively, $C_m = \frac{m}{q \cdot V}$ and $C_n = \frac{n}{q \cdot V}$.

Strouhal number The Strouhal number $Str = \frac{f \cdot D}{U_\infty}$ is the nondimensionalization of the vortex shedding frequency. This phenomenon is described in the section 1.5.

1.3. Aerodynamics derivative and polar

The change of a quantities “X” with respect to an another quantity “i” $\frac{\partial C_X}{\partial i}$ is called aerodynamic derivative when it involves aerodynamic quantities. It will equally be written : C_{X_i} . For instance, the variation of lift coefficient with respect to angle of attack is then written as: C_{L_α} . Aerodynamic derivatives of interest in our study are C_{L_α} , C_{D_α} , C_{m_α} , C_{Q_β} , C_{D_β} , C_{n_β} , they are the slope of the curves in the graphs $C_{L,D,m} - \alpha$ or $C_{Q,D,n} - \beta$.

Plotting the results: A common representation mostly used for wings or whole aircraft is the polar curve. The polar curve is a graph plotting the drag coefficient as a function of the lift coefficient. It can be done for any body and usually it looks like figure 1.2. As we do aerodynamics around an airship, polar curve makes less sense and we will rather plot our experimental results in lift, drag side force or moment curve. Those graphs displays the quantity of interest versus the angle of attack as in figure 1.3¹. If needed polar curve can still be drawn from those curves.

1.4. Longitudinal static stability

To ensure the longitudinal equilibrium of an air vehicle, the sum of forces in the plane of symmetry and the sum of moments in the normal direction with respect to the symmetry plane must be null. Figure 1.4 represents the aerodynamic moment coefficient around the center of mass of the air vehicle as a function of the angle of attack (AoA) α . There are two conditions to

¹ source: <http://flyacro.us/spintraining.html>

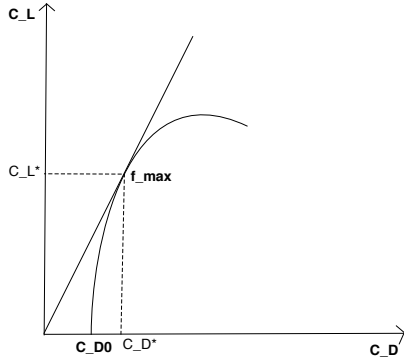


Figure 1.2: Polar of a wing.



Figure 1.3: Exemple of the way our result will be plotted

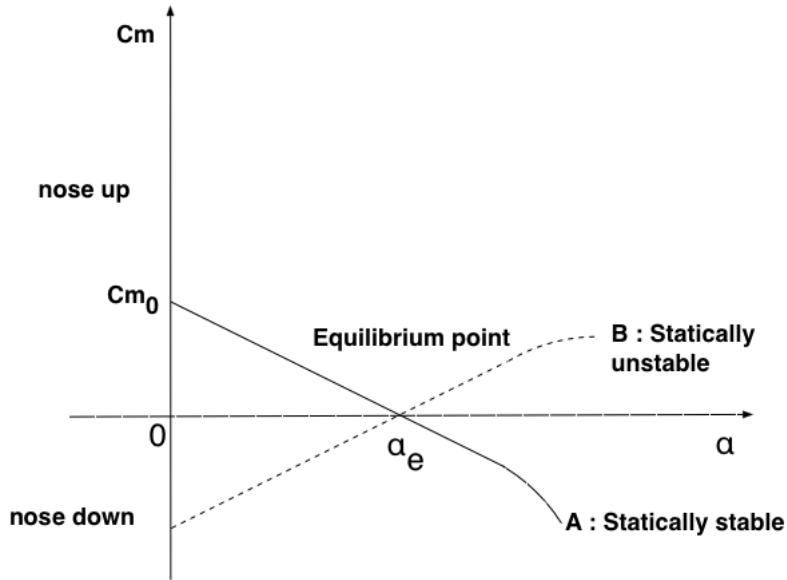


Figure 1.4: Pitching moment in function of the angle of attack (AoA)

ensure the longitudinal static stability:

$$\frac{\partial C_m}{\partial \alpha} < 0 \quad (1.1)$$

and

$$C_{m,0} > 0 \quad (1.2)$$

For the curve A in the figure 1.4, the airship is stable. Indeed, when the angle of attack, the pitching moment coefficient decreases which leads to the decreasing of the disturbances.

For the curve B in the figure 1.4, the airship is unstable. Indeed, if a perturbation increases the angle of attack, the pitching moment coefficient increases which leads to the increase of the disturbances.

1.5. Vortex Shedding: Strouhal number

The vortex shedding is an instability that takes place when a fluid passes around a blunt body at given velocity. Depending on the size, the shape of the body and the velocity of the flow, the vortices appear at the back of the body and separate periodically from either side of the body producing von Karman vortex street as illustrated on figure 1.5.

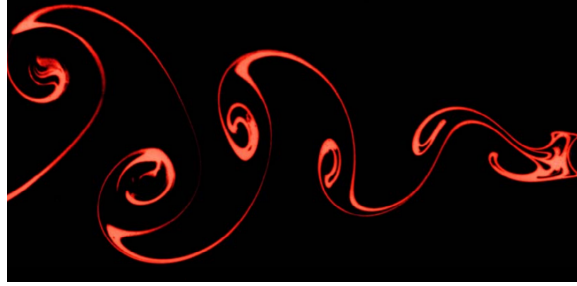


Figure 1.5: Von Karman vortex street, flow going from right to left [6].

Resonance may occur if the vortex shedding frequency is close to the natural frequency of the body. The Strouhal number Str , is usually used as a measure of the predominant shedding frequency f_s . It is defined as:

$$Str = \frac{f_s \cdot D}{U_\infty}$$

Where D is the diameter of the body and U_∞ is the flow velocity. We can also see in figure 1.6 that for sub-critical flow, $Str \approx 0.2$.

Strouhal Number vs. Reynolds Number The relationship between the Strouhal number and the Reynolds number for a circular cylinder is given in the following graph:

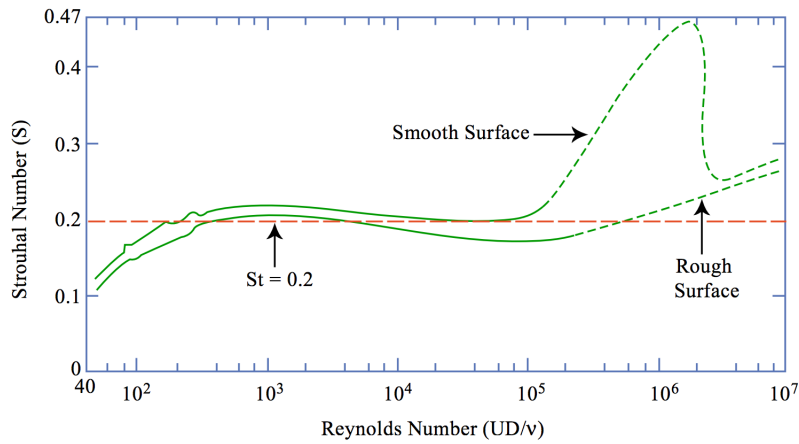
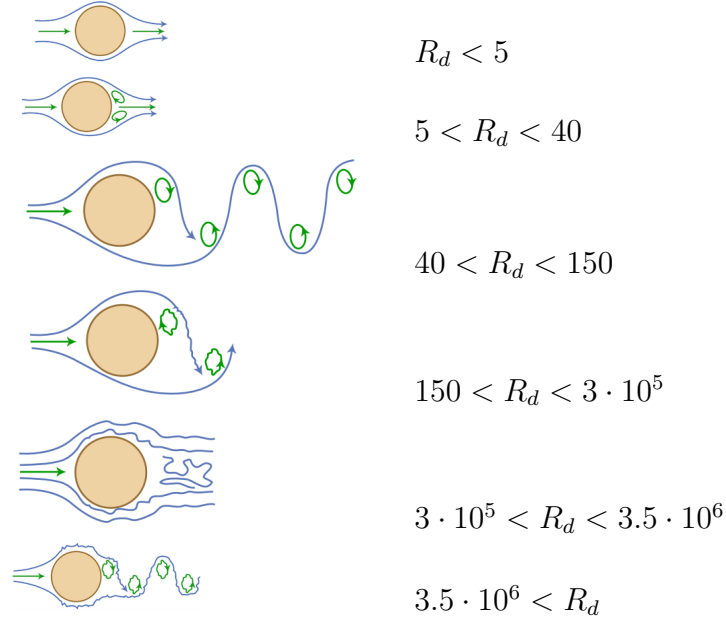


Figure 1.6: Strouhal Number vs. Reynolds Number (based on diameter D)[7]

Reynolds Number Dependency [7] Different regimes for the vortex shedding can be identified based on the Reynolds number.



- For $R_d < 5$: There is boundary layer separation.
- For $5 < R_d < 40$: The boundary layer separates to form a pair of vortices in the near wake.
- For $40 < R_d < 150$: The vortex street is laminar.
- For $150 < R_d < 300$: The vortices start to become turbulent.
- For $300 < R_d < 3 \cdot 10^5$: This is the sub-critical region. In this region the Strouhal number is constant like we can see in the figure 1.6. The vortex street is here fully turbulent.
- For $3 \cdot 10^5 < R_d < 3.5 \cdot 10^6$: This is the transition range where the boundary layer starts to become turbulent.
- For $3.5 \cdot 10^6 < R_d$: Re-establishment of turbulent vortex street.

1.6. Kelvin-Helmholtz instability

The Kelvin-Helmholtz instability is a wave motion that appears at the contact surface of two thermally stable fluids which are moving at different speed or which have different density. When instabilities appears (figure 1.7), they perturb the contact surface which eventually breaks into a turbulent flow with a wave pattern (figure 1.8). An example is wind blowing over water: the instability manifests in waves on the water surface. The phenomenon also appears in a fluid of uniform density with the fluid layers having different velocity profiles as for blown air jet.

For a continuous variation of density and speeds, the instability of Kelvin-Helmholtz develops at a certain value of Richardson number which is defined as:

$$R_i = \frac{g \nabla \rho}{\rho (\nabla u^2)^2}$$

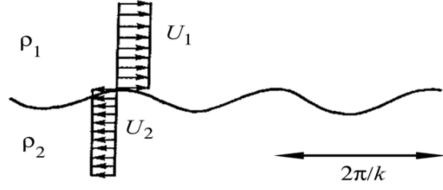


Figure 1.7: "Kelvin-Helmholtz instability developing from a wave-like perturbation of wave-number k at the interface between two vertical regions." [8]

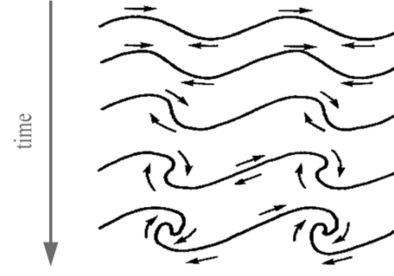


Figure 1.8: The interface breaks then mixes in a golf like pattern. Figure from [8]

Where g is gravity, ρ is the density and u is the speed of the flow. Richardson number is a non-dimensional number that expresses the ratio between the buoyancy and the flow shear. The range value of this non-dimensional number is between 0.1 and 10. If $R_i < 1$, the flow is turbulent.

The existence of those instabilities had an impact on the design of our experiment as we explain in part 3.2.

1.7. Incompressible flow hypothesis

First of all, the Mach number for our model is given by :

$$M = \frac{u}{a} = \frac{u}{\sqrt{\gamma \cdot R \cdot T}}$$

If we assume a constant velocity of $u = 35[m.s^{-1}]$ with $\gamma = 1.4$, $R = 287[J.kg^{-1}.K^{-1}]$ and $T = 20[^\circ C] = 293,15[K]^2$, this give $M = 0.102$.

As developed in the course note of **Fluid Mechanics and Transfers II** [18] we have from the Bernoulli equation:

For compressible flow

$$\frac{p_0}{p} = \left(\frac{T_0}{T}\right)^{\frac{\gamma}{\gamma-1}} = \left(1 + \frac{(\gamma-1)}{2} \cdot M^2\right)^{\frac{\gamma}{\gamma-1}}$$

$$\frac{\rho_0}{\rho} = \left(\frac{T_0}{T}\right)^{\frac{1}{\gamma-1}} = \left(1 + \frac{(\gamma-1)}{2} \cdot M^2\right)^{\frac{1}{\gamma-1}}$$

Using a Taylor series development around 0, we have the following expressions:

$$p_0 = p + \rho \cdot \frac{u^2}{2} \cdot \left(1 + \frac{M^2}{4}(1 + (2 - \gamma)\frac{M^2}{6}(1 + \dots))\right)$$

$$\frac{\rho_0}{\rho} = 1 + \frac{M^2}{2}(1 + (2 - \gamma) \cdot \frac{M^2}{4}(1 + \dots))$$

² We choose here the minimal temperature that we have during the experimentation days

Combining these two result gives:

$$p_0 = p + \rho_0 \frac{u^2}{2} \left(1 - \frac{M^2}{4} + (2\gamma - 1) \frac{M^4}{24} + \dots\right)$$

We thus obtain that

$$p_0 = p + \rho_0 \frac{u^2}{2} \left(1 - \frac{M^2}{4} + \dots\right)$$

For an incompressible flow: we have:

$$p_0 = p + \rho_{cst} \frac{u^2}{2}$$

Where: p is the pressure, ρ : the density , ρ_0 the density at the stagnation condition and M the Mach number.

The substitution of Bernouilli equation for incompressible flow with the Bernouilli equation for compressible flow is good as long as $\frac{M^2}{4} \ll 1$, which represents the amplitude of the relative difference/error.

In our case, we have $M \approx 0.1$ then we obtain a relative difference/error of 0.26%. Mach number doesn't exceed 0.3 which is the maximum Mach number admitted for a maximum relative error of 2.5%. For such flows we can say that a compressible flow behaves in the same way than an incompressible flow. In others words, the pressure difference $p_0 - p$ measured in the flow at a location where the velocity is u ($u = 35 [m.s^{-1}]$ in our experiments) will be essentially the same in both cases.

1.8. Statistic for experimental measurements

In order to properly compute the mean and standard deviation of our measured data, we used tools from ANOVA (anaysis of variance) theory. We have repeated most of the experiments three times. We had to find a method that could give an approximately value of the mean error for these three experiences.

Assume that when we measure an experimental data point, the computer already computes it by taking the average value of N points which will be noted $\bar{X}$, the standard deviation relative to this average will be noted s . By repeating the experiment n times we then record the values $\bar{X}_1 \dots \bar{X}_n$ and $s_1 \dots s_n$. From ANOVA theory:

The grand mean of our measurements is computed as:

$$GM = \frac{\sum_i^n \bar{X}_i}{n}$$

The grand variance and the grand standard deviation for the mean value are computed as:

$$GV = \frac{SST}{n \cdot N - 1}$$

$$GSD = \sqrt{GV}$$

where SST is the sum of squared difference of the dependant variable and its means. It can be computed as:

$$SST = SSM + SSE$$

where:

$$SSM = N \cdot \sum_i^n ((\bar{X}_i - GM)^2)$$

And

$$SSE = (N - 1) \cdot (\sum_i^n s_i^2)$$

2. State of the art

2.1. Wind tunnel

The main type of wind tunnel are either build with closed or open return with either an open or a closed test section.

Open return The ambient still air is accelerated straight from the inlet to the exhaust through the different organs of the wind tunnel. The main advantages of this design are the lower construction cost and the purging problem avoidance when the flow is inseminated by gas or smoke. During engine testing or flow visualization for example. Its main drawbacks are the increase of energy consumption and a higher level of operation noise. Finally, it requires high quality flow at the inlet and the outlet of the wind tunnel to be ensured.

Closed return The air flowing in the wind tunnel circulates in a closed loop and there is little to no exchange with the air of the room. The advantages are a lower energy consumption with respect to the test section size or the velocity as well as a lower operation noise. Furthermore it is easier to ensure the flow quality thanks to the use of turning vanes or honeycomb panel. The quality of the flow is then decoupled from the ambience of the building.

The wind tunnel we used in the TFL facilities is a closed return with open test section. It is described later in section 3.1. Closed return wind tunnel

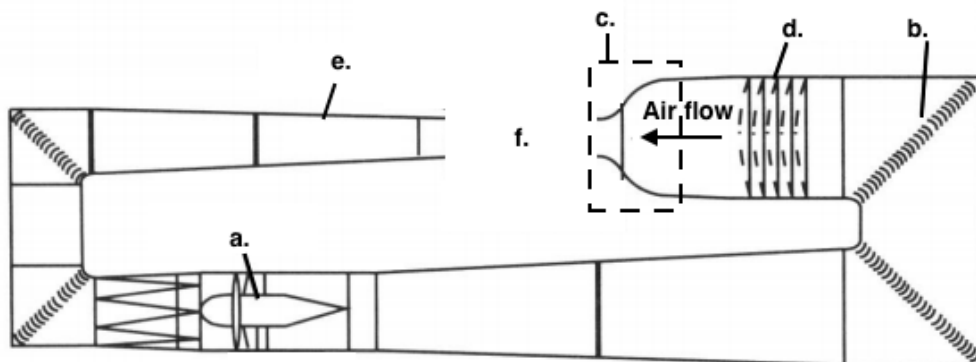


Figure 2.1: General representation of a closed return with open section wind tunnel. Based on a picture from [9]

are generally composed of the following organs referenced on figure 2.1

a. The power train: Usually an electric motor driving a propeller.

- b. **The turning vanes:** They ensure that the flow does not lose too much energy in the turn and allow the flow to be straight all over the circuit.
- c. **The convergent:** It accelerates the flow smoothly.
- d. **Honeycomb:** Before the convergent there is a honeycomb screen which is a flow conditioner that breaks large vorticity structures and straighten the flow.
- e. **Diffuser:** Typically the diffuser is a conical expansion cone whose goal is to slow down the flow and recover pressure. It is a tricky part to design because it is essential to avoid boundary layer separation. In the wind tunnel that we used, the diffuser has constant section pipe.
- f. **Test section** Open section where we can place the model. Above or below this section stands an aerodynamic balance to which the model is attached.

2.2. Experimental measurement

2.2.1. Flow velocity

In every wind tunnel experiment it is crucial to measure and monitor the flow velocity. This is generally achieved with a Pitot tube device commonly called "Pitot" (see figure 2.2). The Pitot tube measures the dynamic pressure P_{dyn} by subtracting static pressure to total pressure. This dynamic pressure can be expressed in Pascal or in mm_{H_2O} . In any case, converting dynamic pressure into velocity requires the measure of other parameters:



Figure 2.2: Pitot tube of the iMMC-LEFT wind tunnel

Temperature The measure of ambient temperature can be made using a thermocouple. Before each experimentation we thus measure temperature T .

Pressure The measurement of ambient pressure P is done using a barometer.

Air density To determine this value, we just use ideal gas law

$$PV = R^* \cdot T$$

then:

$$\rho = \frac{P}{R^* \cdot T}$$

We can then have the velocity v , using the pressure given by the pitot tube and the density calculated previously:

$$P_{dyn} = \frac{1}{2} \cdot \rho \cdot v^2$$

then:

$$v = \sqrt{2 \cdot \frac{P_{dyn}}{\rho}}$$

We start the experiment when $v = 35[m.s^{-1}]$ for the given pressure from the pitot tube.

Humidity: Air humidity measurements can be achieved with a hygrometer. To have a more accurate value of the air density, we should have taken into account the air humidity because it modifies the specific constant of the air R_h .

The specific constant of humid air is given by

$$R_h = \frac{R_s}{1 - (\phi \cdot \frac{p_{sat}}{p}) \cdot (1 - \frac{R_s}{R_v})} \quad (2.1)$$

with:

- $R_s = 287,06[J.kg^{-1}.K^{-1}]$, the specific constant of dry air.
- $R_v = 461[J.kg^{-1}.K^{-1}]$, the specific constant of water vapour.
- ϕ , the relative humidity given by the hygrometer.
- p , the air pressure.
- p_{sat} , vapor pressure of water can be calculated using the Magnus expression:

$$p_{sat} = 611.213 \exp\left(\frac{17.5043 \cdot T}{241.20C + T}\right) \quad (2.2)$$

This expression can only be used for a range of temperature T between $[-30^{\circ}C, 70^{\circ}C]$ and gives the p_{sat} in Pascal.

Table 2.1: Air density for humid and dry air

Φ [%]	30	80	dry air
p_{sat} [Pa]	3201.125	3201.125	-
R_h [$J \cdot kg^{-1} \cdot K^{-1}$]	288.097	289.843	-
ρ [$kg \cdot m^{-3}$]	1.170769	1.163717	1.174999

We did not measure the air humidity during our experiments, we can determine the error it represents:

Ambient relative humidity is usually between 30% and 80% [9]. Assuming the ambient temperature at $T = 25.2 [^{\circ}C] = 298.35 [^{\circ}K]$ and the pressure: $p = 100632 [Pa]$, using equation 2.1 and equation 2.2 we can compute the air density displayed in table 2.1.

Using density displayed in table 2.1 we compute a range of relative errors for air density: $[\frac{\rho_{dry} - \rho_{30\%}}{\rho_{dry}}, \frac{\rho_{dry} - \rho_{80\%}}{\rho_{dry}}] = [0.36\%, 0.96\%]$.

2.2.2. Forces and moment

The most common type of instruments used in wind tunnel for testing a model is an aerodynamic force balance. In general, it must measure six components: three forces (drag, lift and side) and three moments (pitch, roll, and yaw) to completely describe the forces applied on the model.

Simpler balances as the one we used allow measurements along three components, namely the lift force, drag force and pitching moment can be measured. Some balance can be placed externally to the test section holding to model from above or below. Other balance as sting balance are directly inside the support axis which holds the model. It avoid parasitic contribution of the support in the measurements but it require to be inserted into the model from a downstream position in order to not disturb the flow. The external balance we used will be described in 3.1.

We measured moments thanks to a torque meter whose design is explained at section 3.2.1. It measures the deformation of a slat through strain gauges forming a Wheatstone bridge. We used the beam theory to design the slat.

Beam theory: thanks to the course of Machine Design [19], we learned several useful formulas for beam theory which have cross-sections that are symmetrical about a plane perpendicular to the neutral plane:

For bending stress:

$$\sigma = \frac{M \cdot y}{I} \quad (2.3)$$

where y is the distance from the neutral axis to a point of interest ($y = \frac{h}{2}$ in our case), M is the bending moment and I the moment of inertia of the cross section with respect to the neutral axis given by:

$$I = \frac{bh^3}{12} \quad (2.4)$$

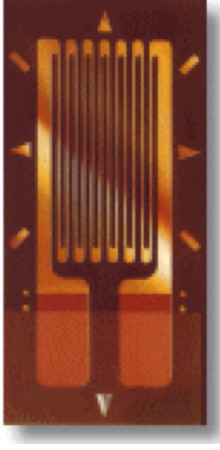


Figure 2.3: Strain gauge [10]

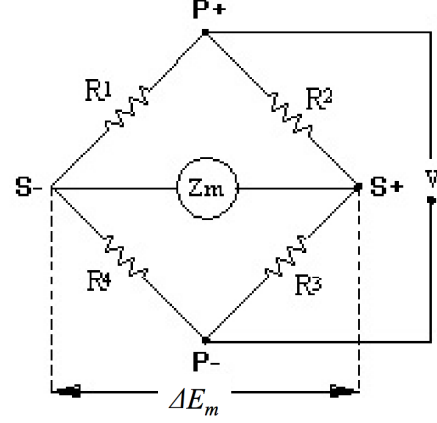


Figure 2.4: Wheatstone bridge [11]

Using both expression 2.3 and 2.4 we derive the expression of the stress in bending:

$$\sigma = \frac{6 \cdot M}{b \cdot h^2} \quad (2.5)$$

The shear stress is given by :

$$\tau = \frac{T \cdot r}{J} \quad (2.6)$$

where T is the torque applied, J is the quadratic moment of torsion depend for the given geometry and r the distance with respect to the torsion axis. The equivalent stress is thus given by:

$$\sigma_{equ} = \sqrt{\sigma^2 + 3 \cdot \tau^2} \quad (2.7)$$

For pure bending (the shear stress is null) we get:

$$\sigma_{equ} = \sigma = \frac{6 \cdot M}{b \cdot h^2} \quad (2.8)$$

Wheatstone bridge: A gauge is made of one thin conductive thread bonded to a substrate like we can see in the figure 2.3. The wires strands constituting the strain gauge are aligned in the measurement direction: we can assume that, the thread undergone the same deformation as the surface on which the gauge is glued.

The most accurate method for measuring resistance variation is to place the gauge in a Wheatstone bridge. When a Wheatstone bridge (figure 2.4) is made up of 4 equivalent resistors (4 strain gauge) and supplied by a constant voltage source in $P+$ and $P-$, we obtained by symmetry, a zero difference potential between $S-$ and $S+$.

If the resistance R_2 varies slightly, this imbalance is measured by the galvanometer Z_m .

R_2 and R_4 operate in the positive direction (increase of the resistance) while

R_1 and R_3 act in the opposite direction.
Therefore we have:

$$\left(\frac{Z_m}{V}\right)_1 = \frac{R_2}{R_2 + R_3} - \frac{R_1}{R_1 + R_4} \quad (2.9)$$

When it is a zero potential difference ($Z_m = 0$) we have:

$$\frac{R_1 + R_4}{R_1} = \frac{R_2 + R_3}{R_2}$$

which leads to:

$$R_1 \cdot R_3 = R_2 \cdot R_4$$

2.3. Visualization

2.3.1. PIV

PIV stands for Particle Image Velocimetry. It is a non invasive visualization technique which allows to capture vector fields of interest from the flow. The flow in the wind tunnel is inseeded with particles which have the right density in order to follow the streamlines. These particles are illuminated by an intermittent laser sheet and a camera then takes double shot of the illuminated section. A computer then uses statistical methods to correlate particles between the two shots and the two velocity components in this plane of interest are extracted. Afterwards a vector field of the velocity flow can be drawn and information as vorticity, streamline or shear stresses can be computed. A more complex technique called stereographic PIV involve two cameras and offers the possibility to extract the three velocity components of the flow.

2.4. Tripping

When a body is placed in a flow, the boundary layer is the region near the surface where viscous effects are of the same order of magnitude or greater than inertia effects. Depending on the flow regime, the boundary layer can be laminar, turbulent or in transition between those two. The thickness of the boundary layer grows along the body in the flow direction.

Boundary layers: The boundary layer thickness is defined as the distance from the body surface up to the point where the velocity is 99% of the freestream velocity. The thicknesses of boundary layers over a flat plane can be expressed as :

- For laminar thickness $\delta_L = \frac{5.2x}{Re_x}^{0.5}$
- For turbulent thickness $\delta_T = \frac{0.37x}{Re_x}^{0.2}$

If the curvature radius of the surface of the studied body is much greater than the boundary layer thickness, we can use the boundary layer thickness

for flat planes as an approximation. At low Reynolds number, the presence of laminar separation bubbles often results in the increase of drag produced by bodies. Then artificially force the transition to turbulent boundary layer can reduce the pressure drag as turbulent boundary layer are more robust to separation. Doing so is called tripping the boundary layer and can be done by placing an obstacle in the flow. Tripping at low Reynolds number generally rely on a trial-and-error approaches. If the friction drag is important with respect to the pressure drag, for long slender object for example, tripping of the boundary layer won't reduce the total drag.

To improve forced transition we can use different types of mechanical turbulators such as zigzag tape, disc (used in our case), triangular patches, vortex generator or tripping wire.

Many parameters influence the quality of the tripping, such as: obstacle heights, locations, geometry, Reynolds numbers, angle of attack and so on. Sadly, a poor understanding of transition enhancement by means of boundary layer trips makes trip optimization difficult. A particular trip configuration optimized for a body may be less favorable for another one.

2.5. Aerodynamic model for airships

2.5.1. Munk's model: potential flow

First aerodynamic models to be developed were based on potential flow theory. It gives a good approximation for the pressure distribution of the front part of the hull where viscosity effects are small. Such model has been reported by Munk in 1924 (in [20]). By applying a slender body assumption, the aerodynamic force per unit length normal to the hull can be computed as:

$$\frac{dF_N}{d\epsilon} = (k_2 - k_1)q_0 \frac{dS}{d\epsilon} \sin 2\alpha \quad (2.10)$$

For a given angle of attack α and with ϵ the longitudinal distance from nose, k_1 and k_2 are the added-mass factors of ellipsoids in the longitudinal and lateral directions taken from figure 2.5. Those have been derived by Lamb in 1932 and are function of the fineness ratio which is defined as L_a/D . In the present study, fineness ratio is 3.95 and $k' = k_2 - k_1 \approx 0.6$. Finally S is the local cross section area of the hull. Normal force is obtained by integrating equation 2.10:

$$F_N = \int_0^{L_a} (k_2 - k_1)q_0 \frac{dS}{d\epsilon} \sin 2\alpha d\epsilon \quad (2.11)$$

This latter integral is null. Moment is obtained by the following integration:

$$M_N = \int_0^{L_a} (k_2 - k_1)q_0 \frac{dS}{d\epsilon} (\epsilon_m - \epsilon) \sin 2\alpha d\epsilon \quad (2.12)$$

With ϵ_m the position of the volume center from the nose of the airship.

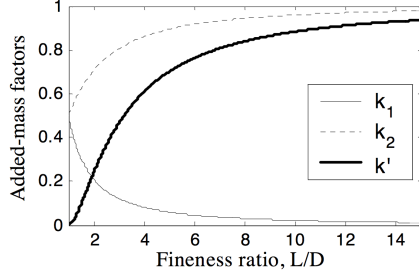


Figure 2.5: Added-mass factors. [12]

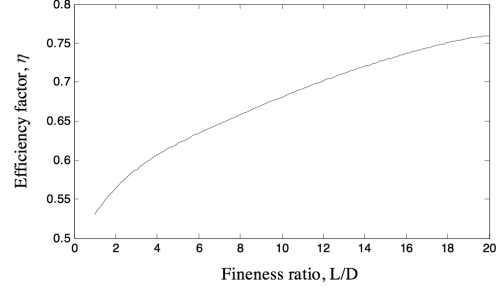


Figure 2.6: Efficiency factor η . [12]

2.5.2. Allen's model

Semi-empirical methods have later been developed to account for viscosity effects. In [21], Allen corrected Munk's model by adding a viscous term. He assumed that each cross section of the airship is subjected to the same viscous effect that an infinite length cylinder normal to the flow would be subjected at. He models this phenomenon by introducing the cross flow drag coefficient $C_{DC} \approx 1.2$ of the cylinder. Allen's model for normal force by unit length:

$$\frac{dF_N}{d\epsilon} = (k_2 - k_1)q_0 \frac{dS}{d\epsilon} \sin 2\alpha \cos \frac{\alpha}{2} + 2q_0 R \eta C_{DC} \sin^2 \alpha \quad (2.13)$$

Where R is the local radius of the hull and η is an efficiency factor function of the fineness ratio which is taken from 2.6. Normal force is obtained by integrating equation 2.13:

$$F_N = \int_0^{L_a} (k_2 - k_1)q_0 \frac{dS}{d\epsilon} \sin 2\alpha \cos \frac{\alpha}{2} d\epsilon + \int_0^{L_a} 2q_0 R \eta C_{DC} \sin^2 \alpha d\epsilon \quad (2.14)$$

Moment is obtained by the following integration:

$$M_N = \int_0^{L_a} (k_2 - k_1)q_0 \frac{dS}{d\epsilon} (\epsilon_m - \epsilon) \sin 2\alpha \cos \frac{\alpha}{2} d\epsilon + \int_0^{L_a} 2q_0 R (\epsilon_m - \epsilon) \eta C_{DC} \sin^2 \alpha d\epsilon \quad (2.15)$$

2.5.3. Hopkins's model

Hopkins also developed a semi-empirical method (in [22]) in which he assumed that before a certain longitudinal position, normal force can be computed from potential flow theory and beyond this point it is computed using a cylinder cross section drag model similar to the one developed by Allen. Normal force distribution becomes:

$$\frac{dF_N}{d\epsilon} \begin{cases} 2(k_2 - k_1)q_0 \frac{dS}{d\epsilon} \alpha & \text{if } 0 \leq \epsilon \leq \epsilon_v \\ 2q_0 R \eta C_{DC} \alpha^2 & \text{if } \epsilon_v \leq \epsilon \leq L_a \end{cases} \quad (2.16)$$

Based on experimental results Hopkins found an empirical way to fix the transition point $\epsilon_v = 0.378L_a + 0.527\epsilon_1$ with ϵ_1 the longitudinal position at which $dS/d\epsilon$ has the maximum negative value.

2.5.4. Yuwen Li's model

The aerodynamic model developed by Yuwen Li in his thesis [12] is based on the Hopkins model formulated slightly differently as force normal to centerline is:

$$F_N = -q_0 \sin 2\alpha (k_2 - k_1) \int_{\epsilon_v}^{L_a} \frac{dS}{d\epsilon} d\epsilon + q_0 \eta C_{DC} \sin^2 \alpha \int_{\epsilon_v}^L 2R D \epsilon \quad (2.17)$$

And the corresponding moment:

$$M_N = -q_0 \sin 2\alpha (k_2 - k_1) \int_{\epsilon_v}^{L_a} \frac{dS}{d\epsilon} (\epsilon_m - \epsilon) d\epsilon + q_0 \eta C_{DC} \sin^2 \alpha \int_{\epsilon_v}^{L_a} 2R (\epsilon_m - \epsilon) d\epsilon \quad (2.18)$$

All the coefficients being already defined previously.

Evaluation of the hull axial drag coefficient:

It can be estimated by Hoerner's formula presented in [23]:

$$C_{DH0} = C_F \left(4 \left(\frac{L_a}{D} \right)^{1/3} + 6 \left(\frac{L_a}{D} \right)^{-1.2} + 24 \left(\frac{L_a}{D} \right)^{-2.7} \right) \quad (2.19)$$

Where C_F is the skin friction coefficient and is approximated by Yuwen Li in [24] by the skin friction of an equivalent flat plate: $C_F = 0.045 Re_{L_a}^{-1/6}$, with Re_{L_a} the Reynold number based on the hull length. Both Allen's and Hopkins' models should be accurate up to $20[^\circ]$ of angle of attack.

We will compare the models described above with the results of our experiments in section 6.1.

2.5.5. Fin aerodynamic

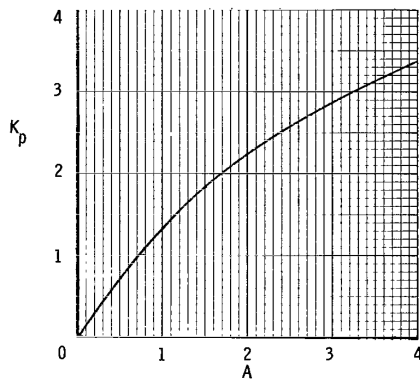


Figure 2.7: Variation of K_p with A (aspect ratio) for delta wings. Source [13]

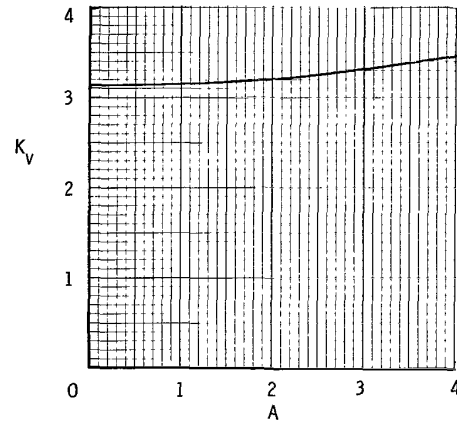


Figure 2.8: Variation of K_v with A (aspect ratio) for sharp-edge delta wings. Source [13]

The theory described in [13] gives a method to compute the lift coefficient for sharp-edge delta wing. It says that lift is the combination of a potential

flow lift and vortex lift due to sharp leading-edge vortex separation. It is demonstrated that total lift coefficient can be determined from:

$$C_L = K_p \sin \alpha \cdot \cos^2 \alpha + K_v \cos \alpha \cdot \sin^2 \alpha \quad (2.20)$$

With the parameters K_p and K_v taken from figures 2.7 and 2.8 respectively.

3. Design of the experimental setup

To give an idea of the time spent on the design process, the whole design process occupied us from September to April because it is an iterative process and we decided to integrate the couple meter before the January exam session. From April another month has been required to obtain the pieces from all the different suppliers and the experiments itself could only begin in mid May despite continuous work all year long.

3.1. Facility characteristics

General description: The iMMC-LEFT facility consists in a fan driven closed return low speed wind tunnel. The sinusoidal convergent nozzle contracts flow from a $1.02 \times 1.12 [m]$ section to a $0.56 \times 0.42 [m]$ open jet test section. There is a circular inlet of $0,8 [m]$ of diameter without diffuser (constant inlet pipe section). The figure 3.1 shows a global view of the wind tunnel that we used for our experiments.



Figure 3.1: Global view of the wind tunnel [14]

Flow conditioning: Before the convergent nozzle, there is a honeycomb screen to straighten the flow and break big vorticity structures [25]. In each

of the four square of the wind tunnel, lies turning vanes which prevent the total pressure loss in the corner. It also maintains the flow more uniform over the section.

Measurement device: Above the test section lies an external three component aerodynamic balance shown on figure 3.2.

The three components it can measure are lift force (vertical component in the balance framework), drag force (horizontal component in the balance framework) and pitching moment. The maximum loads permitted on the balance are: 3,6 [kg] in drag, 9,6 [kg] in lift and 0,2 [kgm] in pitch [26]. We will only use it for the lift and drag measurements. Forces are converted into voltage by means of inductive sensors. The outputs voltages are read with a voltmeter.

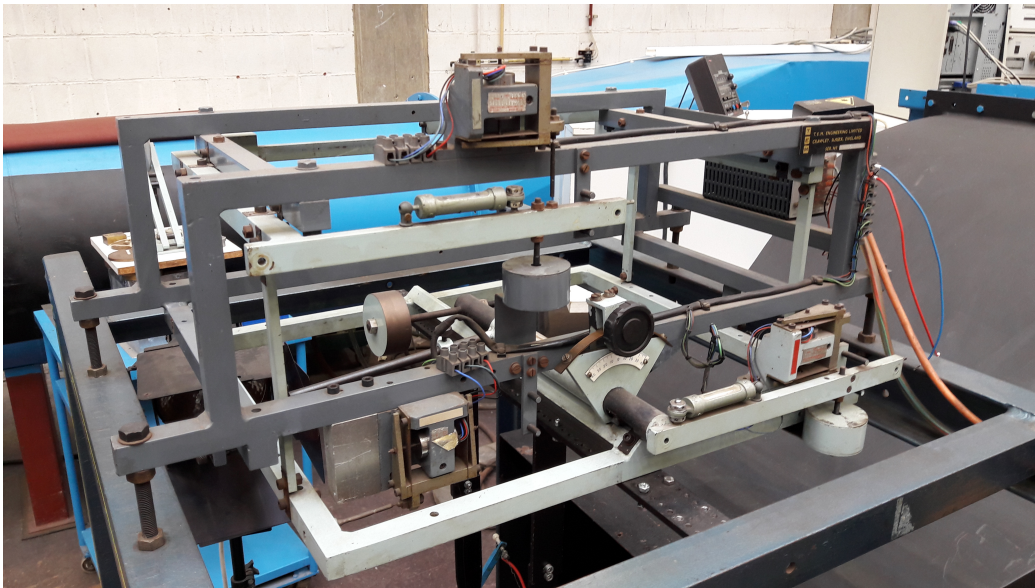


Figure 3.2: Aerodynamic balance in the TFL's facility

3.2. Design of the "airship" experiment

To design the experiments we were subjected to some constraints. One was to use a maximum of the elements already in place in the UCL facilities such as the convergent nozzle of the wind tunnel and the aerodynamic balance. We wanted the model to be as big as possible in order to be closer to the Reynolds number of the demonstrator (see Table 3.1). We wanted to limit the vibrations induced by the vortex shedding. We wanted to measure lateral, lift and drag forces undergone by the airship for different angle of attack α and sideslip angle β as well as pitching and yawing moment. Lateral force, drag and lift will be measured with the aerodynamic balance. We could have used the same balance to measure the moments by connecting a thin steel cable between the balance and the rear of the model. It would also have measured a moment contribution from the support which would have required tedious

trigonometric correction to cancel it. So we designed an “inboard” torque meter which measures aerodynamic moment exerted between the airship and its support. Its description is in section 3.2.1. In the table 3.1, we observe

Table 3.1: Dimensions of the demonstrator vs. the model

	Demonstrator	Model
Length [m]	15	0.316
Maximum Diameter [m]	3.8	0.080
Fineness ratio of the hull [.]	3.95	3.95
Location of the center of volume [<i>m</i>]	6.97	0.147
Volume [<i>m</i> ³]	127	$1.1863 \cdot 10^{-3}$
Volume based Reynolds number, $Re_V = \frac{U_\infty \cdot \sqrt[3]{V}}{\nu}$:		
At $U_\infty = 10$ [m/s]	$3.222 \cdot 10^6$	/
At $U_\infty = 35$ [m/s]	/	$2.360 \cdot 10^5$
Length based Reynolds number, $Re_{La} = \frac{U_\infty \cdot La}{\nu}$:		
At $U_\infty = 10$ [m/s]	$9.615 \cdot 10^6$	/
At $U_\infty = 35$ [m/s]	/	$7.090 \cdot 10^5$

that the Reynolds number of the demonstrator will not be conserved in our wind tunnel experiment thus we tried to artificially increase the turbulent behavior of the boundary layer by inserting several tripping discs in the nose of the airship. We build several tripping discs of different diameters, they are shown on figure 3.3. All the experiments with a tripping disc inserted in the nose as been realised using the red toothed disc as we thought it would be the most efficient to trigger turbulence. This disc has an outer diameter of 61.93[mm] with 2[mm] high teeth. It has been cut through a plastic sheet using pinking shears¹.

We could not test the effect of other discs but it would be an interesting extension of our work.

3.2.1. Hull

We designed the hull of the airship model in five axisymmetric sections. The front ellipsoid is split in two sections in order to be able to insert a tripping disc. The rear ellipsoid is also split in two sections in order to switch from a smooth stern to a stern with fins. Ellipsoid parts are turned in aluminum. The central cylindrical part of the hull is made of a PVC tube section which if necessary can be sacrificed. Stern with ailerons is 3D-printed in ABS. The 3D Solidworks model is shown in the figure 3.4. Plans of the experiment are in appendices.

¹ Sewing scissors with sawtoothed blades

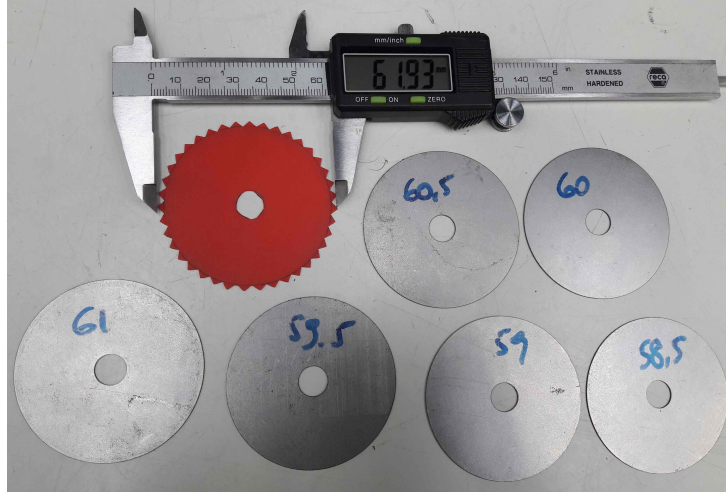


Figure 3.3: Tripping disc to insert in the nose of the airship

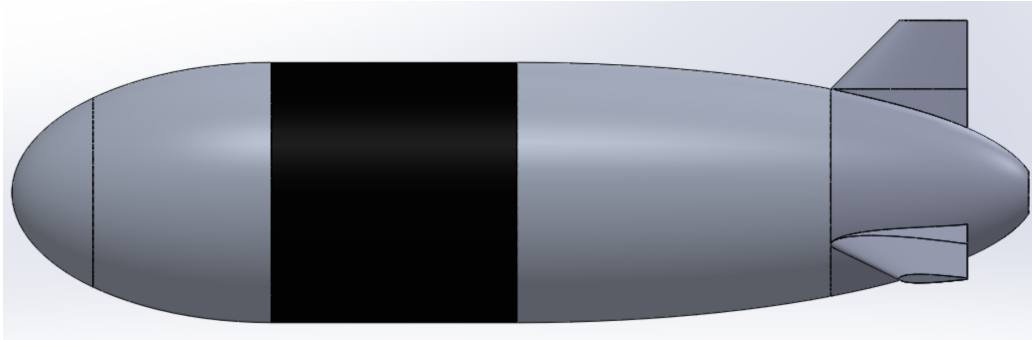


Figure 3.4: Solidworks representation of the airship.

Torque meter

Inside the rear of the airship we have integrated the torque meter (see figure 3.9 and 3.10). This torque meter measures the torque between the volume center and a point fixed with respect to the model by measuring the strain deformation of a test body: an aluminium slat.

Aerodynamic moment applied on the airship will tend to swing the airship around the volume center. This moment is transmitted to the aluminium slat in which an opposite pure bending moment appears. The aluminium slat deforms and this deformation is measured through strain gauges forming a Wheatstone bridge (described in section 2.2.2).

As it is shown on figure 3.5, the core piece of the airship is fixed to the support rod and to the axis passing through volume center of the airship. This axis is connected to the airship with ball bearing which allows all the airship to pivot about the volume center (V.C), with the less friction possible. The moment is then counteracted almost only by the slat.

To design the strain gauge, we used the numerical estimation of an aerodynamic moment (figure 3.6) which was done by the TFL research team and given to us in the early stage of the design. From the value of this pitching

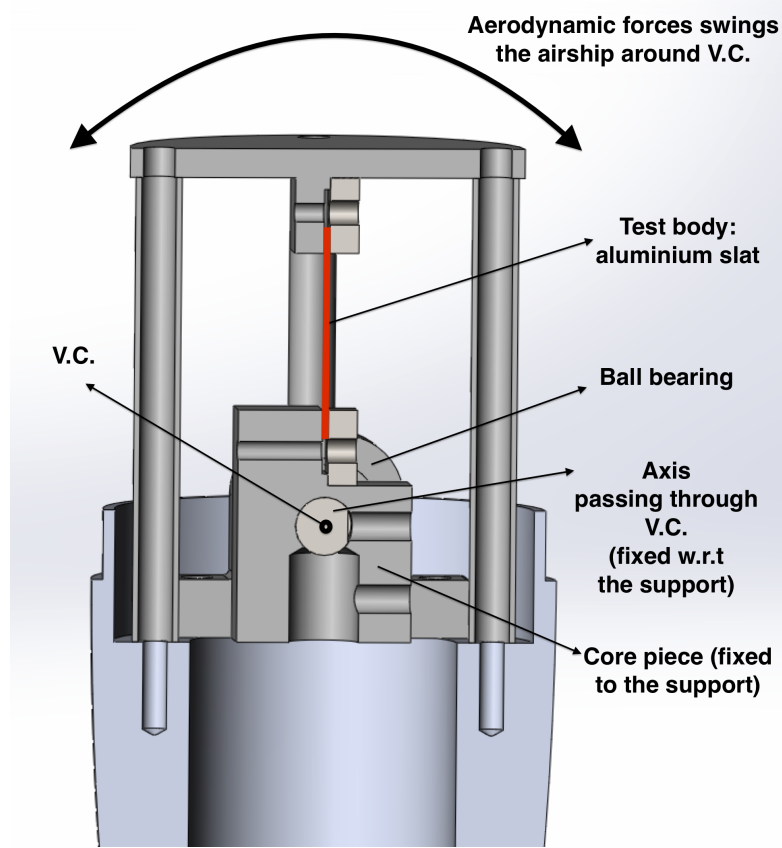


Figure 3.5: Torque meter operation

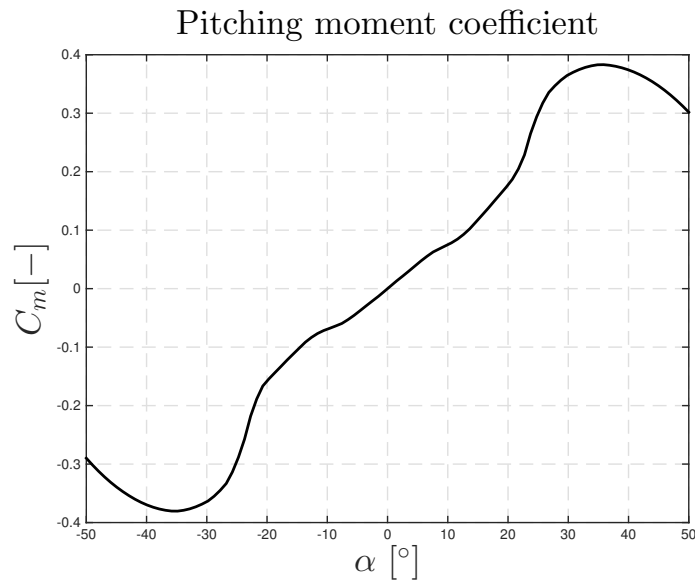


Figure 3.6: Pitching moment coefficient

moment coefficient we can recover the pitching moment $M = C_m \frac{1}{2} \rho U_\infty^2 V$. We sized our slat so we can measure such a moment through its deformation. Because the direction of deformation is imposed by the design of the torque meter, we supposed our slat would work in pure bending and thank to the

equation 2.8 according to a given thickness h that we fixed, we can determine the width of the slat as:

$$b = \frac{6M}{\sigma_{equ} \cdot h^2} \quad (3.1)$$

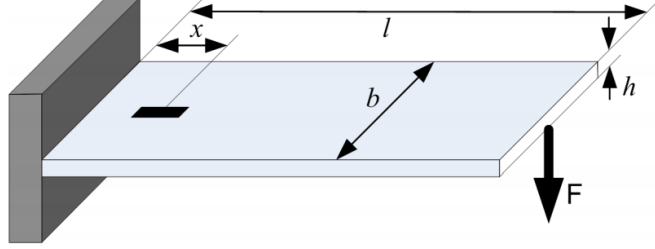


Figure 3.7: Slat considered as a cantilever beam

To determine the unit deformation of the slat we proceed as follow:
If we consider the slat as a cantilever beam (see figure 3.7), we have the following deflection:

$$y = \frac{4 \cdot l^3(1 - \nu)}{Ebh^3} \cdot F$$

Where: ν is the Poisson's ratio, E is the Young's modulus, l the length of the slat and F the applied force.

The unitary deformation of the upper fiber with a gauge oriented in the longitudinal direction and located at a distance x from the embedding point is:

$$\epsilon_1 = \frac{6(l - x)M}{Ebh^2l} \quad (3.2)$$

If the gauge is oriented in the direction of the width b of the beam, the unit elongation is equal to:

$$\epsilon_2 = -\nu \frac{6(l - x)M}{Ebh^2l} \quad (3.3)$$

The negative sign here reveals that the elongation is a shortening. To determine the unitary deformation, the length of the slat and the distance x at which the center of the gauge will be with respect to the end of the slat are fixed. We chose to design our slat for a unit deformation in the length direction.

Numerical application If we choose a slat made of aluminum 2024-T4, by fixing the length $L = 30 [mm]$ and a thickness $h = 0.8 [mm]$ we obtain thanks to equations 3.1 and 3.2 respectively a width of $b = 14 [mm]$ and an unitary deformation of $\epsilon_1 = 0,33\% = 3300 [\mu Strain]$ for a gauge oriented in the length direction.

Four strain gauges glued to the slat: two on its upper face and two on its lower face. They are symmetrically arranged to measure each $\frac{0.33}{4} = 0.0825\%$ of the deformation. One side of the slat is shown in figure 3.10.

After our numerical calculation, we used the software Solidworks to confirm our assumptions like we can see on figure 3.8 for the slat made of aluminum 2024-T4. We obtain an unitary deformation along the length

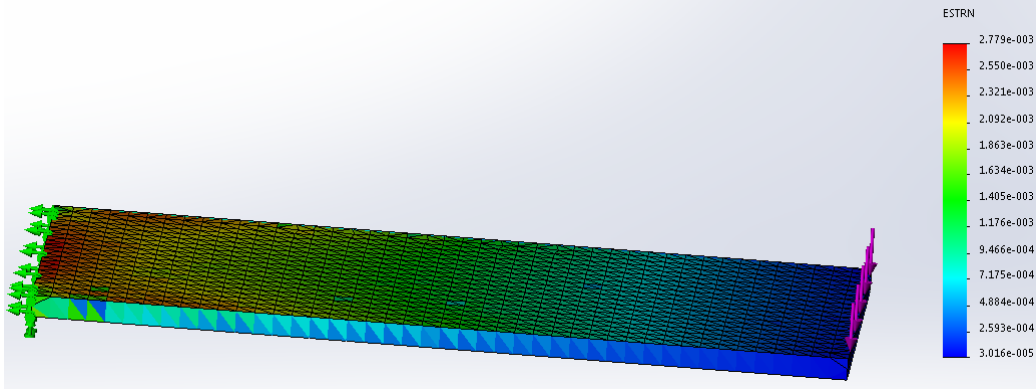


Figure 3.8: Solidworks simulation of a slat made of aluminum

of $\epsilon = 0,27519\% = 2751,9 [\mu Strain]$. Compared to analytically computed estimation ϵ_1 , the unitary deformation computed by simulation is lower but close as $\frac{\epsilon_1}{\epsilon} = \frac{0.33}{0.275} = 1.2$.

3.2.2. Support

In order for the support not to perturb the flow in front of the fins we decided to hold the airship by the stern. A tube was planted along the axis of symmetry of revolution of the model. This tube was welded to a transverse support bar in order to link lateral rotary bracket. The gap between lateral brackets was established to keep all the support but the transverse bar outside the flow (see figure 3.11 and 3.12). We measured with the Pitot tube the spacing needed between brackets in order to remain out of the flow. We have taken care that no part of the support would strongly interact with shear layer vortices (see section 1.6) generated at the slip surface between high velocity flow and still ambient air. Those develop at the edges of the convergent. We mounted discs on the rotary bracket to be used as disc brake and as a protractor to choose and set the incidence angle of the airship. A clam between fixed brackets and brake disc allow us to set an angle of attack to the model. It can be seen on figure 3.13.

We tried to evaluate beforehand the vibrations to which the system will be subjected. As the system is quite complex, analytical computation of the vibration mode will not be accurate and we did not manage to find an accessible numerical tool to simulate it. Still we can estimate which frequency will be triggered by the vortex shedding. The diameter based Reynolds number of our experiment is $Re_d = 1.51 \cdot 10^5$. Using theory explained in 1.5, when the airship is set vertical as in figure 3.12, we can assume Strouhal number is constant and equal approximately to 0.2. As $Str = \frac{f \cdot D}{U_\infty} \approx 0.2$, we can estimate frequency of the vortex shedding experienced by the airship knowing the maximum diameter of the airship $D = 0.08[m]$ and $U_\infty =$

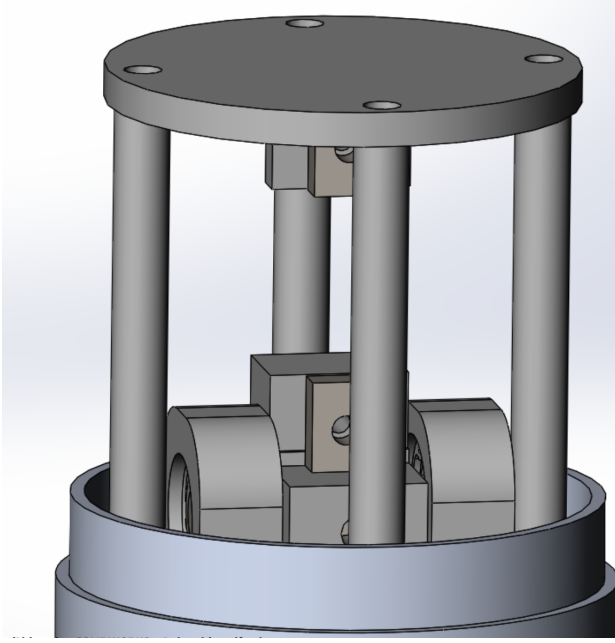


Figure 3.9: Solidworks representation of the device where the slat is climbed

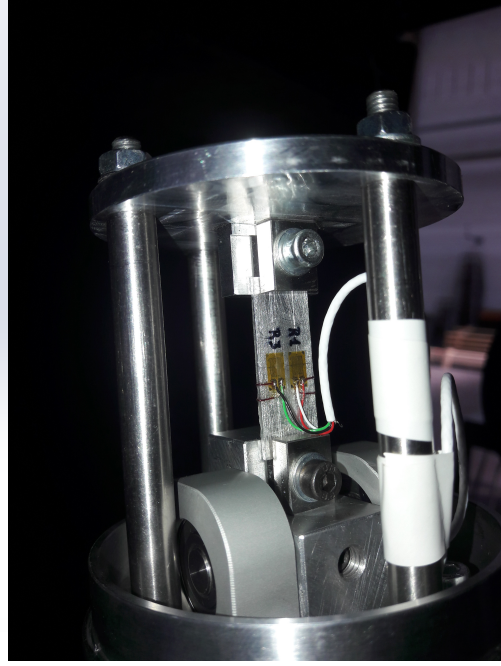


Figure 3.10: Photography of the torque meter inside the airship

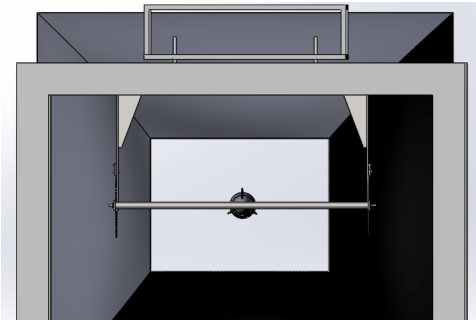


Figure 3.11: Solidworks view of the experiment facing the flow direction (0 degree angle of attack)

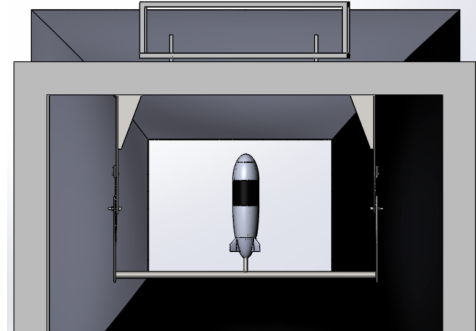


Figure 3.12: Solidworks view of the experiment facing the flow direction (90 degree angle of attack)

$35[m/s]$. This gives $f \approx 0.2 \frac{U_\infty}{D} \approx 87.5$ [Hz]. Similarly the frequency of the vortex shedding experienced by the transverse rod is $f \approx 330$ [Hz]. We can see on figure 3.13 the general representation of the experience made with Solidworks.

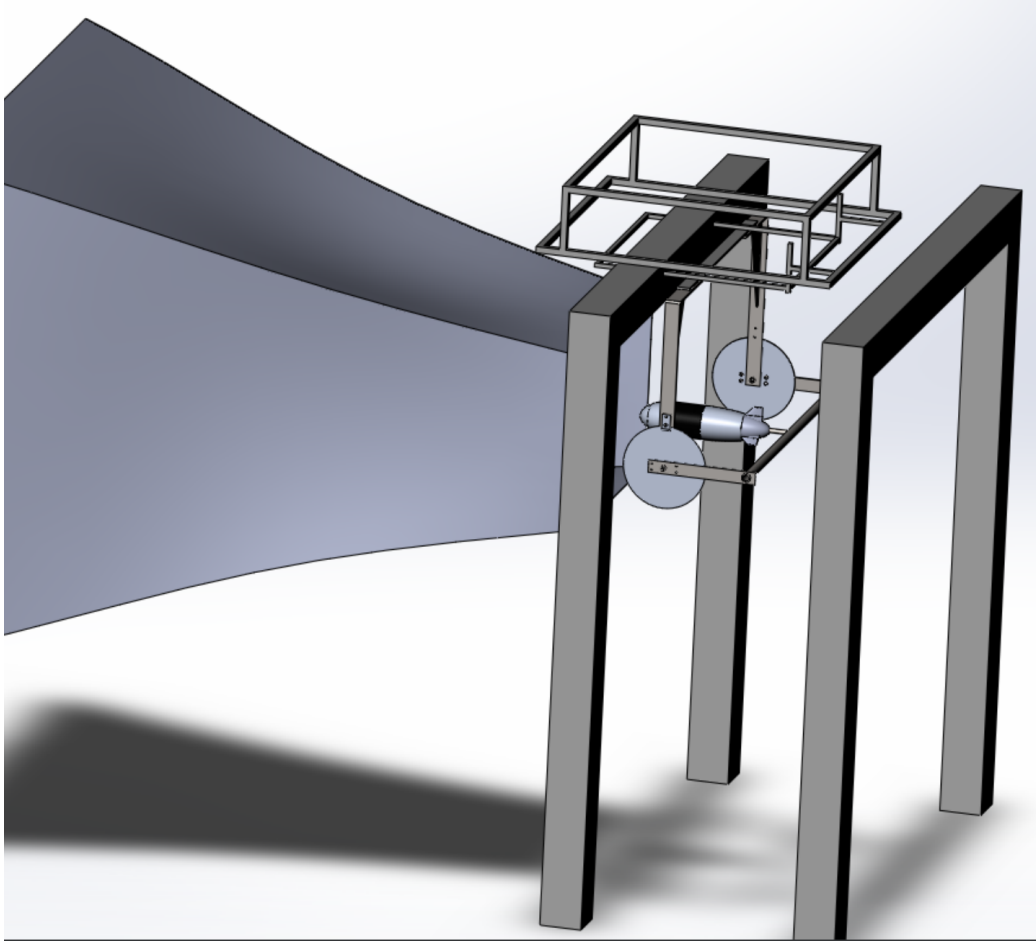


Figure 3.13: Solidworks representation for the whole experimental set-up.

3.3. Design of the "0 degree of angle of attack" experiment

We realized later that we needed a better way to measure lift and drag forces at zero angle of attack as the contribution of the transverse rod was not easily removed. We thus designed another experiment in order to get those measures. It consists of a rigid fixed structure on which the airship is mounted with zero angle of attack as shown in figure 3.14. The "T" part is made of two flat steel pieces welded together, horizontal branch of the "T" will be screwed to the aerodynamic balance. The tube which will hold the airship is made of stainless steel and is also welded to the bottom of the "T"

3.4. Design of the fin experiment

Using the same tiltable support as for the airship experiments, we made a setup allowing us to get the polar of the fins. This setup consists in a double fin paired symmetrically by their root and linked by a core piece (see figure 3.15). The dimensions of this paired fin are 124[mm] for the middle chord and 179 [mm] for the span. Each fin is a scale up of a factor 2.857 relative to

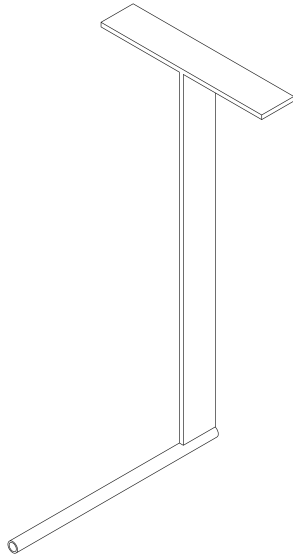


Figure 3.14: Solidworks representation of the "0 degree of angle of attack" experiment

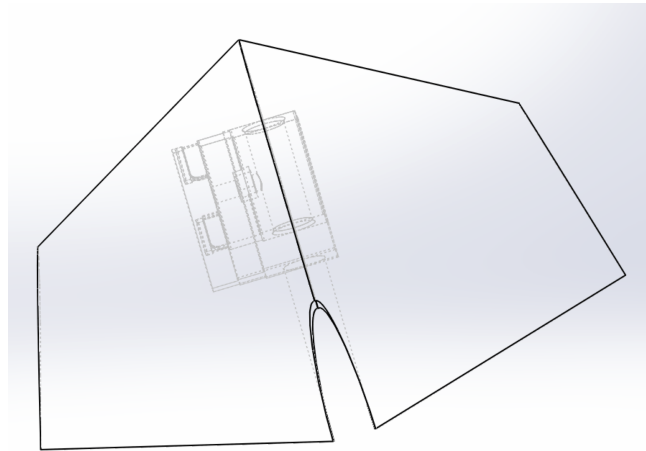


Figure 3.15: Solidworks view of the paired fin

the fin on the stern of the airship experiment. The core piece holds on the support tube with a pressure screw and is nested in both fins. All the three parts have been 3D-printed with ABS. The core is glued to the left wing and the right wing is attachable to the core by means of a slide system which make it a non permanent assembly.

The experiment is made of a pair of fin to avoid wingtip like effect on the root side of the fin. We will then be careful to divide by two the measured drag and lift forces to get the performances of one fin only.

4. Airship experiment

4.1. Balance calibration

Before doing any measurements, we have to calibrate the balance in order to verify that the linearity of the measurements is ensured despite the rather heavy weight of our experimental setup. It turns out that the balance is linear as shown in the Figure 4.1. We still have to be careful as if the slope observed during the calibration is constant - no matter ambient conditions - it is not the case for the “zero”. Thus, before each measurements series, we have to carefully read the current “zero”.

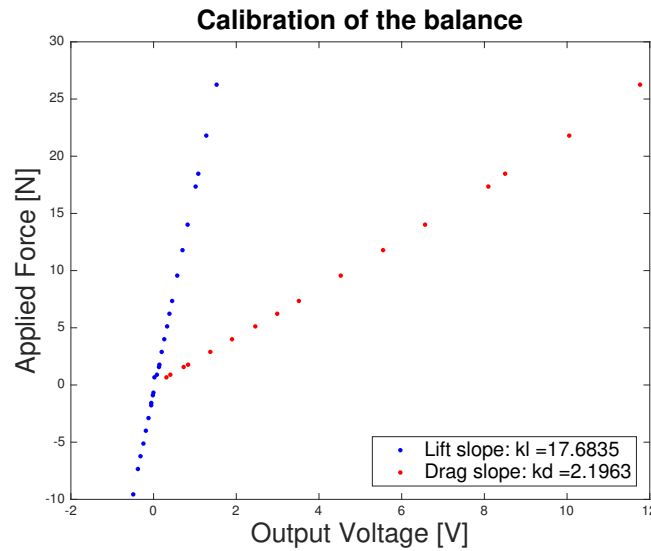


Figure 4.1: Experimental calibration points of the balance

To calibrate the balance, we took a series of weights going from tens of grams to several kilograms and we suspended them to the support reading the output voltages of the balance with a voltmeter. For the calibration of the balance in the z direction (lift), we just suspended the weights freely to the support. For the calibration in the x direction (drag) we used a pulley to pull horizontally on the support.

4.2. Torque meter calibration

The figure 4.3 shows that the torque meter also has a linear behavior, we calibrate it the same way we have calibrated the balance in the x direction.

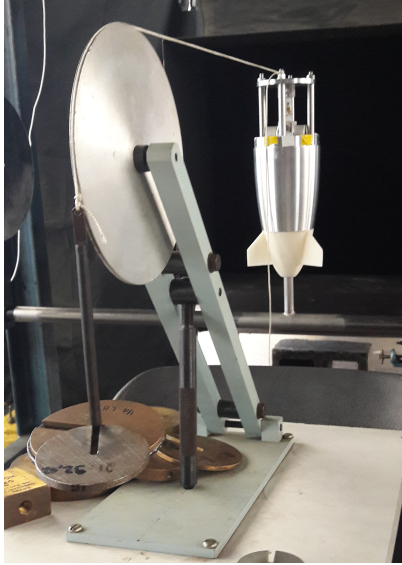


Figure 4.2: Set up for torque meter calibration

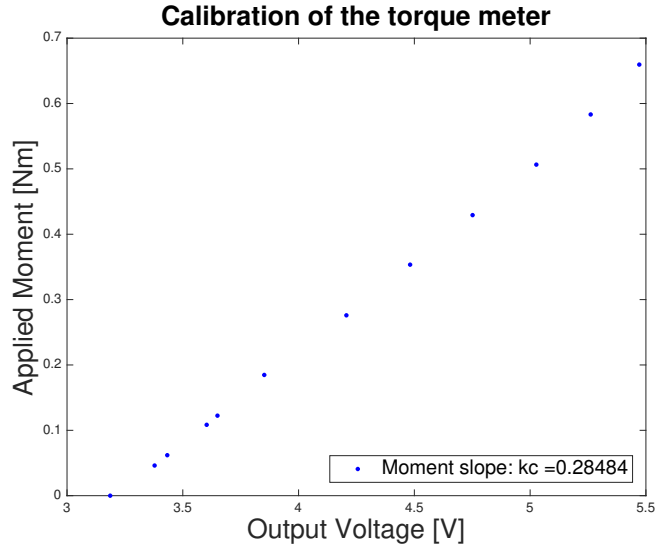


Figure 4.3: Experimental calibration points of the torque meter

We impose a torque with weight and a pulley for pulling horizontally then we measure output voltage. The calibration set up is shown in figure 4.2.

4.3. Experimental procedure

4.3.1. Setup

Set the rotating support in place by screwing it to the perforated slat of the balance provided for this purpose.

Table 4.1: Summary of airship experiments

		Pitch+	Pitch-	Yaw
No Fin	No Tripping	EXP1		
	Tripping	EXP2		
Fin	No Tripping	EXP3	EXP4	EXP5
	Tripping	EXP6	EXP7	EXP8

Set the airship in place: First, choose an experiment from the table 4.1 then assemble the stern depending on the chosen experiment: stern can be rotated by 90 degrees steps. All the measurements are done along the same balance axis. It is the stern orientation which determine if we are doing measurements in pitch or in yaw.

Then assemble ball bearings and support core on the rear ellipsoid piece then assemble caging tube and slat support disc.

Next, Impale the airship on its support and fix it on the shaft with the pressure screw and tighten the aluminium slat between the two jaws.

Finally, put or not a tripping disc in the nose of the airship and connect the rear part of the airship to the front part of the airship with the PVC cylinder. Those three sub-assemblies are held by friction.

Data acquisition

During a campaign of measure i, we measure drag and lift or moment going from $-15[^\circ]$ to $98[^\circ]$ of angle of attack. Generally, we tried to have three campaigns of measurement per experiment in order to ensure its accuracy. Before each campaign we record the zero of the balance V_{0i} , the atmospheric pressure, the temperature and we ensure the Pitot is set at $0[mm_{H20}]$ as on figure 4.4. As explain in 2.2.1, it allows us to get ρ and U_∞ when we combined them with the Pitot measurements once airflow set in movement.

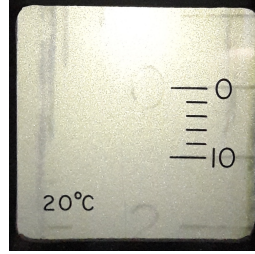


Figure 4.4: Pitot well tared at zero

Drag and Lift: At each angle of attack j set with the protractor disc, we record one voltage data point for drag and one for lift. Each of those data points ($\bar{V}_{ij}$) is the mean of 50 sampled voltage point taken every 0,3 seconds by the computer. We also record each standard deviation ($s_{V,ij}$) relative to this mean. Each data point is converted into nondimensional coefficient using following relations:

$$\bar{V}_{ij} \leftrightarrow C_{ij} = \frac{(\bar{V}_{ij} - V_{0i}) \cdot k_i}{(\frac{1}{2}\rho U_\infty^2)_i V^{\frac{2}{3}}}$$

$$s_{V,ij} \leftrightarrow s_{C,ij} = \frac{s_{V,ij} \cdot k_i}{(\frac{1}{2}\rho U_\infty^2)_i V^{\frac{2}{3}}}$$

With k_i either equal to k_l or k_d , the Newton to Volt conversion factor, depending if it is a lift or a drag measurement. The volume of reference V is the volume of the airship.

Moments: At each angle of attack j set with the protractor disc, we record one data point ($\bar{V}_{ij}$) which is the mean of 5000 sampled voltage points taken every 1 millisecond by the computer. We also record each standard deviation ($s_{V,ij}$) relative to this mean. Each data point is converted into a nondimensional coefficient using following relations:

$$\bar{V}_{ij} \leftrightarrow C_{ij} = \frac{(\bar{V}_{ij} - V_{0i}) \cdot k_i}{(\frac{1}{2}\rho U_\infty^2)_i V}$$

$$s_{V,ij} \leftrightarrow s_{C,ij} = \frac{s_{V,ij} \cdot k_i}{(\frac{1}{2}\rho U_\infty^2)_i V}$$

With k_i equal to k_c , the Newton meter to Volt conversion factor.

Mean of the campaigns: Once the three campaigns of an experiment have been nondimensionalized, we compute their mean and standard deviation using the theory explained in section 1.8.

For instance, in the case of forces measurements, where each point i is the mean of 50 measurements it gives:

Experiment Grand Mean:

$$\bar{C}_j = \frac{1}{3} \sum_{i=1}^3 C_{ij}$$

Experiment Grand Standard Deviation:

$$s_{Cj} = \sqrt{\frac{50 \cdot \sum_{i=1}^3 ((\bar{C}_j - C_{ij})^2) + (50 - 1) \cdot (\sum_{i=1}^3 s_{C,ij}^2)}{3 \cdot 50 - 1}}$$

4.3.2. Data correction

Lift and drag measurements: cancelling the support contribution

Direct subtraction of the support Our first idea was to subtract the drag and lift coefficient of the support alone from that of the experiments. It gives odd results such as negative drag coefficient. We then thought to implement a law of subtraction where a percentage of the drag of the support would be subtracted depending of the percentage of area hidden by the airship model. We had no conclusive results either.

Correction using the "zero degree angle of attack (AoA) experiment"

We decided afterwards to design a new experiment where support contribution would be much lower and which would give us a reliable value for lift and drag coefficient at zero angle of attack. This experiment is shown in the figure 4.5. Again we subtracted support drag and lift to that of the measure. We conducted this experiment for the different configurations: results are displayed in the table 4.2. We obtained a plausible value of C_{D_0} . We used them to translate every point of our C_D and C_L curves so that the coefficient value at zero angle of attack corresponds to that given by this experiment.

Table 4.2: Experimental C_{D_0} of the airship

	No Fins	Fins
Smooth prow	0.02769	0.04294
With toothed tripping disk	0.05175	0.06043



Figure 4.5: Zero degree angle of attack experiment

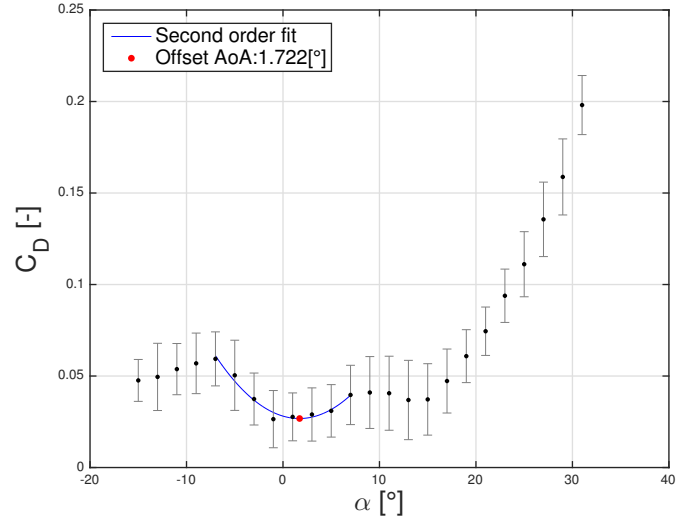


Figure 4.6: AoA offset identification

Offset to true zero angle of attack

After doing EXP1 (see Table 4.1), we expected a symmetric drag curve around 0° of AoA and no lift at zero angle of attack because of the total symmetry of the setup. Focusing on the drag curve, we observed a small offset angle possibly coming from zero placement error on our protractor disc. We computed a fit of the drag curve for small angles between -7 and 7 degrees. As shown in figure 4.6, we used a second order polynomial fit for which the minimum gives us the zero angle of attack offset. We used this offset to correct our C_D and C_L curves.

4.4. Results

The following results were obtained for several configuration of the airship in the wind tunnel. The figures 4.7 and 4.8 illustrate two of the different configurations.



Figure 4.7: Smooth airship in wind tunnel (EXP1)

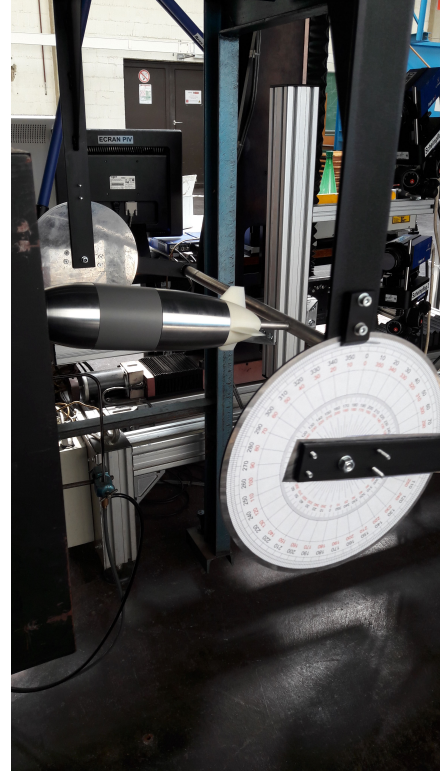
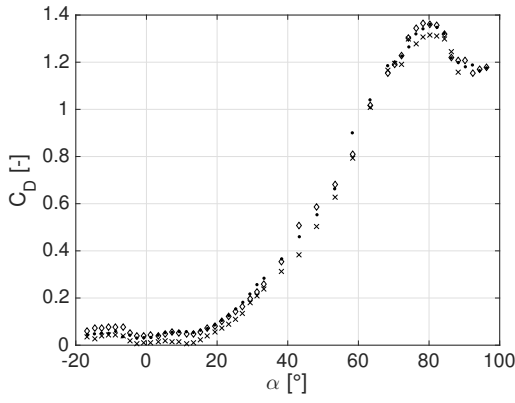


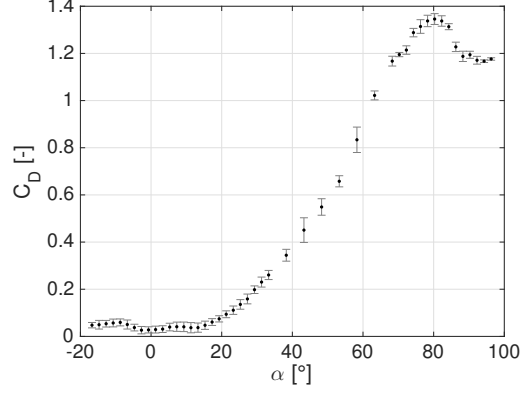
Figure 4.8: Airship with fins in wind tunnel (EXP4)

4.4.1. Bare hull (EXP1) and tripped hull (EXP2)

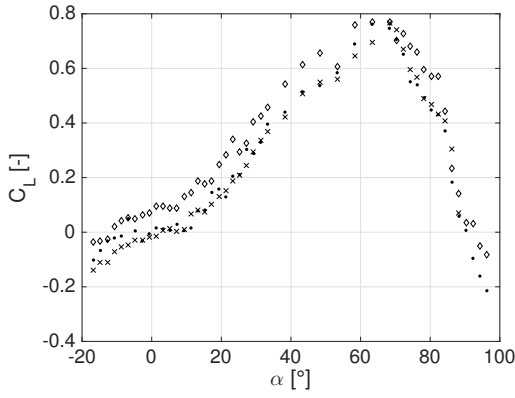
Figure 4.9: Experimental points for the bare hull (EXP1 from the table 4.1)



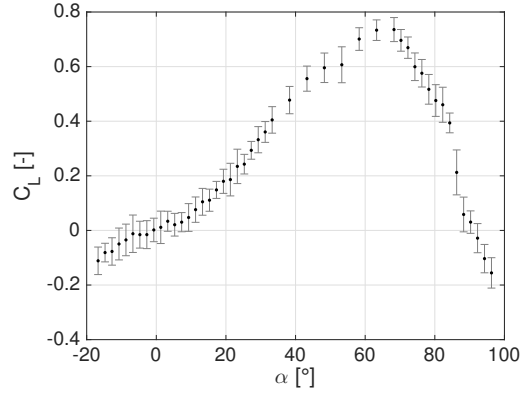
(a) Measured C_D vs. α .



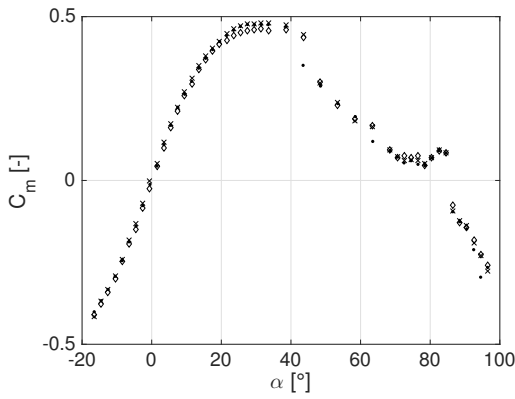
(b) Average C_D and its standard deviation.



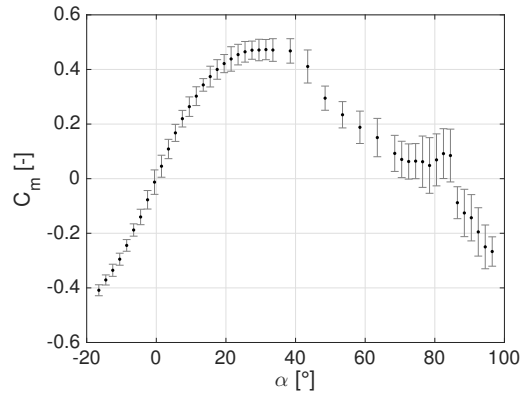
(c) Measured C_L vs. α .



(d) Average C_L and its standard deviation.

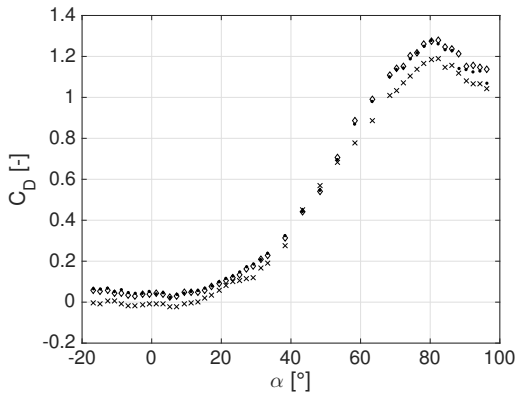


(e) Measured C_m vs. α .

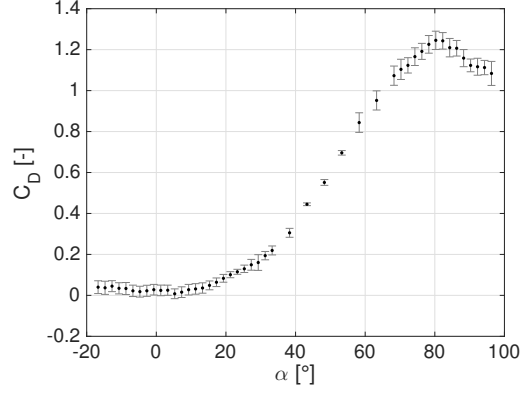


(f) Average C_m and its standard deviation.

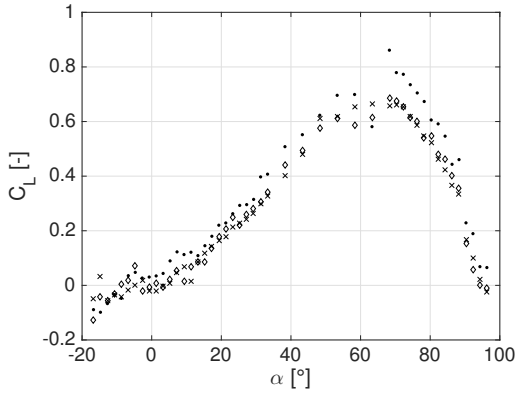
Figure 4.10: Experimental points for the hull with tripping disc (EXP2 from Table 4.1)



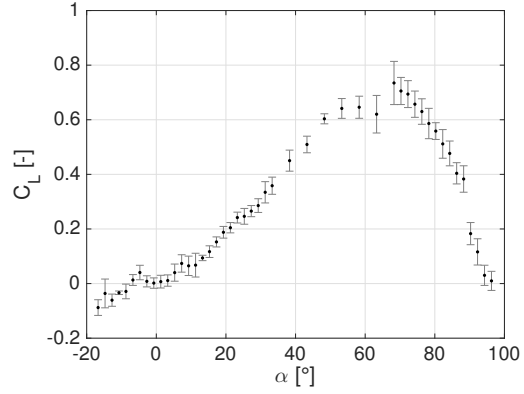
(a) Measured C_D vs. α .



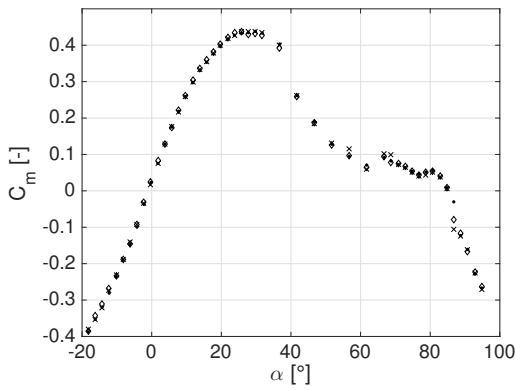
(b) Average C_D and its standard deviation.



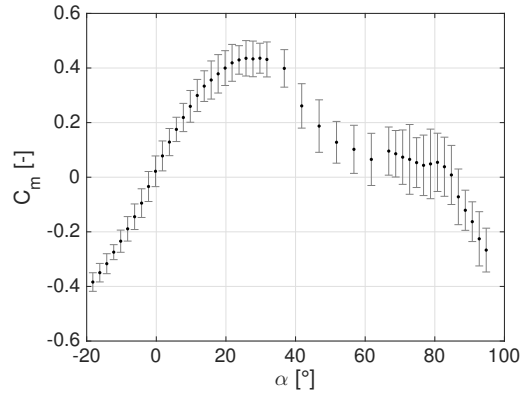
(c) Measured C_L vs. α .



(d) Average C_L and its standard deviation.



(e) Measured C_m vs. α .



(f) Average C_m and its standard deviation.

Observations

It can be noticed by comparing the figure 4.9f with the figure 4.9e as well as the figure 4.10f with the figure 4.10e that despite low dispersion of the

data, the standard deviation of the measurements of the pitching moment continuously increases with angle of attack. This is directly linked to the design of the torque meter which basically acts as a spring subject to vibration induced by the airflow. The steeper the angle of attack becomes, the more excited the system becomes. It is true even when the moment coefficient is on its downward slope. This proves that this is not directly connected to the value of the C_m but is instead connected to the angle of attack. The more vertical the airship is, the more its section seen by the flow is propitious to vortex shedding emergence which will eventually end up triggering Strouhal frequencies into the system.

Despite an increasing of the standard deviation, the different repetitions of this experiment are very close to each other (see figure 4.10e). It is probably because each measurement point is the average of 5000 voltage point taken at 1[kHz]. We saw in section 3.2.2 that the estimated Strouhal frequencies are up to 330[Hz]. At a 1[kHz] rate of acquisition, the 5000 voltages point are a good sample of the sinusoidal oscillation¹ of the airship and the average value doesn't vary much.

It can also be noticed by comparing figure 4.9d with figure 4.9b and figure 4.10d with figure 4.10b that standard deviations for lift measurements are always bigger than for drag measurements. Lift is measured by another sensor than drag which seems more sensitive.

¹ The Shannon sampling theorem says that to correctly sample a signal, the sampling frequency must be at least two times the frequency of that signal.

Effect of the tripping disc on the smooth airship

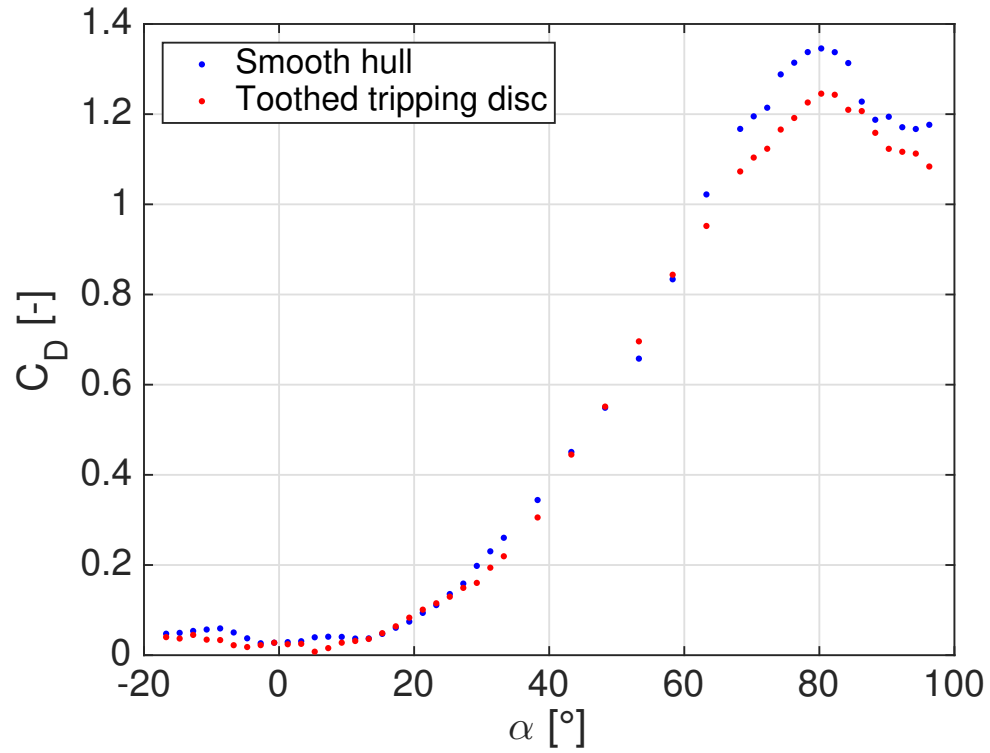


Figure 4.11: Effect of the tripping disc on C_D

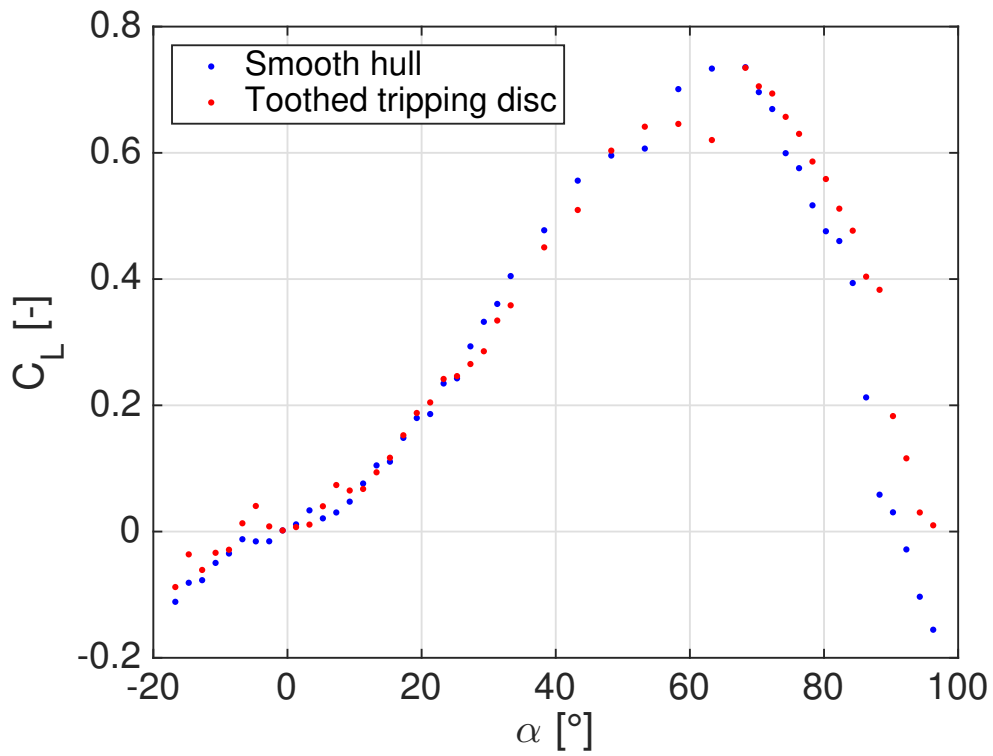


Figure 4.12: Effect of the tripping disc on C_L

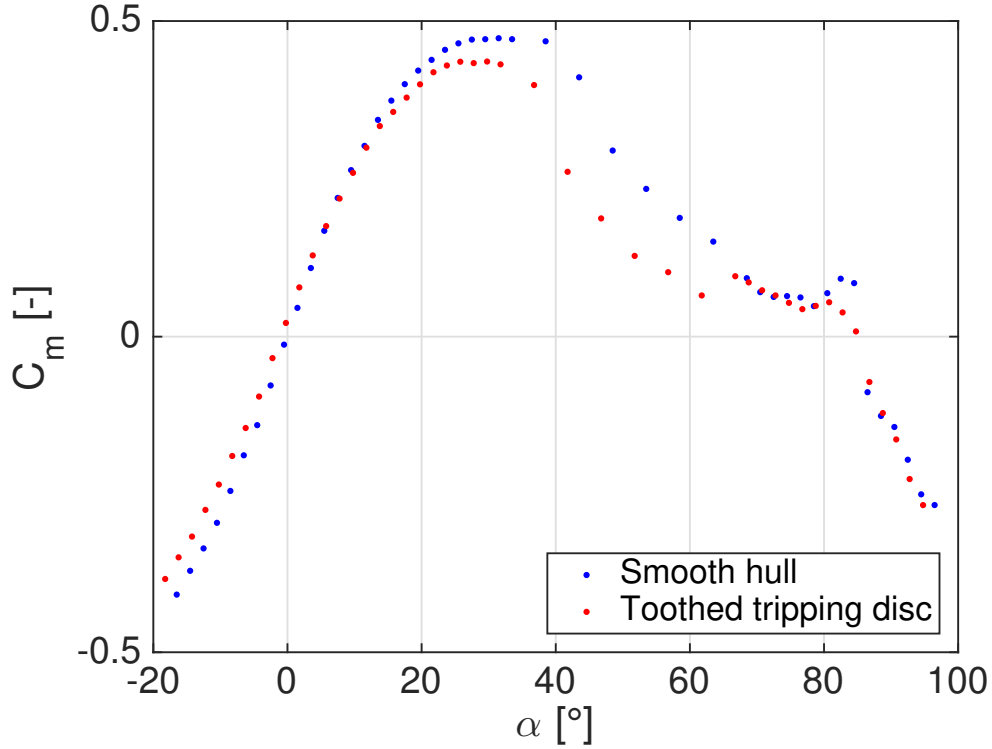


Figure 4.13: Effect of the tripping disc on C_m

We can also remark by looking at figure 4.11 that, the toothed tripping disc compared to the smooth hull doesn't really have an impact on the drag coefficient for α between -15° and $\sim 60^\circ$. On the other hand we observe a reduction of the drag from 65° to 98° for the hull with tripping disc.

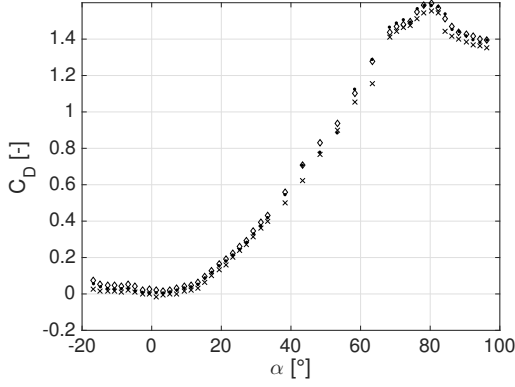
From figure 4.12, we observe that the lift coefficient is quite similar for angle of attack smaller than 25° . After that and up to 68° the hull with toothed disc tend to produce less lift. After 68° , the tripping disc seems to increase lift compared to the bare hull, so its the opposite to what is happening on the drag curve.

Looking at figure 4.13, we can observe that, the toothed tripping disc reduces the moment from $\sim 18^\circ$ to around $\sim 65^\circ$. As for the lift curve, we observe that the two curve fit again for an angle of attack around 68 degrees. It is probably because at those angles tripping has no effect on the boundary layer. We make the hypothesis that, the disc is simply an obstacle subjected to windage: from 68 degrees to upper, and that it pushes the nose upward increasing lift but also forcing the flow to align with its plane. The flow the "sees" a circular cross section instead of a noze which limit circulation over the nose and finally reduces the drag. Those two effect on lift and drag are both in the x-y plane and their effect counteract making the two moment coefficient identical above 68 degrees.

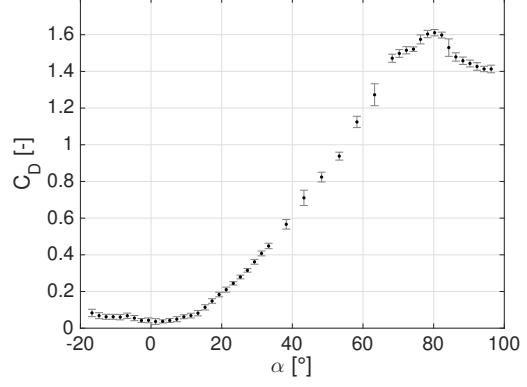
4.4.2. Fins and no tripping disc (EXP3, 4 and 5)

Positive pitching angle

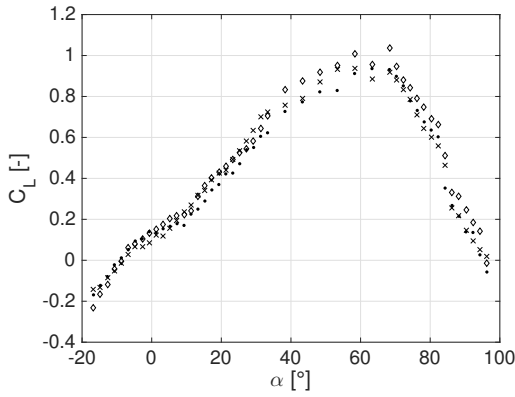
Figure 4.14: Experimental points for positive pitching angle: airship with fins but without tripping disc (EXP3 from Table 4.1)



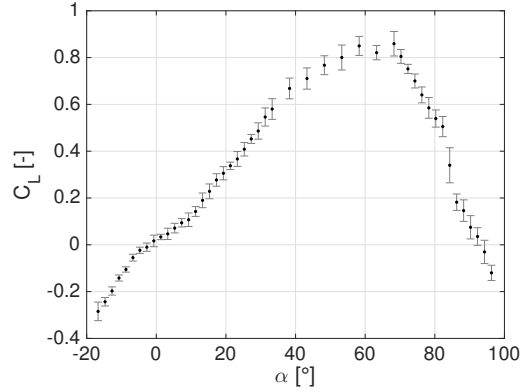
(a) Measured C_D vs. α .



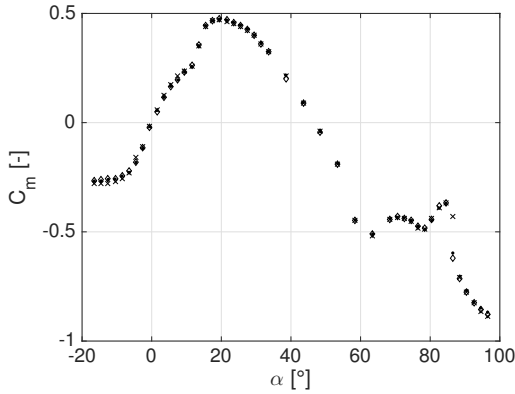
(b) Average C_D and its standard deviation.



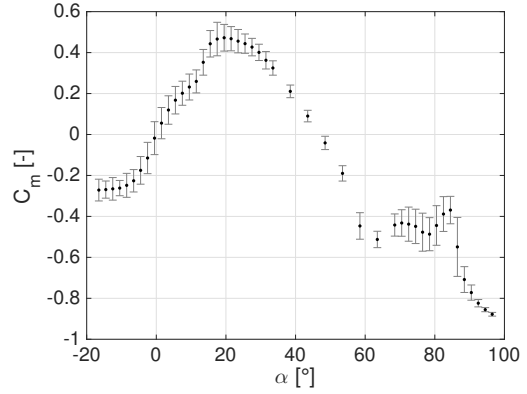
(c) Measured C_L vs. α .



(d) Average C_L and its standard deviation.



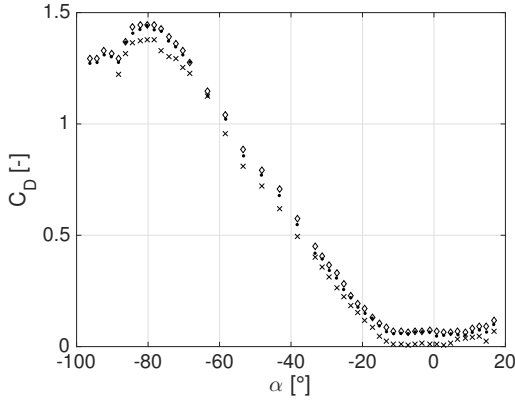
(e) Measured C_m vs. α .



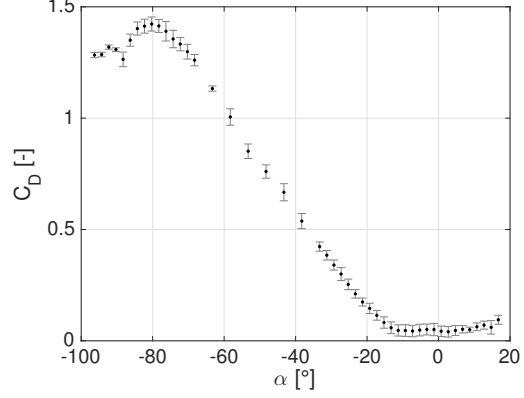
(f) Average C_m and its standard deviation.

Negative pitching angle

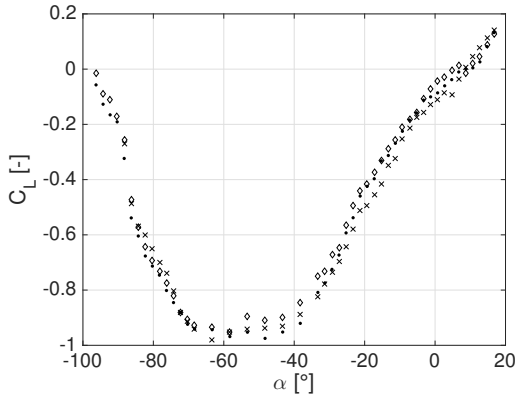
Figure 4.15: Experimental points for negative pitching angle: airship with fins but without tripping disc (EXP4 from Table 4.1)



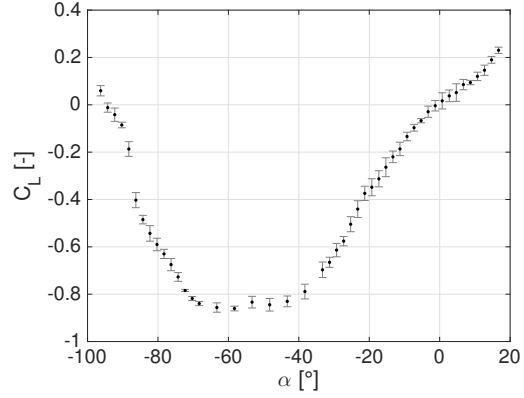
(a) Measured C_D vs. α .



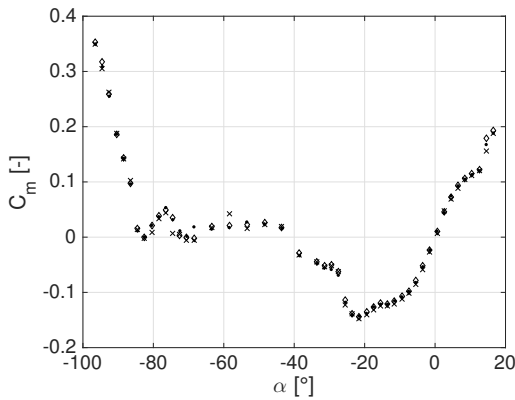
(b) Average C_D and its standard deviation.



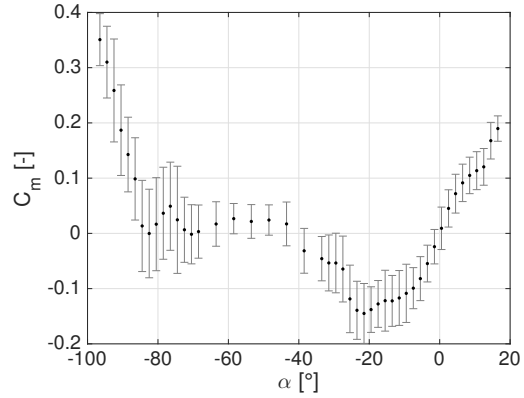
(c) Measured C_L vs. α .



(d) Average C_L and its standard deviation.



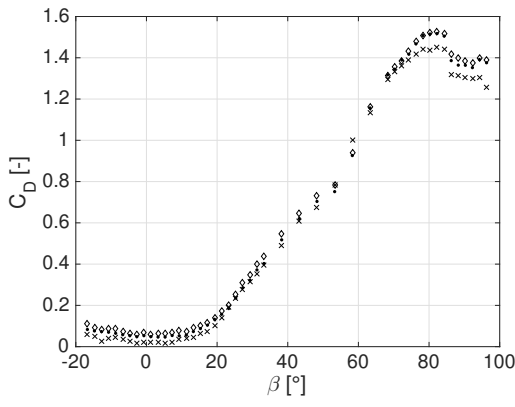
(e) Measured C_m vs. α .



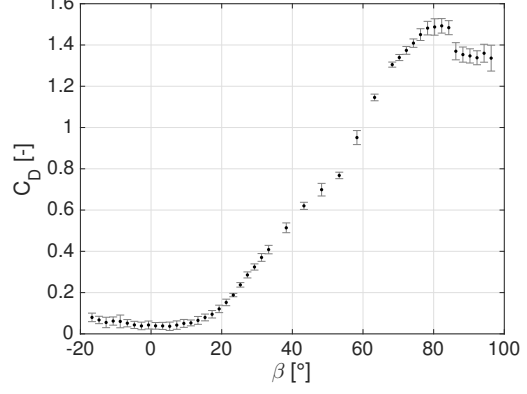
(f) Average C_m and its standard deviation.

Yawing angle

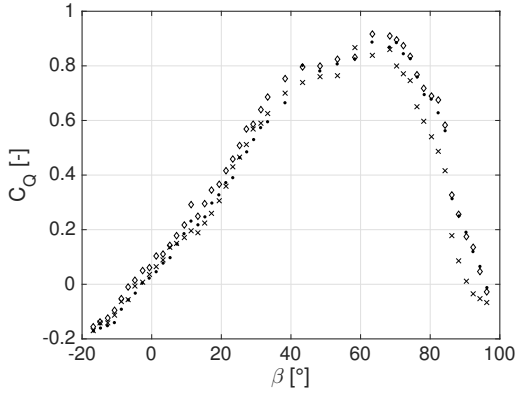
Figure 4.16: Experimental points for yawing angle: airship with fins but without tripping disc (EXP5 from Table 4.1)



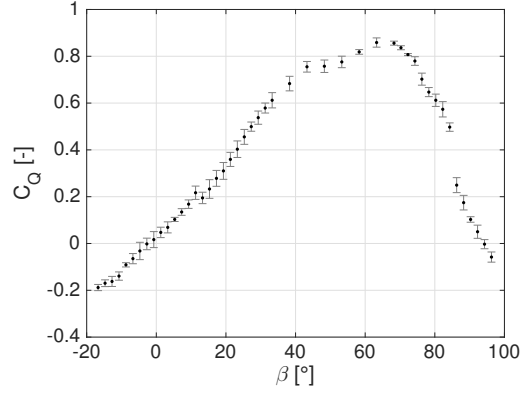
(a) Measured C_D vs. β .



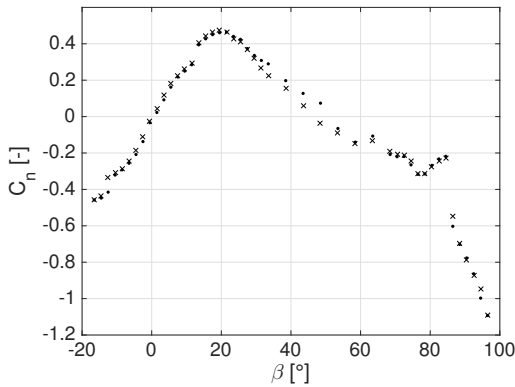
(b) Average C_D and its standard deviation.



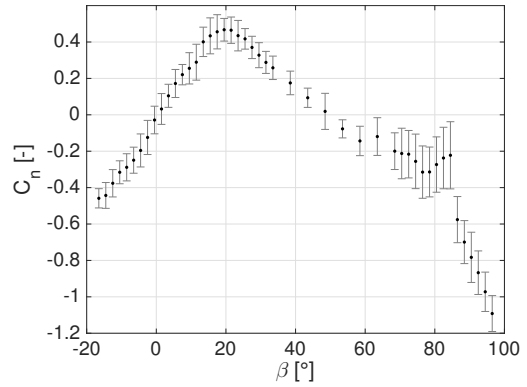
(c) Measured C_Q vs. β .



(d) Average C_Q and its standard deviation.



(e) Measured C_n vs. β .



(f) Average C_n and its standard deviation.

We display the results of those three fins configurations (pitch+, pitch-

and yaw) in the same graphs to show the difference in aerodynamic behaviour with respect to the angle of attack:

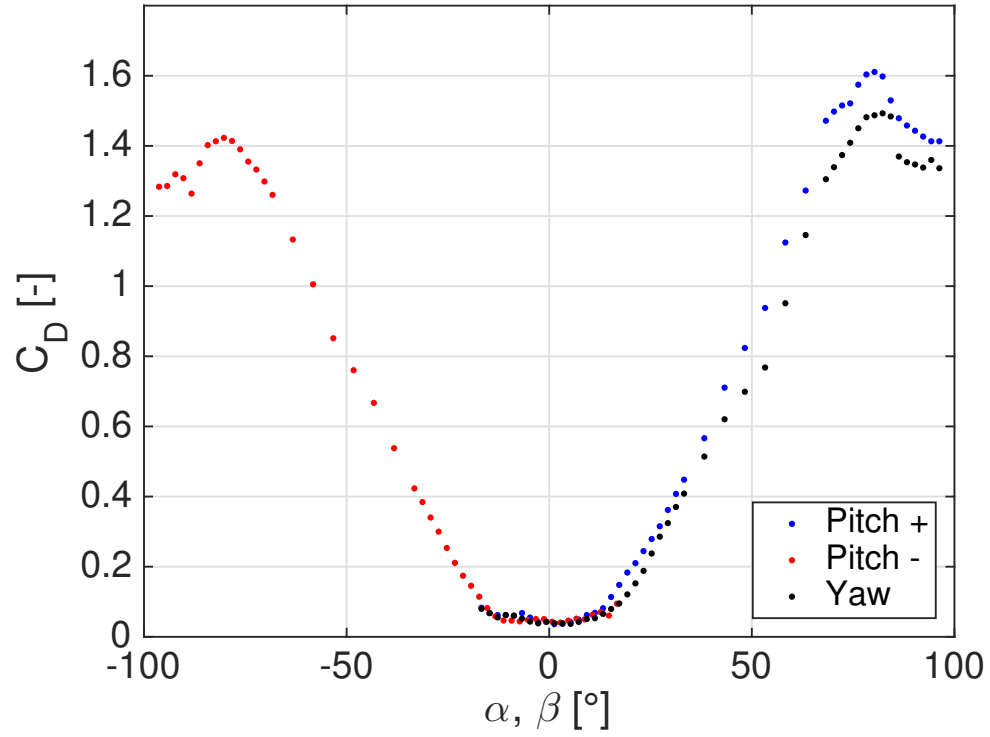


Figure 4.17: Drag coefficient C_D for different AoA

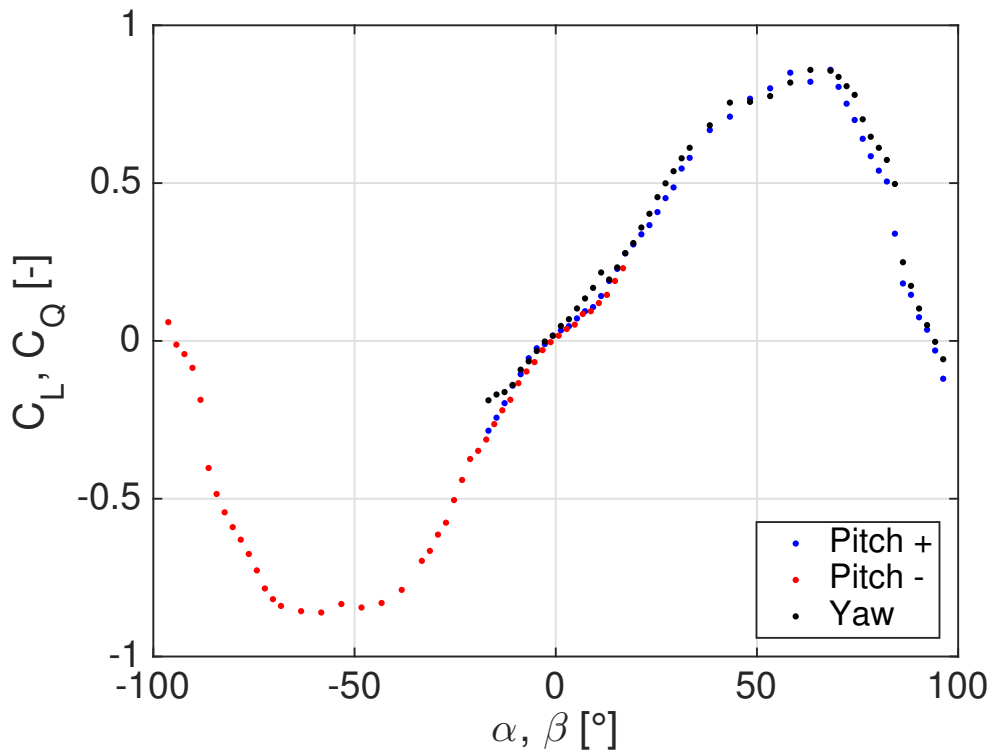


Figure 4.18: Lift coefficient C_L and side force coefficient C_Q for different AoA

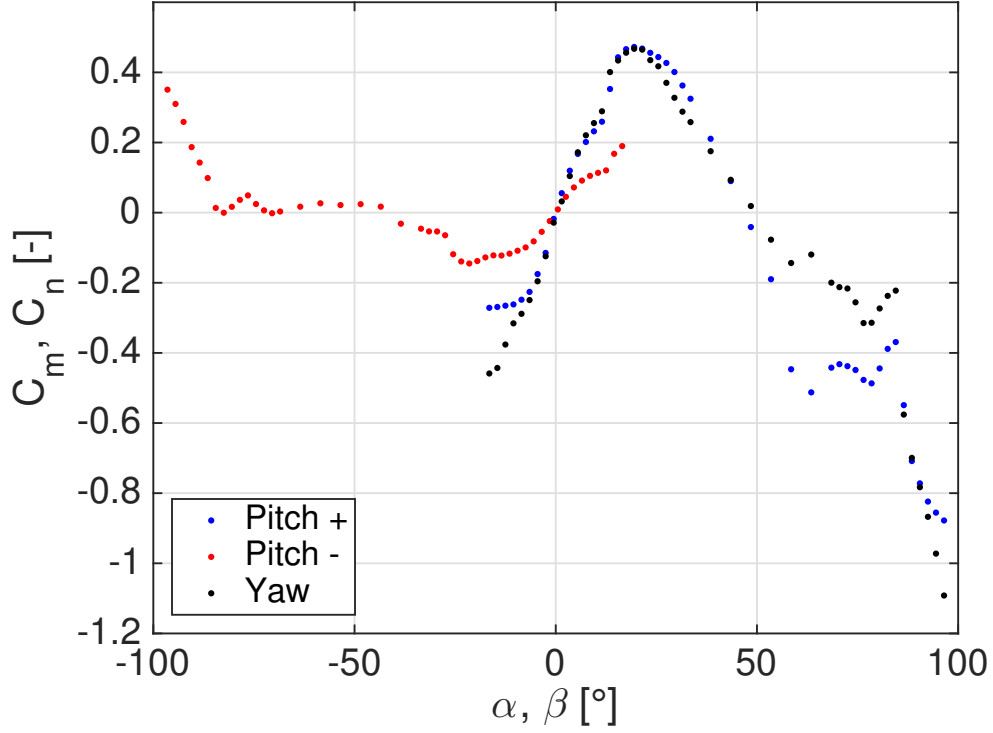


Figure 4.19: Moment coefficient C_m and C_n for different AoA

Observations

If we compare the drag coefficient in the figure 4.14b (EXP3: airship with fins but without tripping disc in positive pitching angle) and figure 4.9b (EXP1: bare hull), the maximum drag coefficient for the airship with fins is higher than the bare hull: the fins induce more drag.

The maximum lift coefficient is more important for the airship with fins than the bare hull as we can see by comparing figure 4.14d with figure 4.9d: the fins also induce more lift.

By comparing the moment coefficient in the figures 4.14f and 4.9f, we can see that, the slope of the moment change sign earlier for airship with fins (at $\sim 20^\circ$ of AoA) than the smooth airship (at $\sim 40^\circ$ of AoA). Moreover the moment coefficient changes sign and becomes negative between 45 and 50 degree for the airship with fins it appends at around 85 degrees for the bare hull.

As we can see on figure 4.19, the airship with fin (either for in pitch or in yaw) is unstable from 0 to 20 degrees, stable from 20 to 50 degrees then unstable again as the C_m changes sign.

We can observe on figures 4.17, 4.18 and 4.19 that the drag, lift and moment are not symmetric between positives and negatives angles of attack. This result is well expected as the fins are not symmetrically disposed about the x-y plane. For the same reason we can observe that yawing moment

and drag are not exactly the same as the positive pitching moment and drag. On the other hand lift and side force are pretty close for those configurations.

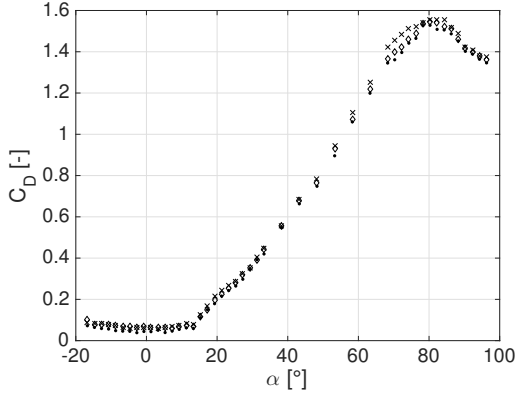
In figure 4.19, the pitching moment for negative AoA doesn't match the pitching moment for positive AoA. We observe that, if we multiply by a factor of two the experimental values obtained for the pitching moment for negative AoA, both graphs fit perfectly. We do not have validated explanation for this observation. We make the hypothesis that it is due to the fact that we conducted the experiment to obtain values of the pitching moment for negative AoA much later compared to the others experiments and after having changed parameter on the acquisition electronics. Moreover the slat positioning in the airship is quite sensitive to the mechanical assembly.

4.4.3. Fins with tripping disc (EXP6, 7 and 8)

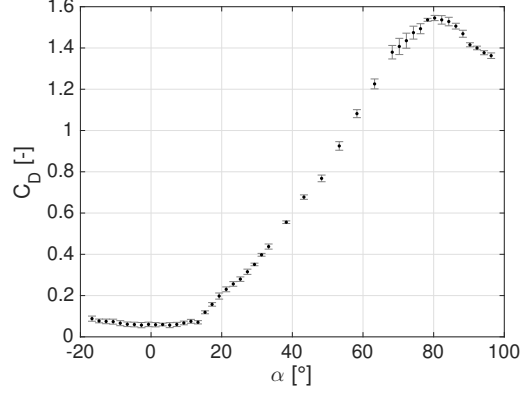
Note that, for theses configuration, we didn't measure the pitching moment. Like mentioned previously, we encountered a problem with the slat. Perhaps it was damaged during the assembling and disassembling process of the slat. Unfortunately, we didn't manage to get the same configuration as before and the calibration process failed for these three experiments.

Positive pitching angle

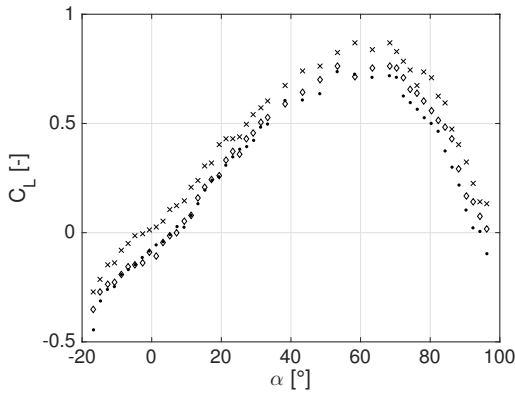
Figure 4.20: Experimental points for positive pitching angle: airship with fins and toothed tripping disc (EXP6 from Table 4.1)



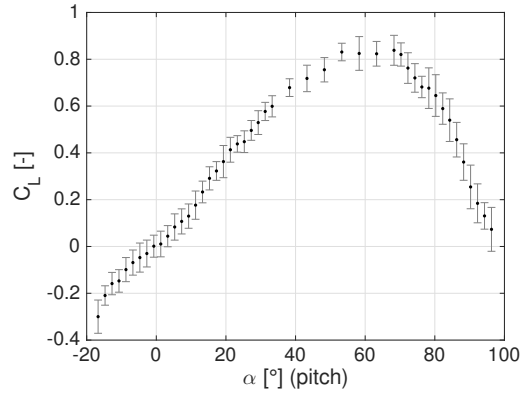
(a) Measured C_D vs. α .



(b) Average C_D and its standard deviation.



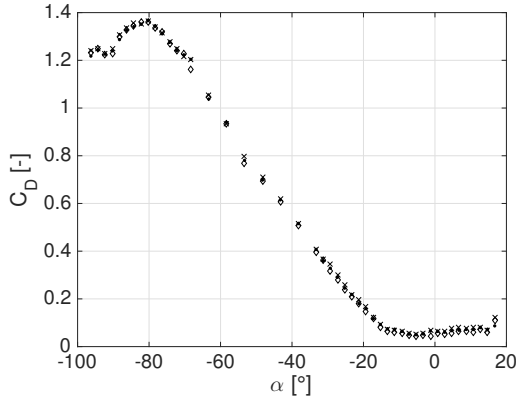
(c) Measured C_L vs. α .



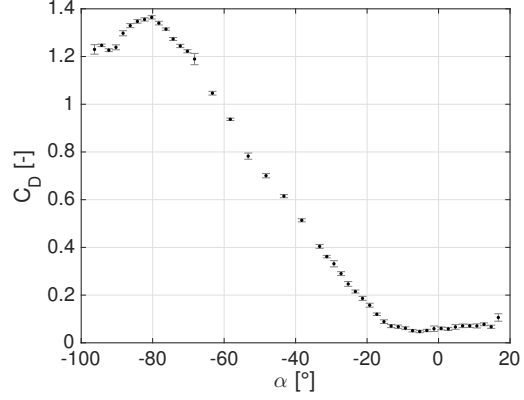
(d) Average C_L and its standard deviation.

Negative pitching angle

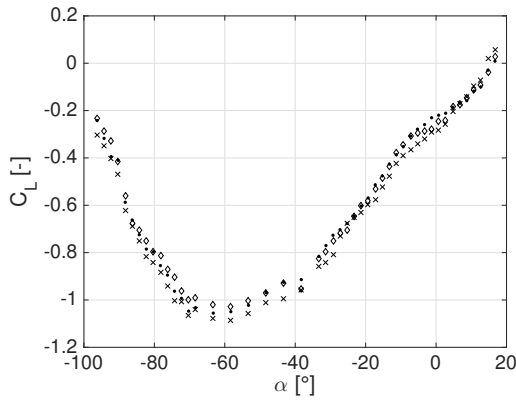
Figure 4.21: Experimental points for negative pitching angle: airship with fins and toothed tripping disc (EXP7 from Table 4.1)



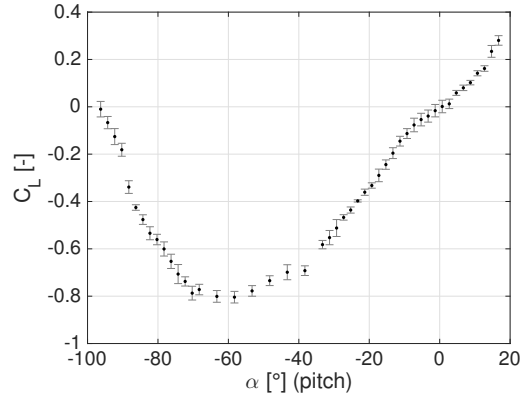
(a) Measured C_D vs. α .



(b) Average C_D and its standard deviation.



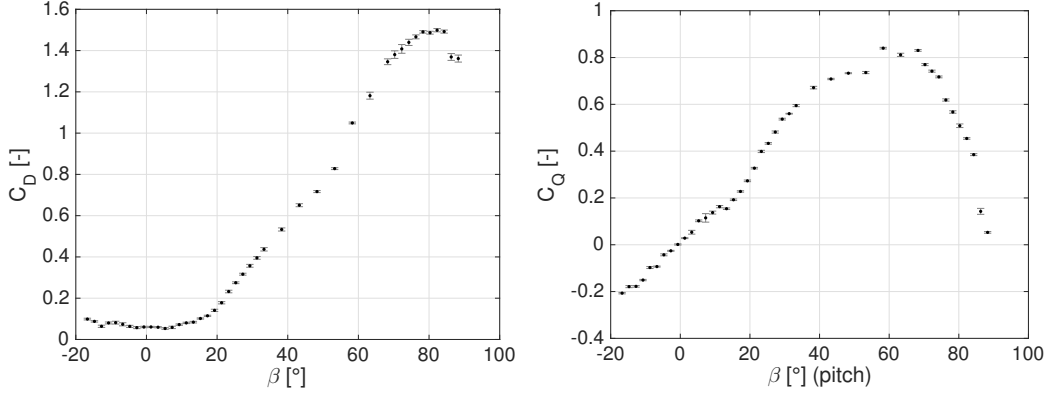
(c) Measured C_L vs. α .



(d) Average C_L and its standard deviation.

Yawing angle

Figure 4.22: Experimental points for yawing angle: airship with fins and toothed tripping disc (EXP8 from Table 4.1)



(a) Measured C_D vs. β and its standard deviation (b) Measured C_Q vs. β and its standard deviation.

Effect of the tripping disc on the airship with tooth tripping disc

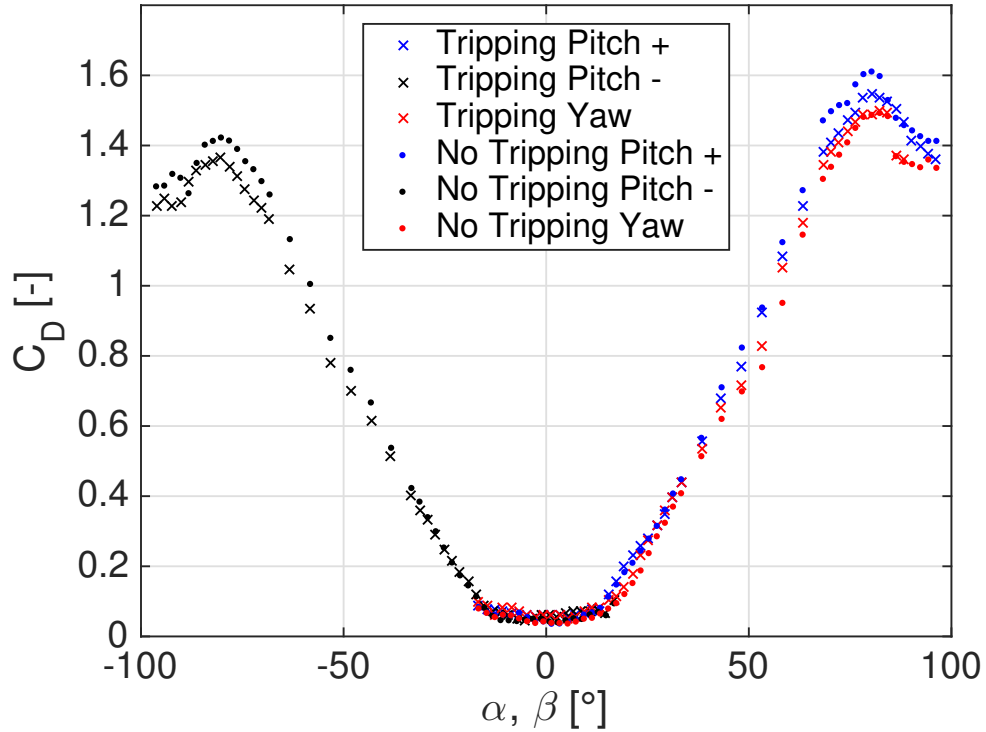


Figure 4.23: Comparison of drag coefficient C_D for finned airship with or without tripping disc

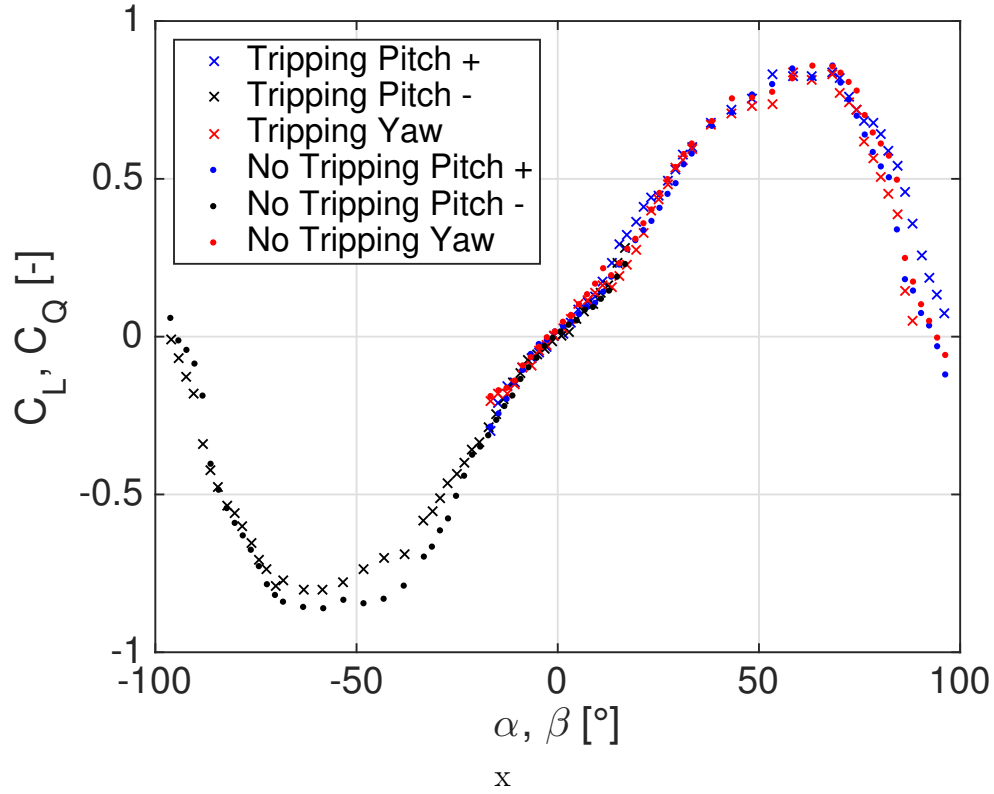


Figure 4.24: Comparison of lift coefficient C_L and side force coefficient C_Q for finned airship with or without tripping disc

Observations

Again we can observe the effect of the tripping disc for the different configurations in figure 4.23 and 4.24.

As we can see in figure 4.23 and 4.24, for the either positive or negative pitching angles of attack as well as for yawing angles of attack, the trip has little effect on the lift and drag coefficient. The tripping disc tend to reduce both lift and drag coefficients, this confirm the observation made for experiments without fins.

We observed that the configuration for which the tripping disc seems to get the most effect is in yaw for the lift coefficients.

5. Fin Experiment

5.1. Experimental procedure

First, we mount the core of the paired fins on the support tube and we tighten it with the pressure screw as shown on figure 5.1. Then we slide in the right fin to get a paired fin as shown in figure 5.2 (junction covered by a black tape).

We read the zero of the balance and we set the desired angle with the "disc brake" and start the measurements. This time only taking measurements with the aerodynamic balance in order to get lift and drag coefficients. As the fins of this experiment are scaled up by a factor 2.857 with regard to the fin of the airship model, we have to adjust the airflow velocity in order to conserve the Reynolds number of the airship experiment. Airflow for this experiment is then set at $35/2.857 = 12.25$ [m/s].

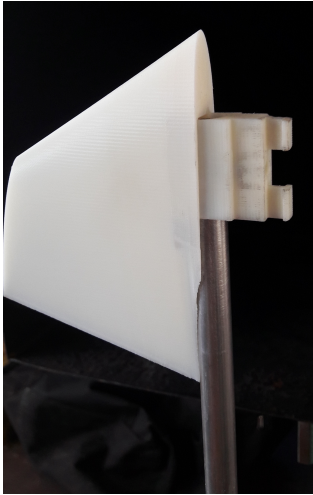


Figure 5.1: Fin core mounted on support axis

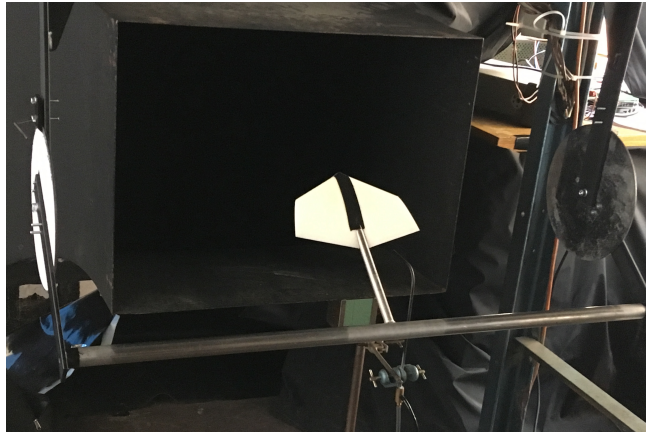


Figure 5.2: Fin in wind tunnel

5.2. Data acquisition and correction

To get the lift and drag curve we repeated the experiment two times recording lift and drag output voltage for angles of interest. The nondimensionalization, average and standard deviation are computed as developed in section 4.3.1 except for the reference surface here taken as the projected surface of the paired fins: 0.014658 [m²].

5.2.1. Offset to true zero angle of attack

The drag curve is expected to be symmetric around the true zero of angle of attack so we make a second order fit of the drag curve datapoints and we computed its minimum (see figure 5.7). Assuming that this minimum gives us the angle of attack offset for this experiment, all our data-points were translated by this offset.

5.2.2. cancelling the support contribution

To get rid of the support contribution in our drag measurement we placed the fin on the “zero degree experiment” to obtain better measurement of the C_{D_0} . We then impose our C_D curve to pass through this point for zero degree angle of attack. To correct the lift curve we translate it downwards to pass by the origin of the $C_L - \alpha$ graph.

5.3. Results

The following figures 5.4 and 5.6 gives the drag and lift average generated by the fin

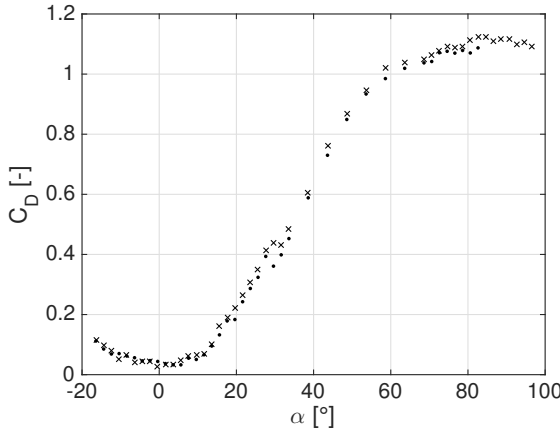


Figure 5.3: Fin: Measured C_D vs. α

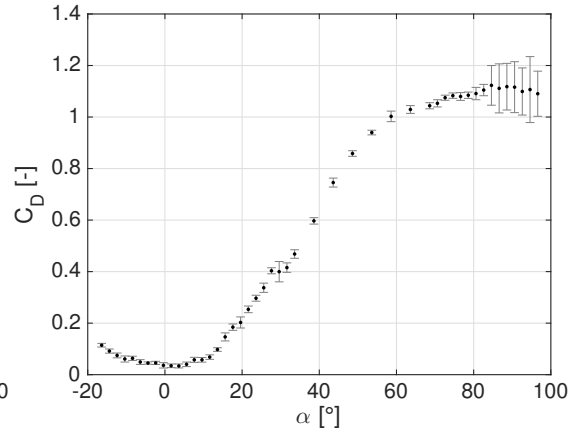


Figure 5.4: Fin: Average C_D and it's standard deviation

Observations

In figure 5.6 it can be seen that the maximum lift appends at 20 degrees of angle of attack. For steeper angles lift seems to remain approximately constant up to 50 degrees before it decreases. The stall point is not clearly established as it could have been in the case of a slender wings. This is probably due to the geometry of the double fin: the aspect ratio $A_R \sim 2.19$ and is close to a delta wing. In this case the lift is produced both by vortex lift and by profile geometry.

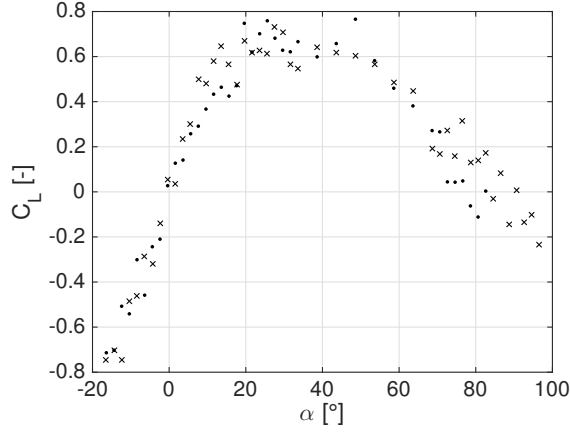


Figure 5.5: Fin: Measured C_L vs. α

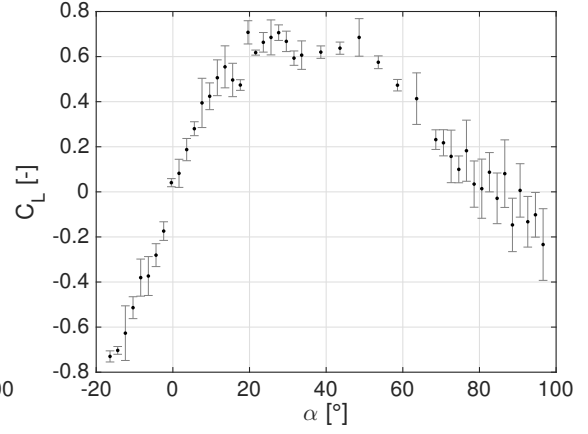


Figure 5.6: Fin: Average C_L and it's standard deviation

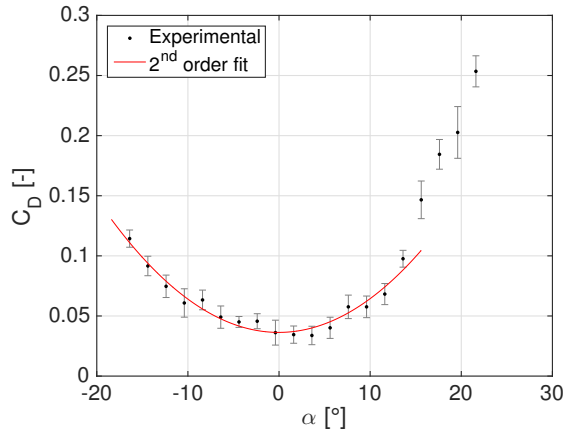


Figure 5.7: Fin- C_D vs. α -small angles and second order fit

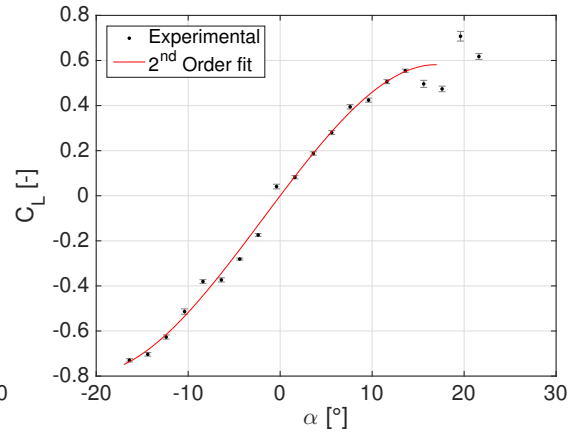


Figure 5.8: Fin- C_L vs. α -small angles and third order fit

6. Comparison with model

6.1. Bare hull aerodynamics

We implemented the models developed in section 2.5 to compare them to our results. Comparison with results of the experiment EXP1 (see table 4.1) are shown in figure 6.1 and figure 6.2. Note that for the Hopkin's model and

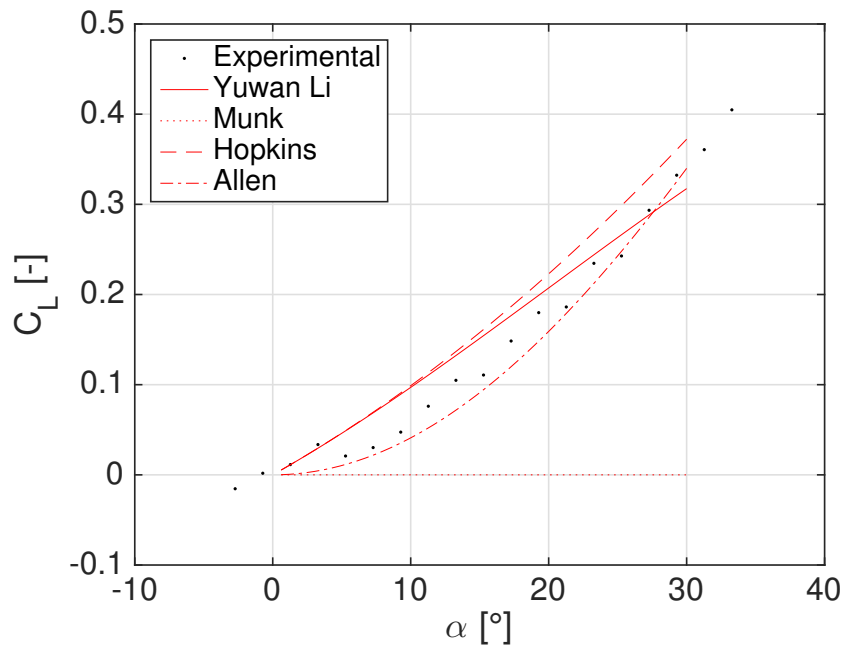


Figure 6.1: EXP1: Bare hull, comparison of experimental data with models for C_L

for the Yuwen Li's model we have a disagreement with how the model has been implemented by Yuwen Li in [24]. Hopkins says in [22] that ϵ_1 is chosen as the "longitudinal distance from body nose to point at which dS/dx has a maximum negative value". We understand it as: the position ϵ_1 such as dS/dx is negative and the closest to zero when Yuwen Li's implementation seems to have been done such as: the position ϵ_1 where $abs(dS/dx)$ is the biggest. We implemented the model according to our understanding as it gave the better results with regard to our measurements.

Looking on figure 6.1 of the lift coefficient, it looks like all the results are close to our experimental points but Allen's model seems to fit the data the better, up to 30 degrees. Other models involving viscosity (Hopkins and Yumen Li) are also close to the data but their fit are worse, especially regarding the curvature.

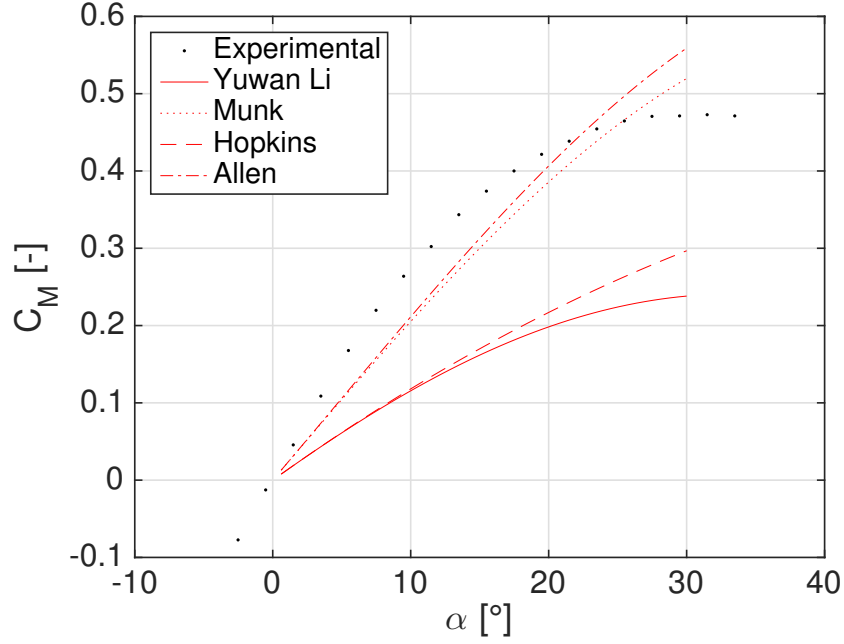


Figure 6.2: EXP1: Bare hull, comparison of experimental data with models for C_M

For the moment coefficient on figure 6.2, no model fit really well the data but as for lift coefficient Allen's model is the closest to our experimental points while Yuwen Li's model is the least convincing model.

Axial drag C_{D0}

We computed an estimation for the axial drag of the bare hull using the formula developed by Hoerner in [23].

$$C_{DH0} = C_F \left(4 \left(\frac{L_a}{D} \right)^{1/3} + 6 \left(\frac{L_a}{D} \right)^{-1.2} + 24 \left(\frac{L_a}{D} \right)^{-2.7} \right) \quad (6.1)$$

with $C_F = 0.045 Re_{La}^{-1/6} = 0.004903$ we obtain $C_{DH0_{HOERNER}} = 0.03954$ which is to be compared to the axial drag at zero angle attack we measure in the "0 degree of angle of attack experiment". This value is displayed in table 4.2 and is $C_{DH0_{EXP1}} = 0.02769$. If we compute the relative error as:

$$err_{C_{D0}} = \frac{C_{DH0_{HOERNER}} - C_{DH0_{EXP1}}}{C_{DH0_{EXP1}}}$$

We get $err_{C_{D0}} = 42.8[\%]$ which is not bad as we approximate friction coefficient in the Hoerner formula. At least the order of magnitude is correct.

6.2. Fin aerodynamics

We used the "vortex lift theory" described in section 2.5.5 and we applied it to our fin geometry. Let's recall the formula for lift coefficient:

$$C_L = K_p \sin \alpha \cos^2 \alpha + K_v \cos \alpha \sin^2 \alpha \quad (6.2)$$

K_p and K_v are taken from figure 2.7 and figure 2.8 respectively and are function of the fin aspect ratio. For our geometry aspect ratio $A_R = \frac{b^2}{S} = 2.18$ then $K_p \approx 2.4$ and $K_v \approx 3.2$. When we plot equation 6.2 on a graph with our experimental result for the fin, we can see that the curve we get with this model fit pretty well our data up to 10° as we can see in the figure 6.3 . It is however below the expected range of angle of attack as Polhamus claim in [13] a validity up to 20° and more. It is maybe due to the geometry of the paired fin as it is not exactly a delta wing nor it has sharp edges.

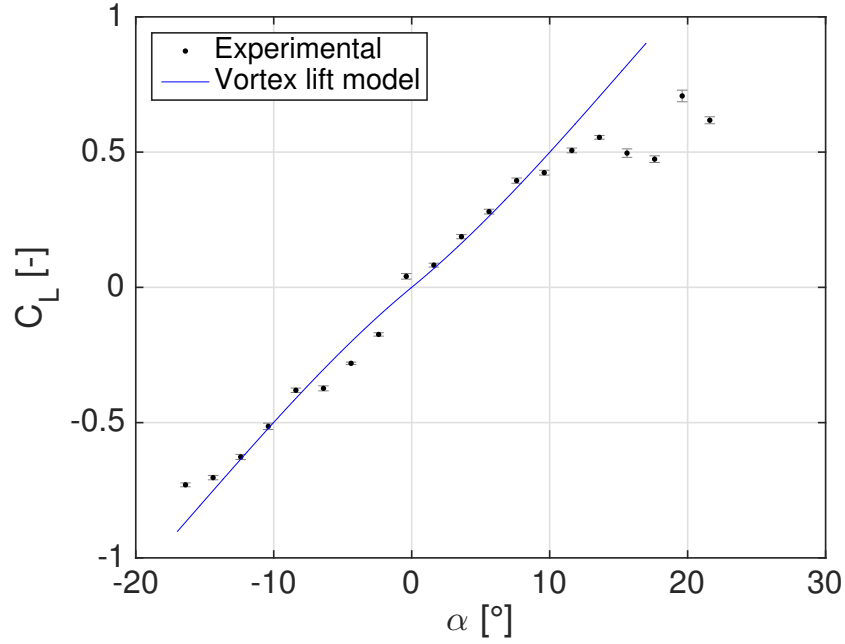


Figure 6.3: Fin - C_L vs. α - small angles and vortex lift curve

7. Flow visualization

7.1. Disposition of the PIV setup

As we can see on figure 7.1, the laser is placed parallel to the x-z plane and the camera is placed almost perpendicularly to the laser plane in order to better capture the flow and avoid distortion. We used the so called **xy table** to move both laser and camera at once in order to keep the carried out calibration and still be able to change the visualization window in the x-z plane.



Figure 7.1: PIV setup

7.2. Calibration and key parameters

PIV measures displacements of particles with a flow by using one, two (or more) cameras. We used only one camera to do visualisation as we were only interested in the velocity component in the x-z plane.

The calibration procedure: First step is to accurately align the calibration plate with the laser light sheet and adjust the laser light thickness to make it as thin as possible.

Remove the filter from camera. The filter is opaque to the entire spectrum of light except to the frequency of the laser. During calibration we would like



Figure 7.2: PIV: calibration plate, model 31

camera 1	no planes	constant local intensity
Fit model: Pinhole model	right handed	RMS of fit: 0.31040 pixel
Size of dewarped image : was specified as 1640 x 1253 pixel		
Camera configuration:		
Focal length f = 53.8252 mm		
Pixel size = 0.0074 mm		
Pixel aspect ratio = 1		
Calibration plate position (z = 0 mm):		
Translation:		Rotation:
T _x = 42.2174 mm	R _x = -2.08166 °	
T _y = -24.0435 mm	R _y = 1.26767 °	
T _z = 653.31 mm	R _z = -1.8186 °	
Camera scale:		
Origin : x _o = 1298.38 pixel		
y _o = 876.383 pixel		
Scale factor: 11.141 pixel/mm		
Image distortion:		
Principal point :		x _p = 800 px
		y _p = 600 px
Radial distortion : 1.order = 0.409541 px		
2.order = -0.03756 px		

Figure 7.3: PIV: calibration properties

to be able to see images from the camera without using the laser.

In DaVis, the dedicated software for PIV, select from a list the type of calibration plate to use, in our case the plate 31 as shown in figure 7.2. Using the software, identify three characteristic points on the plate. This allows the software to know x and y positions from the plate and to compute automatically a correction mapping for the picture taken by the camera (see figure 7.3). Now angles and distances in the visual field of interest are known. Replace the filter on the camera. Following steps now require the use of the laser.

It is now necessary to set a working frequency for the camera. As it have to take double shots, we need to specify the time “dt” between those shots (20 μ s in our case). It is directly linked to the speed of airflow and a small tool in the software compute it easily from the flow velocity.

By a series of trials and errors we defined the laser timing with respect to camera shots. The sequence should be: laser1/shot1/laser2/shot2. Typically, the timing is set within few microsecond in order for the first laser impulse to not illuminate both snapshots. For better result we can also play with laser intensity. As we has a environment that reflect light, as the hull is made of aluminium, we set the laser intensity to the minimum possible (52[%] of the maximum intensity) to still be able to light particles. To reduce reflection we also put a black tape along the upper length of the airship where the laser will hit. It is shown on figure 7.4. Once all the timing is set, acquisition of the flow past the model can begin.

The particles used to insemminate the flow are produced by a smoke generator, the smoke was injected from a position upstream to the test section. We first tried the experiment with water droplets but the droplets were too large and too heavy, they didn’t followed the flow field as their density where too high. Therefore, we used smoke and the result was satisfactory.

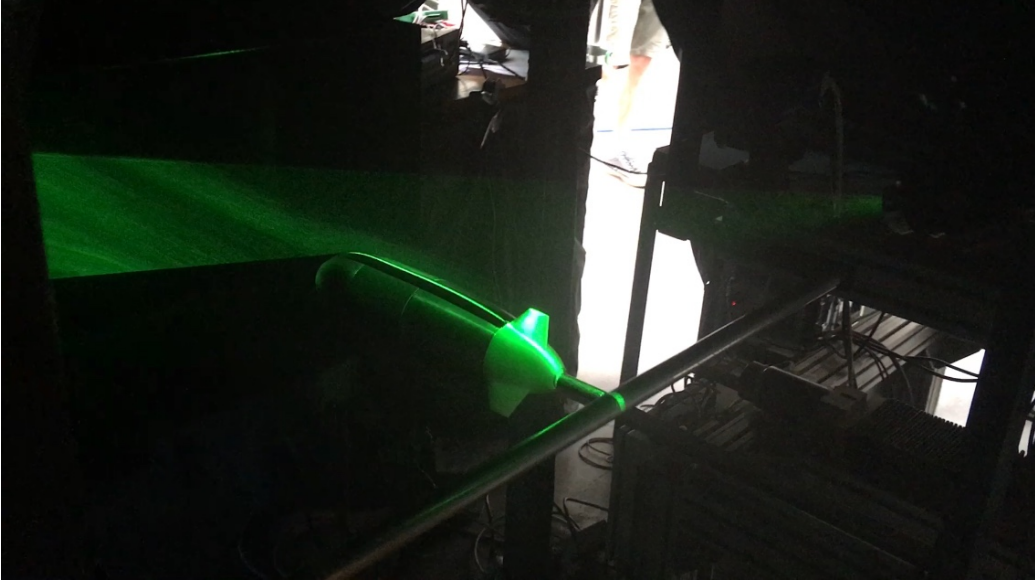


Figure 7.4: PIV on airship with fins but no tripping disc.

In order to compute the velocity fields, the computer did some heavy processing work. The computer interrogates correlation windows in each set of double shot in order to compute the probabilistic correlation within the window. It then determines which one of the particle detected in the window of the first shot has the most probability to be paired in the window of the second shot. We used a two passes process going from windows of $[32 \times 32]$ with 50% overlap pixels to $[24 \times 24]$ pixels with 75% overlap. This gives a very high vector resolution as for each correlation window a vector is generated. As an illustration our setup worked well, the figure 7.5 shows the correlation map made by the software for one of the interrogation window. One very steep peak can be seen. It means the correlation between two particles seen on two the two snapshot is very high. The software is almost certain that it is the same particle on both photos.

7.3. Results

Several model configurations were studied. We first placed the airship with fins, without tripping disc at first, at several angles of attack: 0° , 5° , 10° , 45° , and 65° .

We also studied the configuration with fins and toothed tripping disc at several angles of attack: 0° , 45° , 65° and 75° .

Each of the following figures shows the average of 500 images of the velocity field. Post processing allowed us to get streamlines, vorticity or vector fields representations. We display here the visualisation for angle of attack of 45° and 65° for the airship with fins with or without tripping disc. The rest of the figures with other angles of attacks are shown in the Appendix.

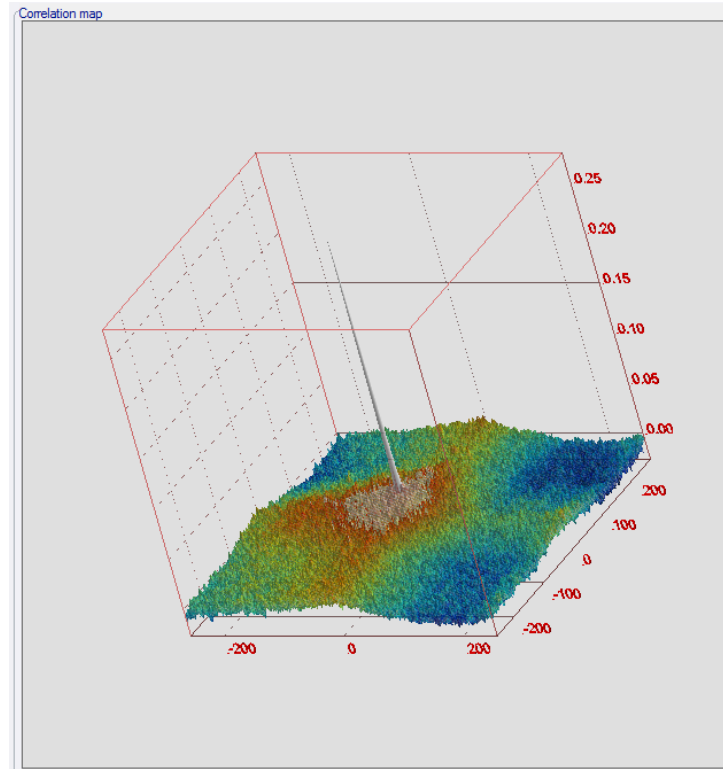


Figure 7.5: Correlation map

Observations

On each figure (from figure 7.6 to figure 7.17), we can see few points which are due to the reflection of the laser beam on the surface of the airship despite the care we took to cover metallic and reflective surfaces.

We can observe that the tripping device had the opposite effect from what we expected. Indeed, on figure 7.11 which represent the vorticity, the boundary layers peels off while in the figure (7.8), which represent the airship without the tripping disc, the boundary layers remains on the surface of the airship. Maybe the toothed tripping disc diameter's is too high with respect to the boundary layer thickness or the toothed geometry is not a good option for triggering the boundary layer. This can also be seen by comparing the streamlines on figure 7.6 and figure 7.9 or the the vector fields on figure 7.7 and figure 7.10 but we find consider vorticity field the most striking representation.

As shown in the figures 7.6, 7.9, 7.12 and 7.15 we don't observe any recirculation the flow behind the airship.

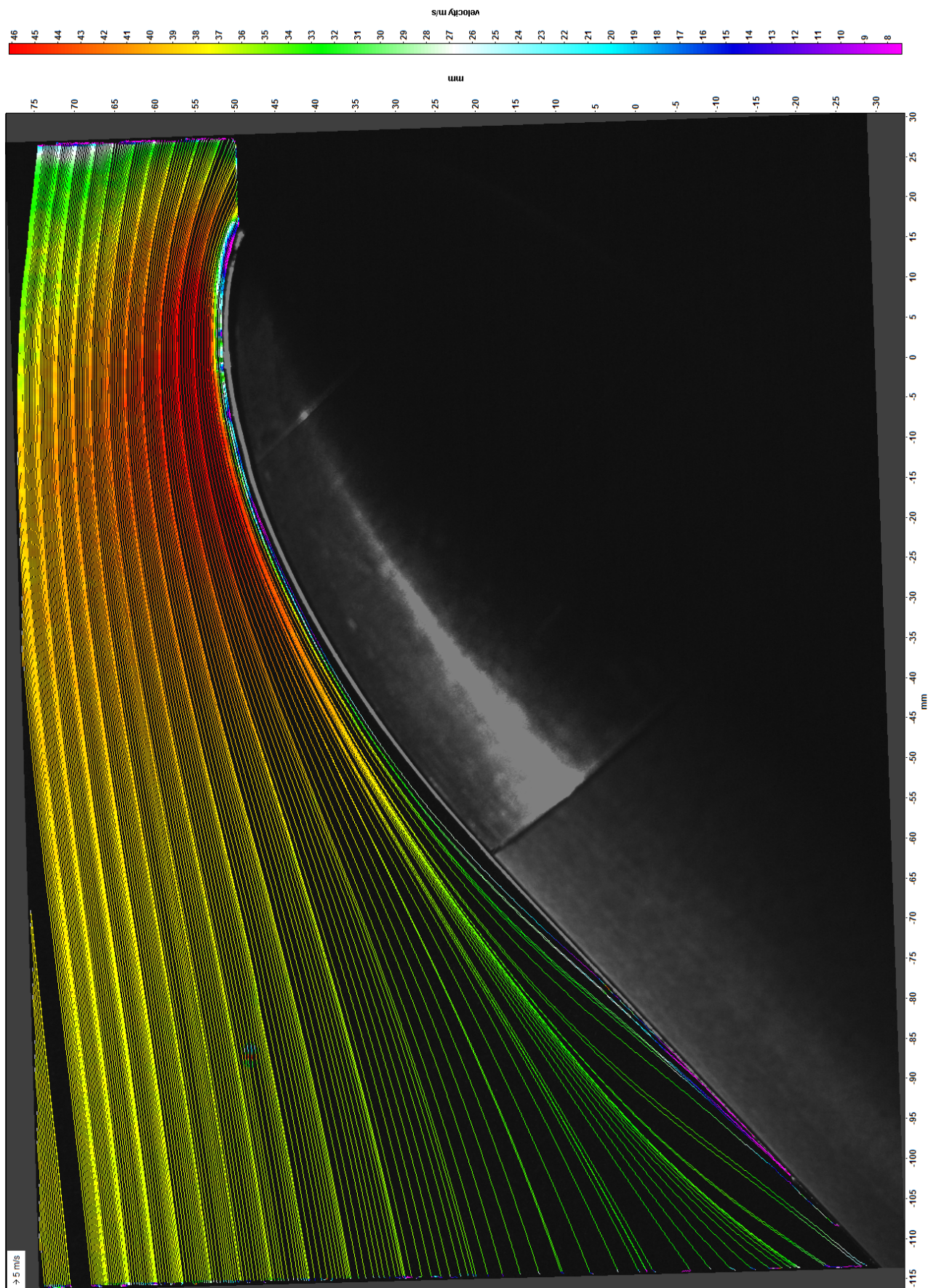


Figure 7.6: EXP3 (Fins without tripping disc, at positive pitching angle of attack) : Streamlines at 45° AoA

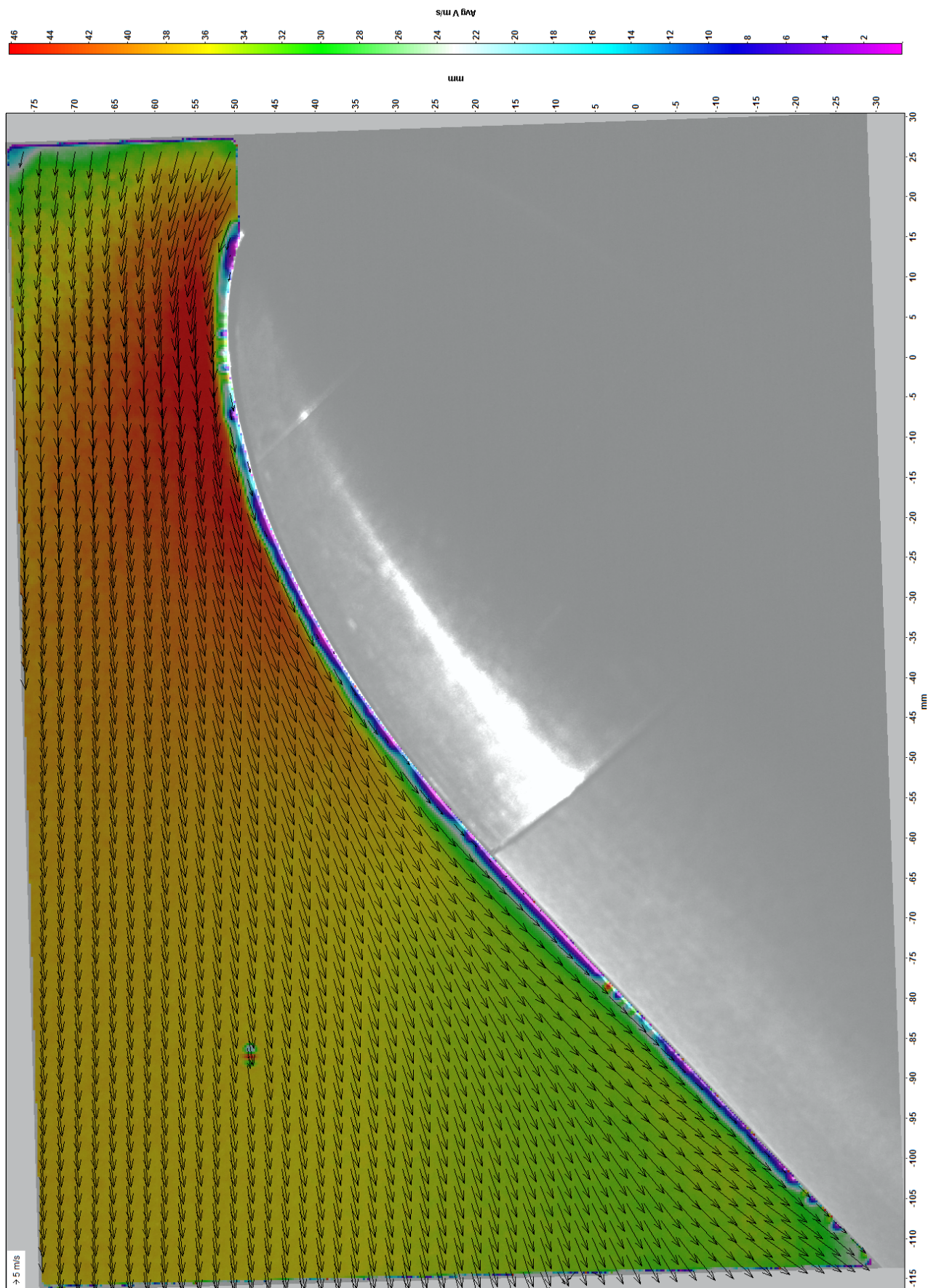


Figure 7.7: EXP3 (Fins without tripping disc, at positive pitching angle of attack) : vector fields at 45° AoA

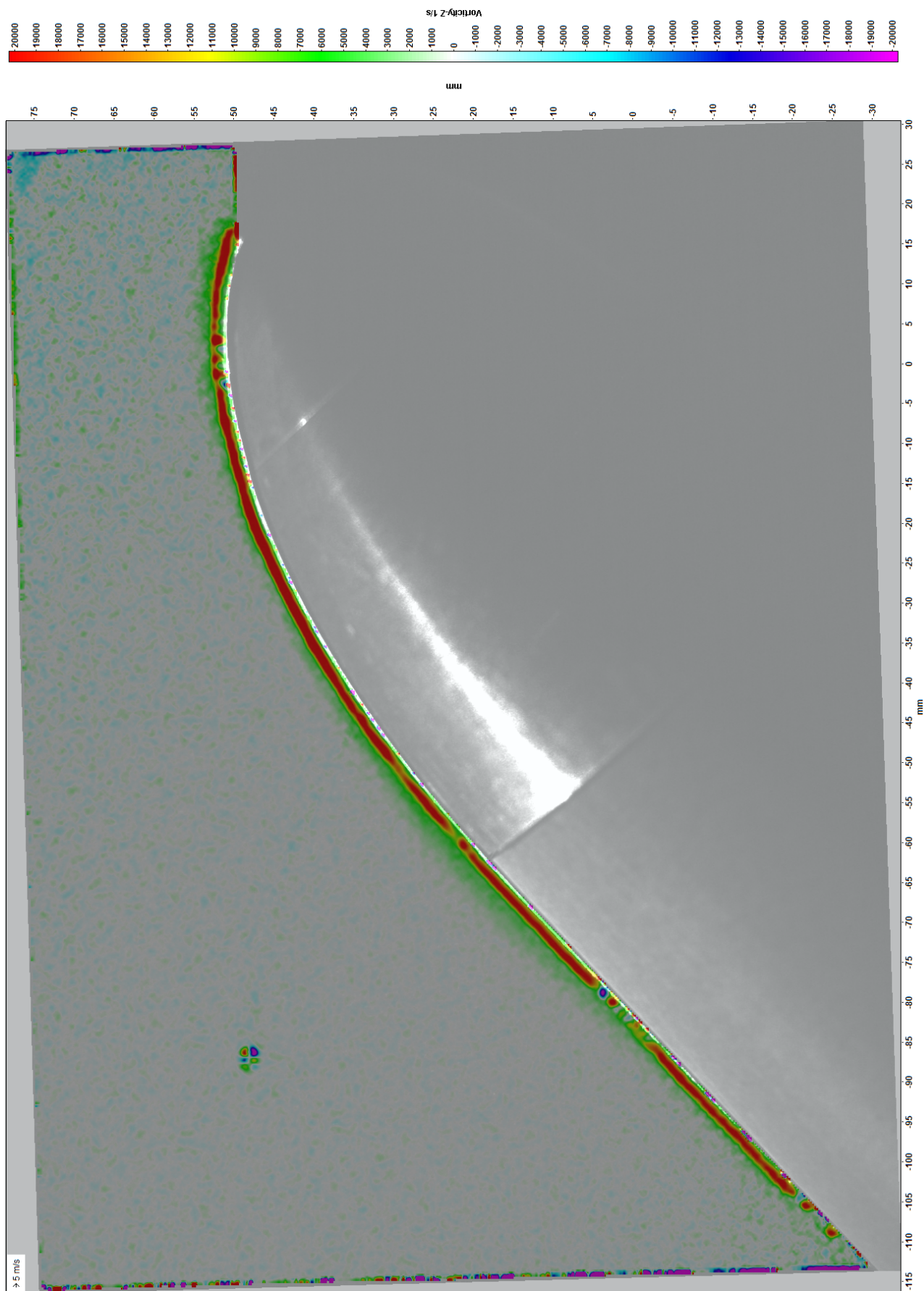


Figure 7.8: EXP3 (Fins without tripping disc, at positive pitching angle of attack) : vorticity at 45° AoA

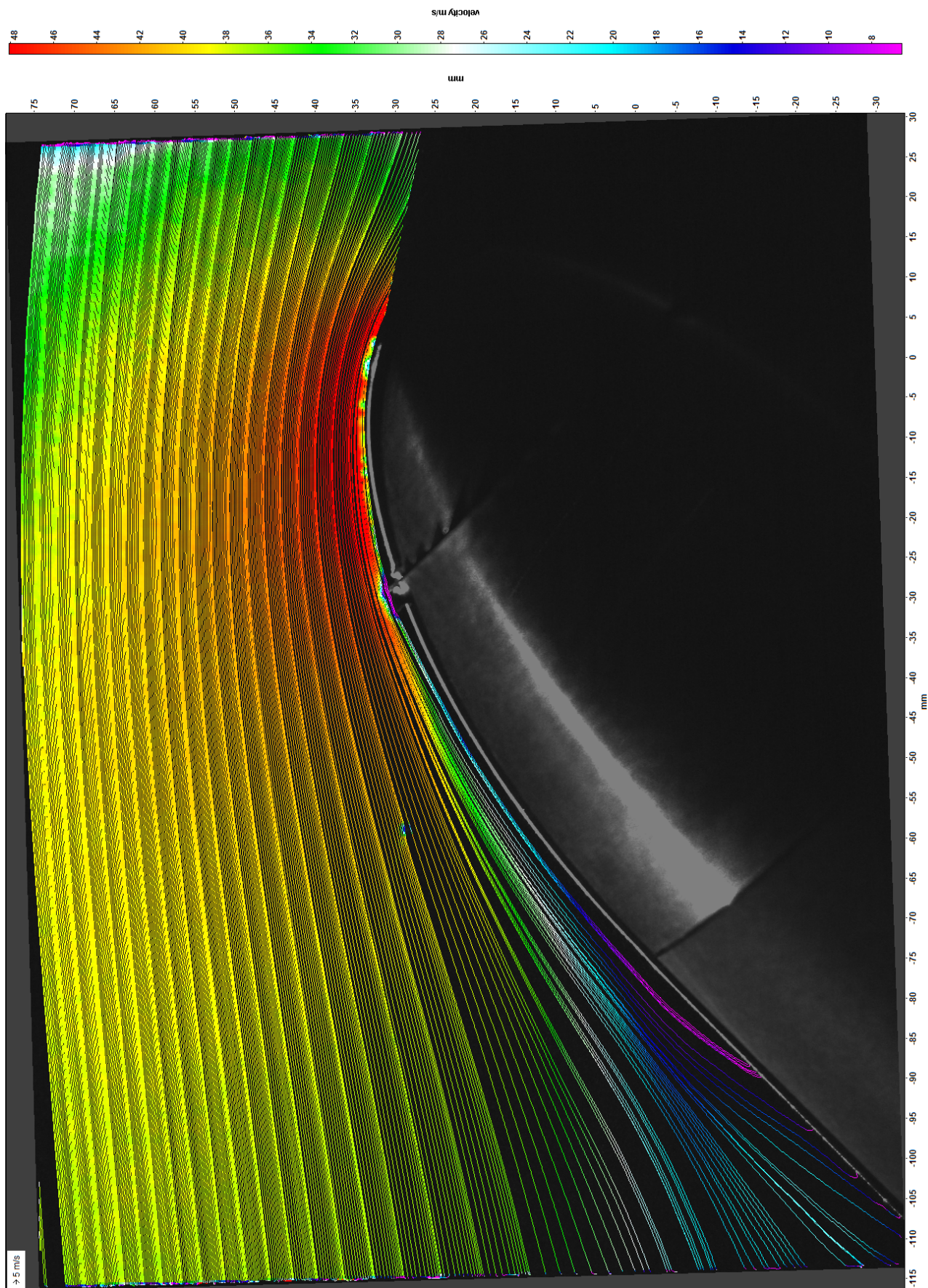


Figure 7.9: EXP6 (Fins with tripping disc at positive pitching angle of attack)
: Streamlines at 45° AoA

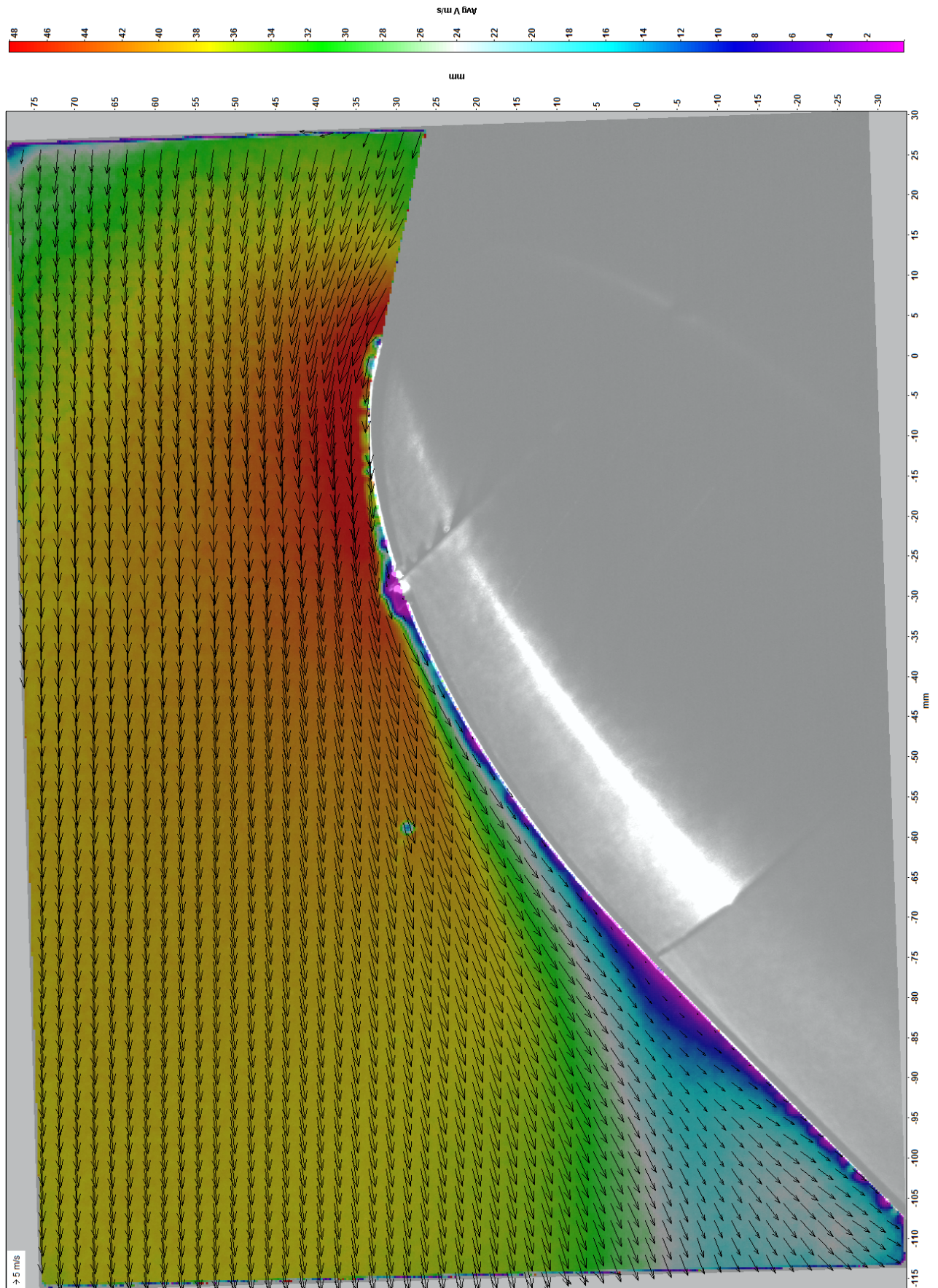


Figure 7.10: EXP6 (Fins with tripping disc at positive pitching angle of attack) : vector fields at 45° AoA

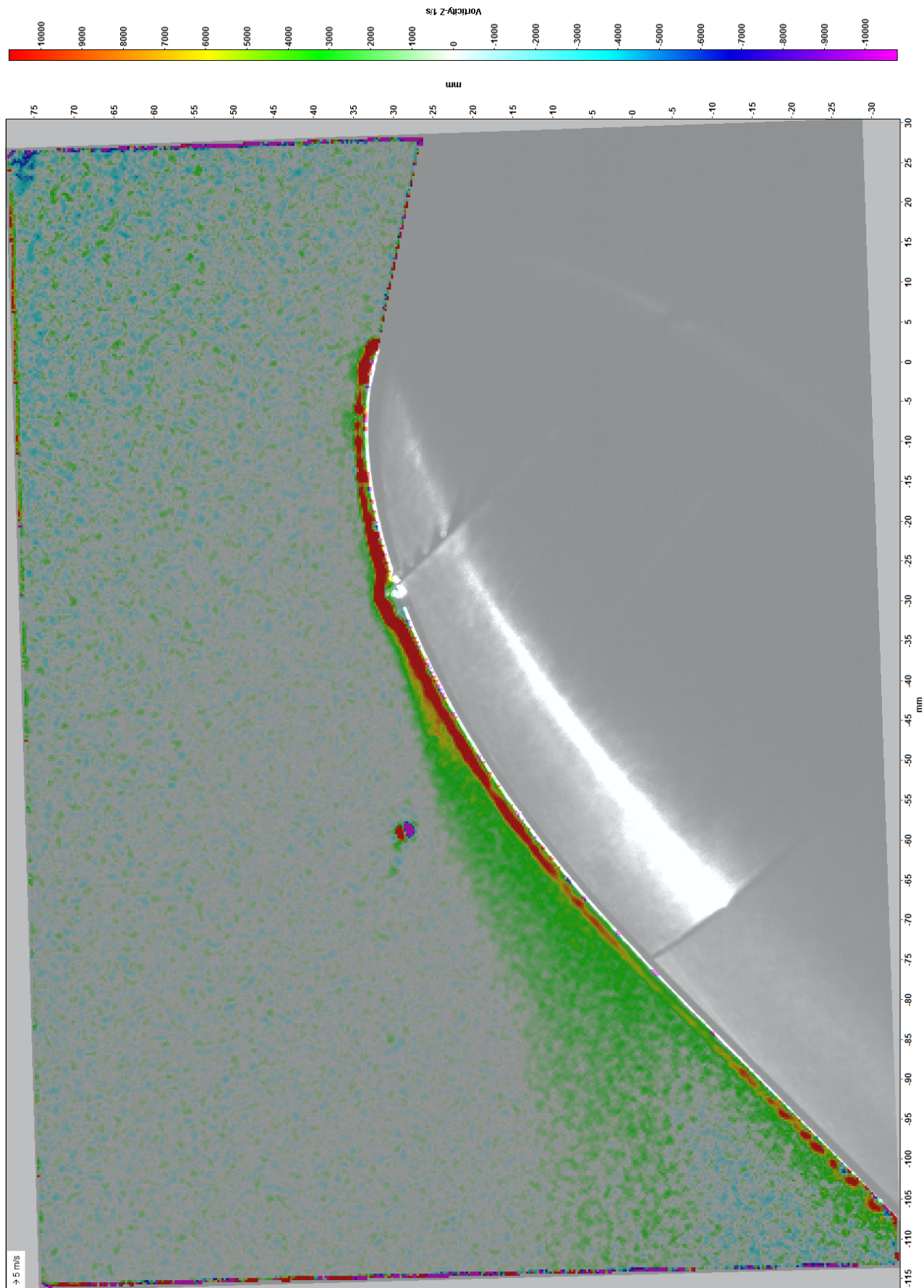


Figure 7.11: EXP6 (Fins with tripping disc at positive pitching angle of attack) : vorticity at 45° AoA

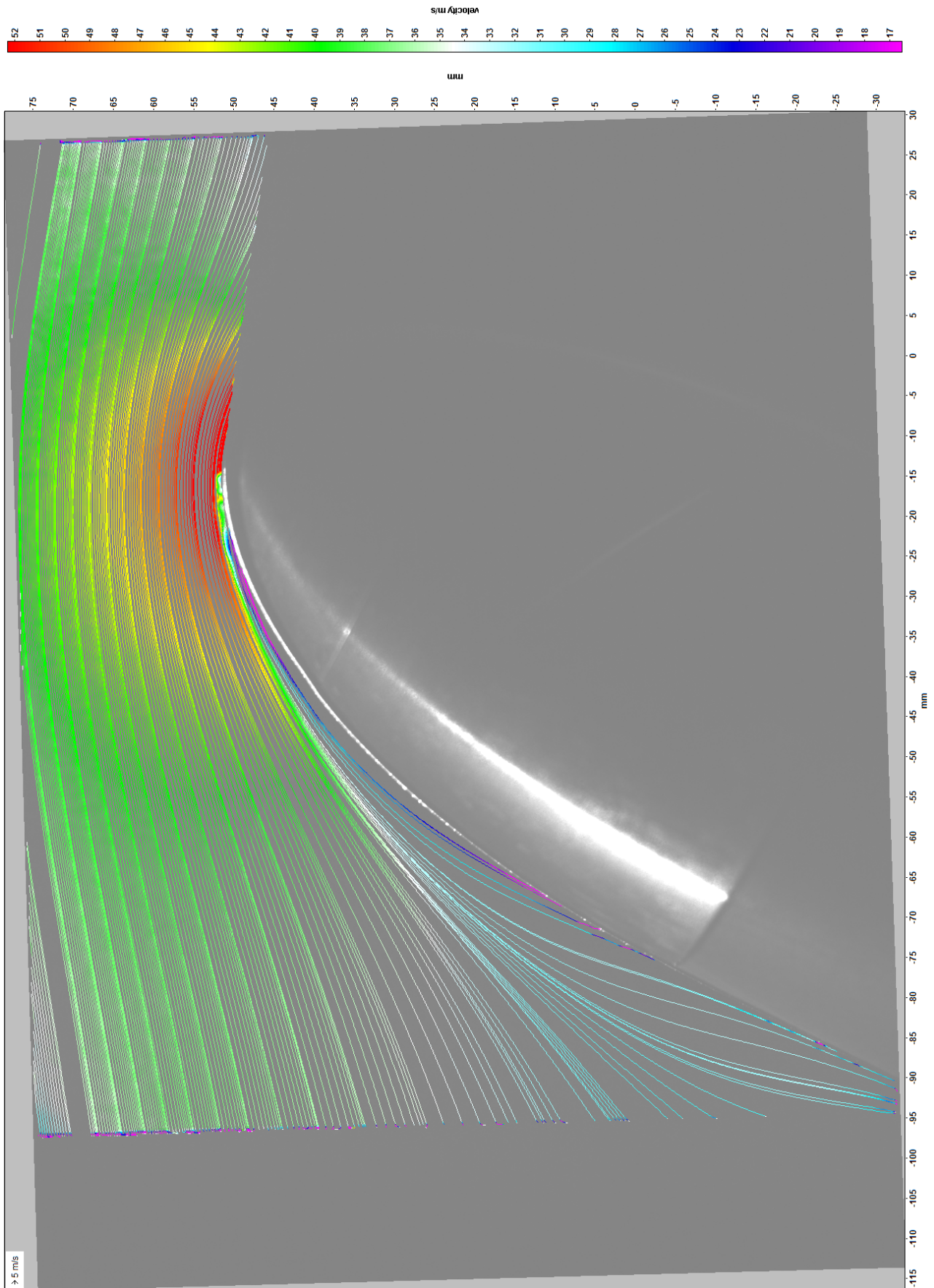


Figure 7.12: EXP6 (Fins without tripping disc, at positive pitching angle of attack) : Streamlines at 65° AoA

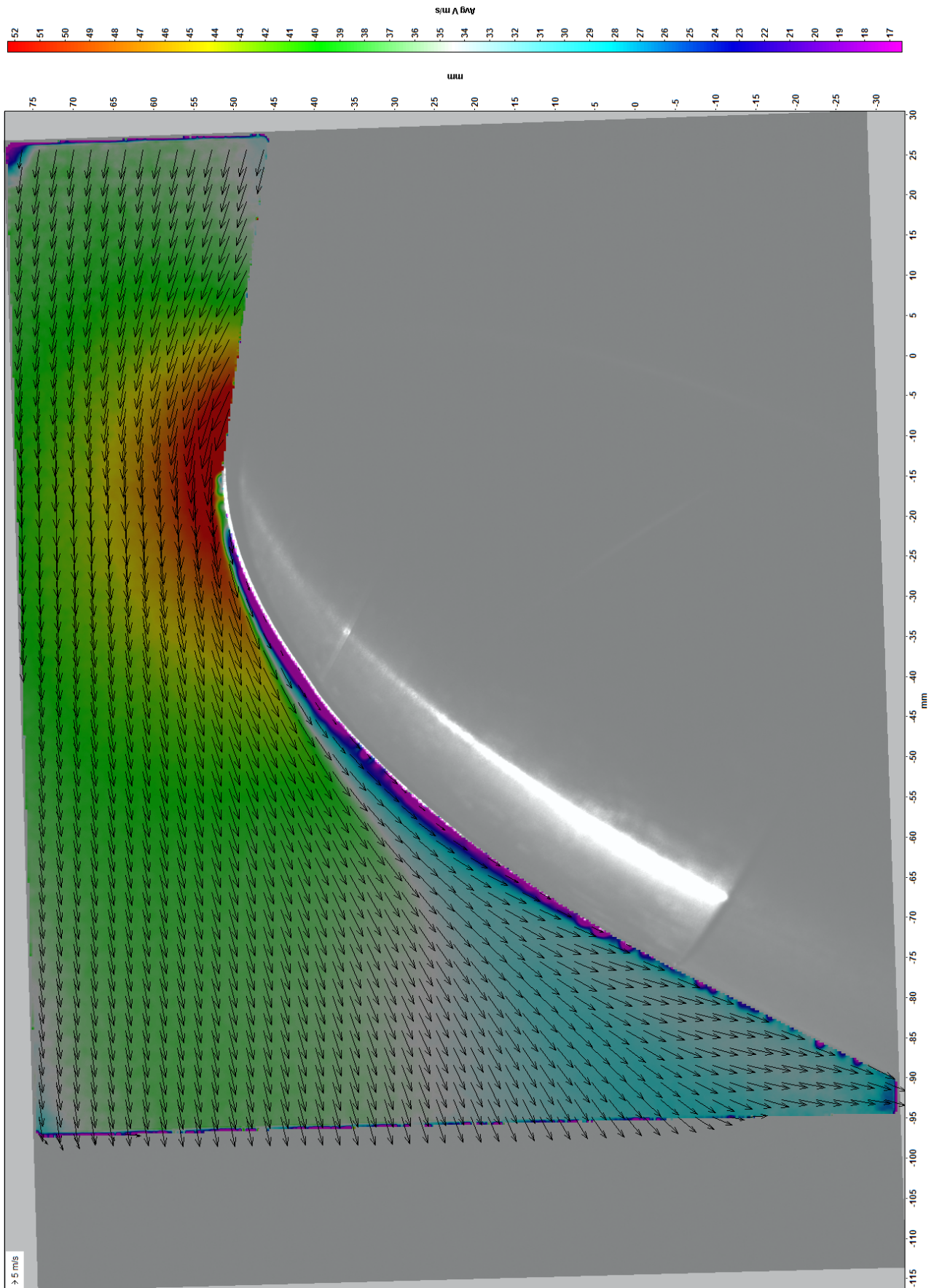


Figure 7.13: EXP6 (Fins without tripping disc, at positive pitching angle of attack) : vector fields at 65° AoA

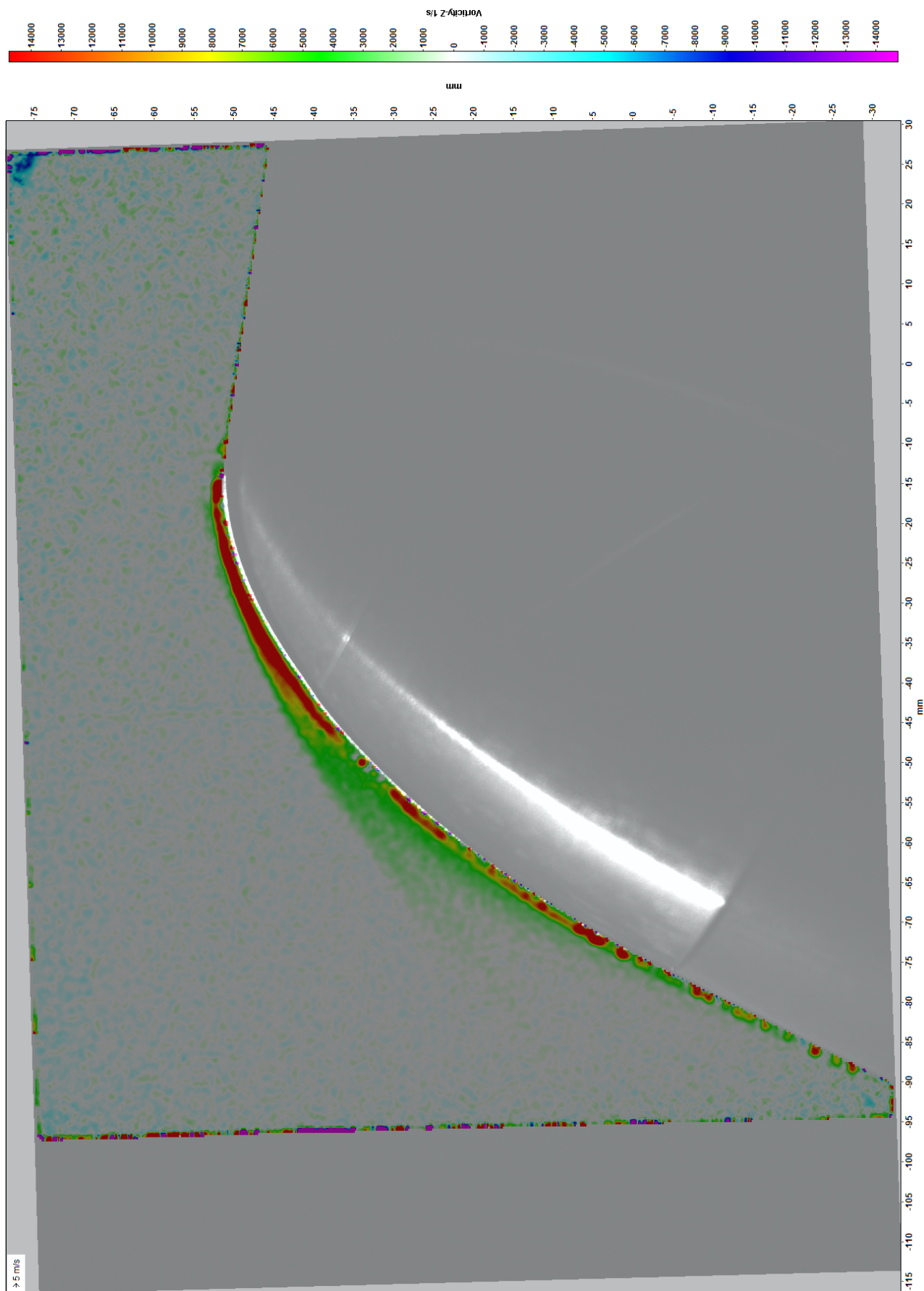


Figure 7.14: EXP6 (Fins without tripping disc, at positive pitching angle of attack) : vorticity at 65° AoA

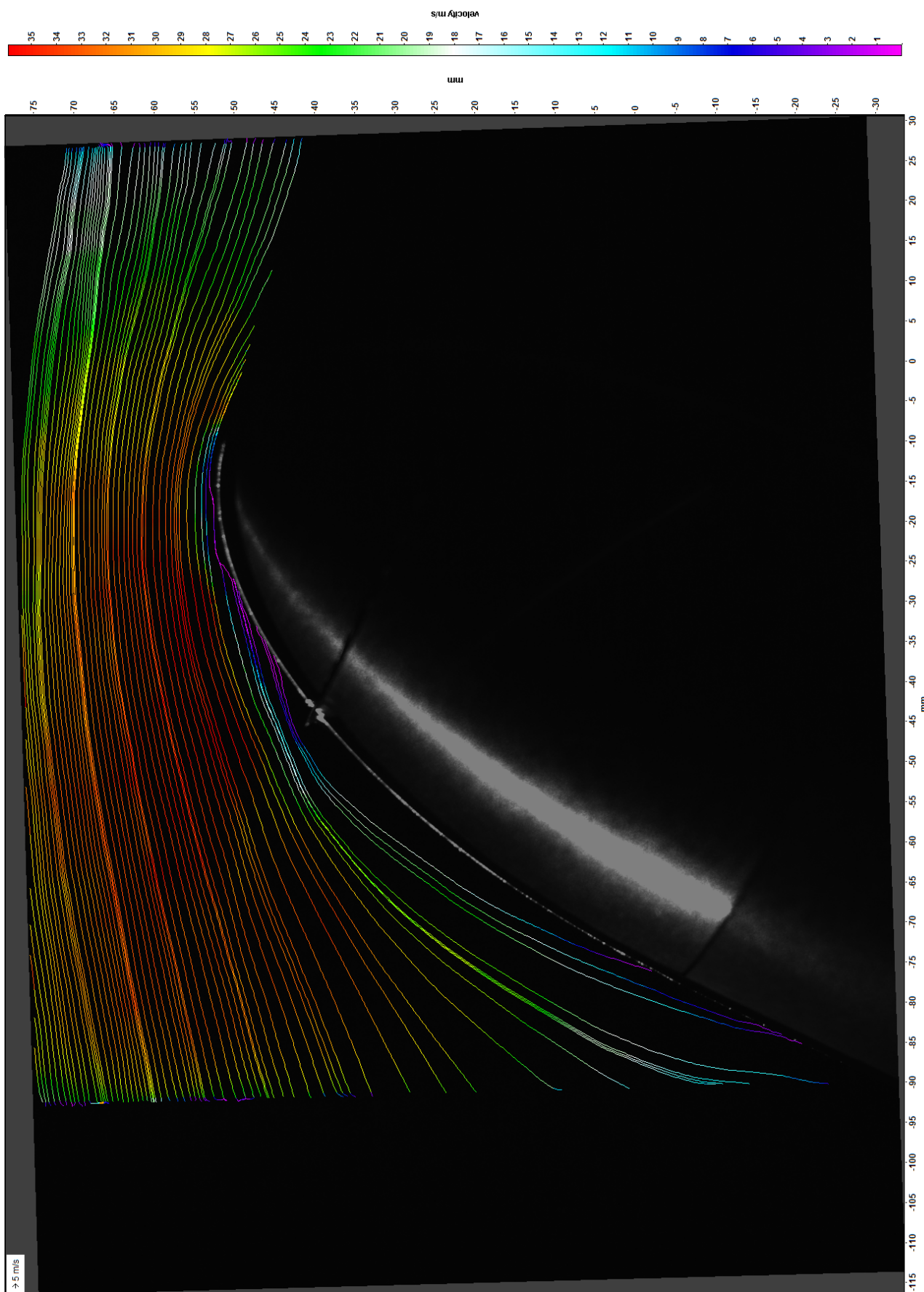


Figure 7.15: EXP6 (Fins with tripping disc at positive pitching angle of attack) : Streamlines at 65° AoA

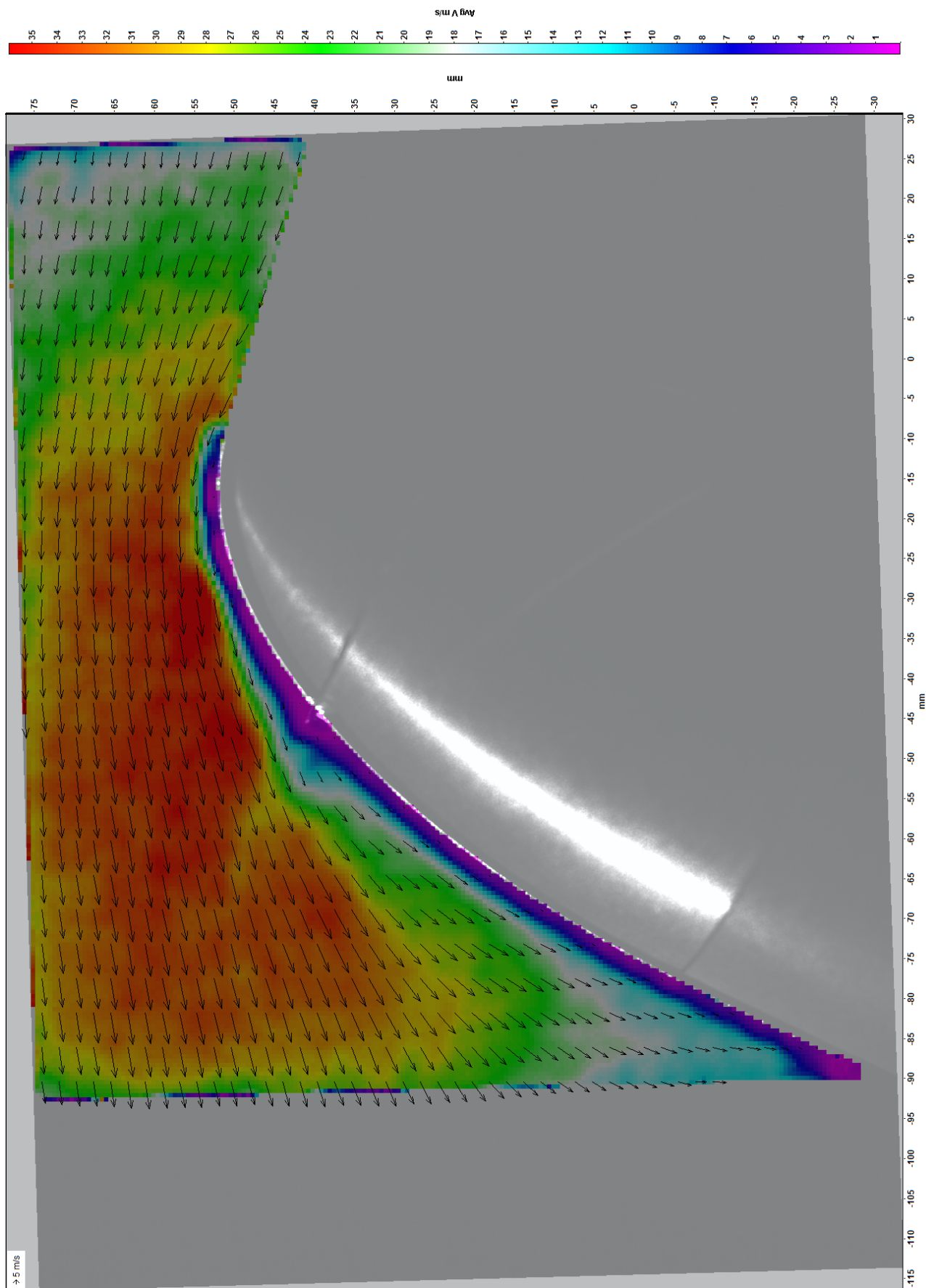


Figure 7.16: EXP6 (Fins with tripping disc at positive pitching angle of attack) : vector fields at 65° AoA

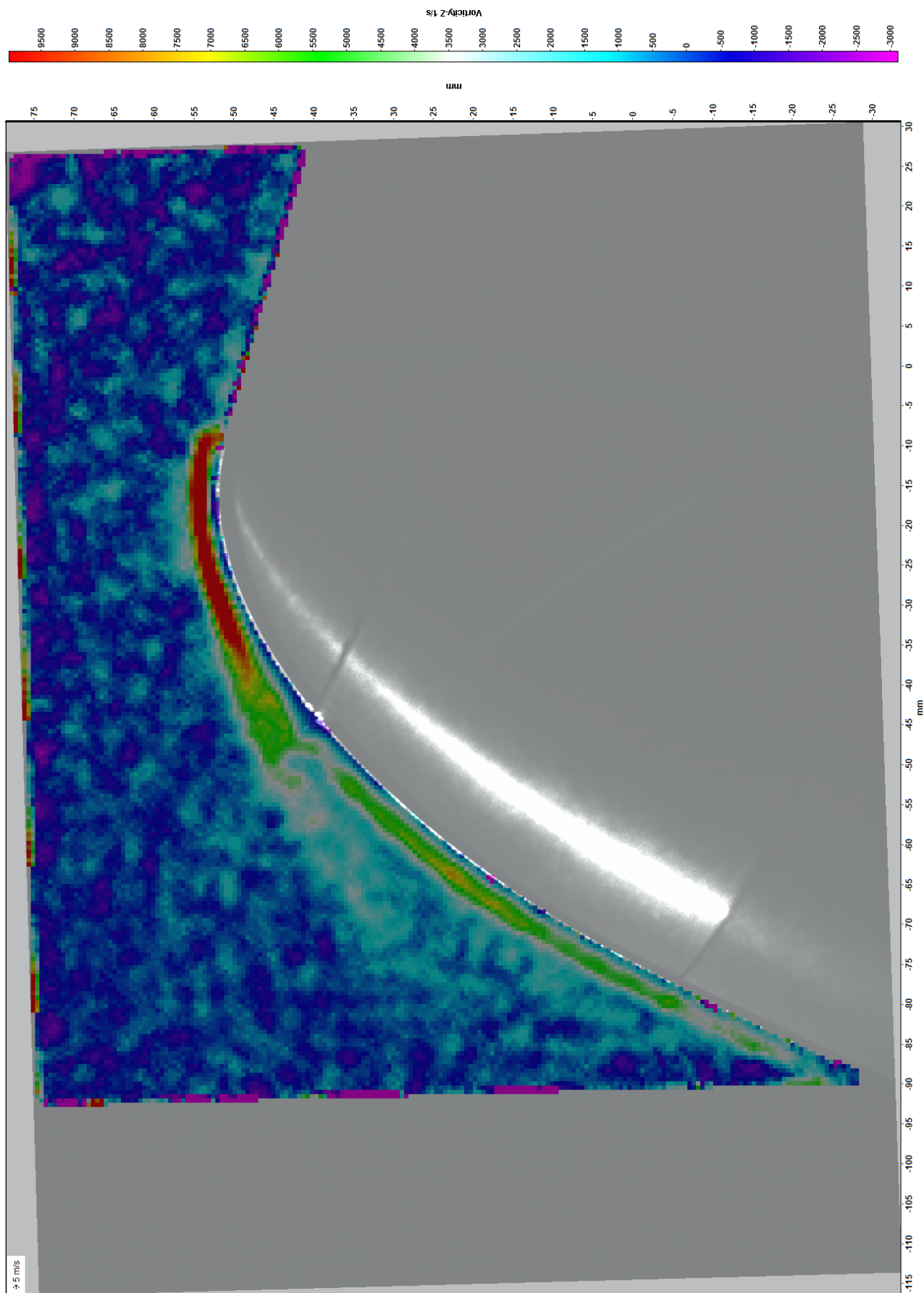


Figure 7.17: EXP6 (Fins with tripping disc at positive pitching angle of attack) : vorticity at 65° AoA

Conclusion

The main goals of our thesis was to design an experimental setup to study the aerodynamic performances - forces and moments coefficients - of an airship model. Then to measure those performances in the wind tunnel of the iMMMC-LEFT laboratory.

We managed to fully design and build an experiment that meets the requirements. The design took most of the year because of the complexity and the numerous iterations inherent in the design process. The most tricky part to design were the steerable support for the airship and the inboard torque meter. Once build, the experiment has assembled perfectly allowing us to make the desired measurements.

During the experimental campaigns, we tried as often as possible to repeat each experiment three times in order to increase the accuracy of the data.

Overall we observe that the drag measurements are very accurate while lift (or side force) measurements are more scattered.

The moments measured using the embedded torque meter appear to be very repeatable but they have a standard deviation increasing with the angle of attack due to the airflow induced oscillation of the airship around its equilibrium position.

For further moments measurements it would be interesting to test a stiffer slat inside the device to reduce vibration amplitude.

In any case one should be careful about the way the slat is mounted, otherwise the measures may be distorted. Unfortunately, after some changes to the settings of the acquisition electronics, and after several assembly and disassembly of the torque meter during which it was operating correctly, torque meter stopped working.

Our experiments shows us that the airship is unstable for small angles of attack whether it has fins or not. It also shows that fins doesn't change the maximum measured moments but they change the angle of attack at which it appears. Fins also make the moments change sign way earlier than for a bare hull. We also observe a well expected result: finned airship induces more drag and lift than a bare hull.

The toothed tripping disc has an impact on the aerodynamic forces of the airship but the aerodynamic behaviour of this later is hard to explain. Indeed it doesn't match the expected behaviour of an airship which we would

have succeeded in tripping the boundary layer. This misbehaviour can be highlighted by PIV flow measurements which shows that the tripping device had the opposite effect from what we expected. Indeed, the vorticity field shows that boundary layer tend to peel off with tripping disc while it remains more attached for airship without tripping device.

The average duration of an experiment is approximately one hour and a half which is the main reason we have not done more repetitions or tested other tripping discs but this would be a nice extension to our work. It would also be interesting to visualise the effect of different tripping discs using Particle Image Velocimetry.

The comparison of the bare hull experimental data with semi empirical aerodynamic models revealed that Yuwen Li's model is not the one which fits the better our data. Both for lift coefficient and for moment coefficient, Allen's model is the better.

It would be interesting to compare our experimental data for fined airship with another aerodynamic model which would include the fins contribution. Our experimental lift coefficients for the fin fit pretty well with the implementation of the "vortex lift theory for sharp edge delta wings" for angles of attack up to ten degrees.

If this work were to be repeated, we would simplify the design of our airship model. Indeed, its took a lot of time to switch from a fined stern to a smooth stern.

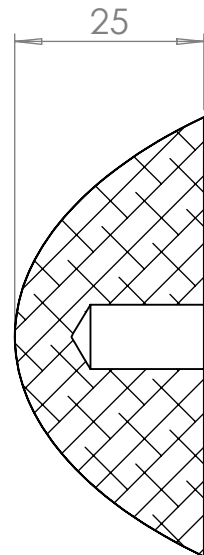
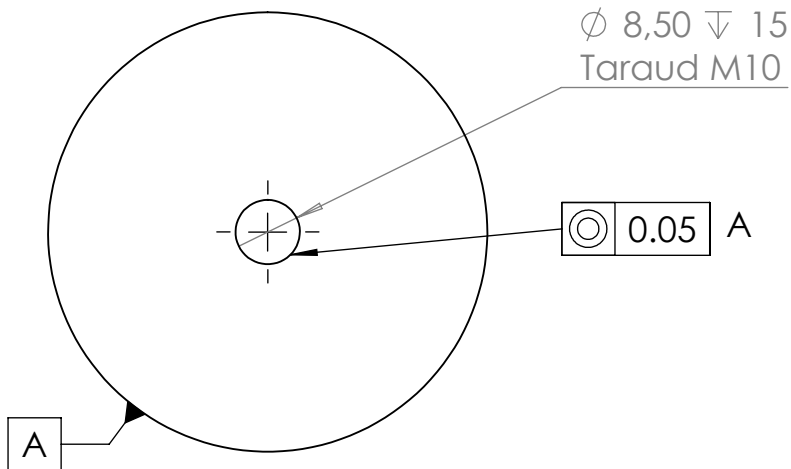
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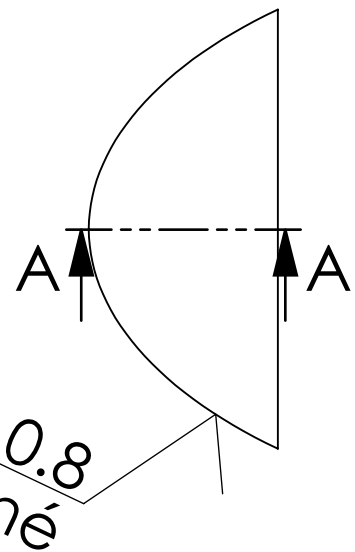
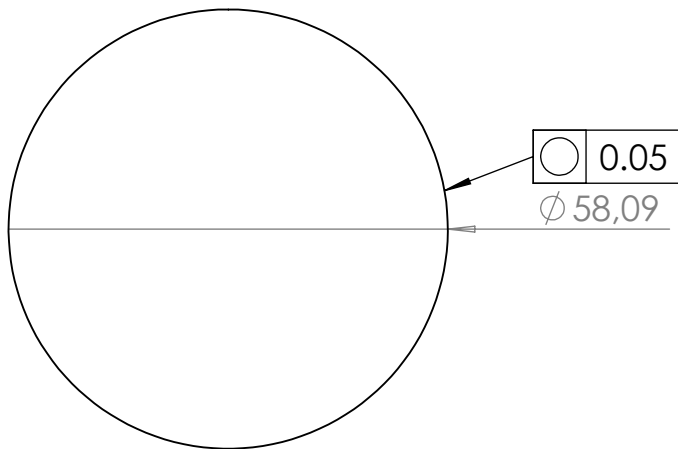
Appendices

A. Airship plans

1 EXEMPLAIRE



COUPE A-A



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TOLERANCES générales: 0.1mm
LINEAIRES:
ANGULAIRES:

FINITION:

CASSER LES
ANGLES VIFS

NE PAS CHANGER L'ECHELLE

REVISION

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VERIF.					
APPR.					
FAB.					
QUAL.					
			MATERIAU:		
			Alliage d'Aluminium 1060		
			MASSE:		

TITRE:

Partie B Nez
Airship

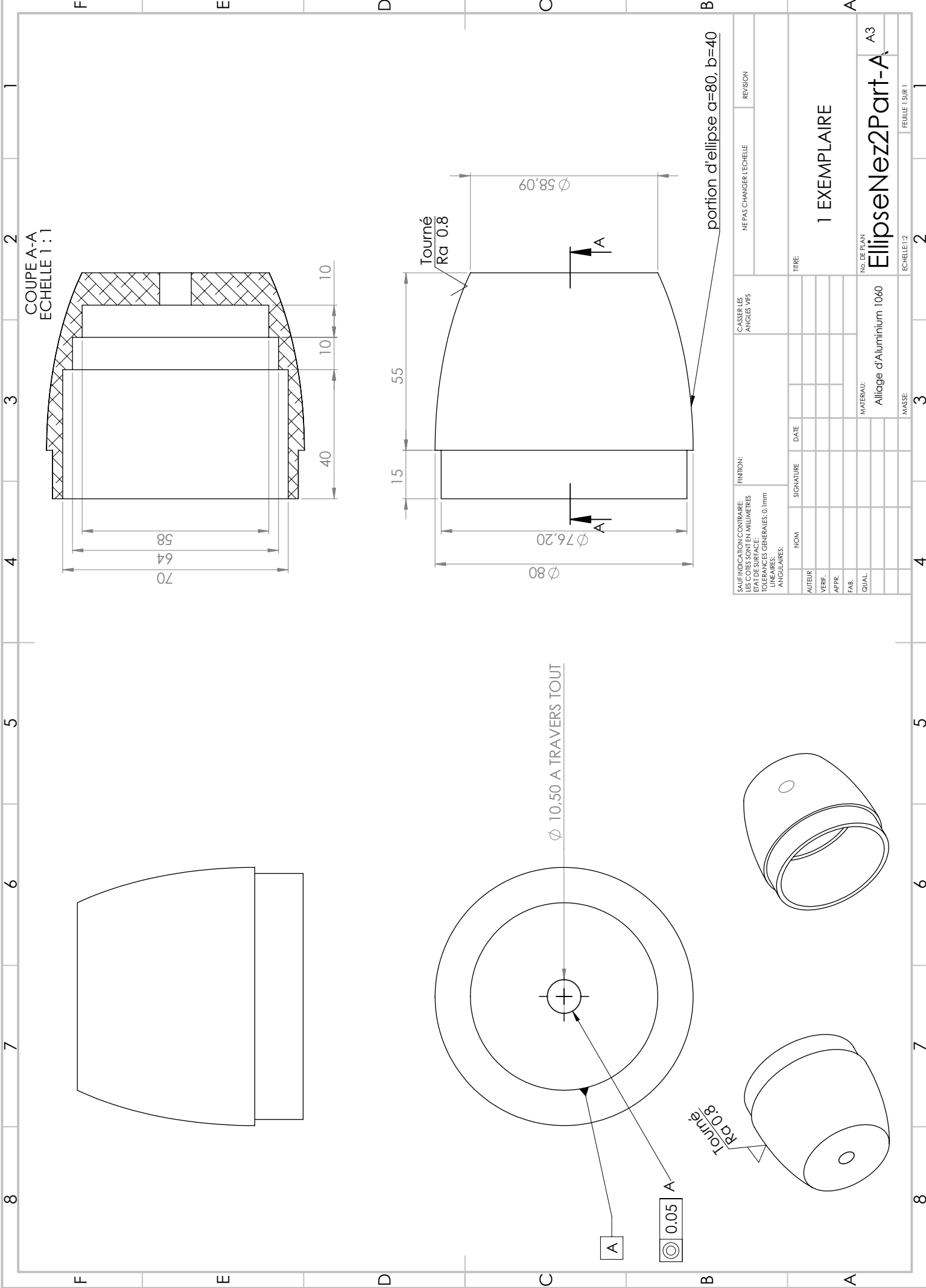
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EllipseNez2Part-B

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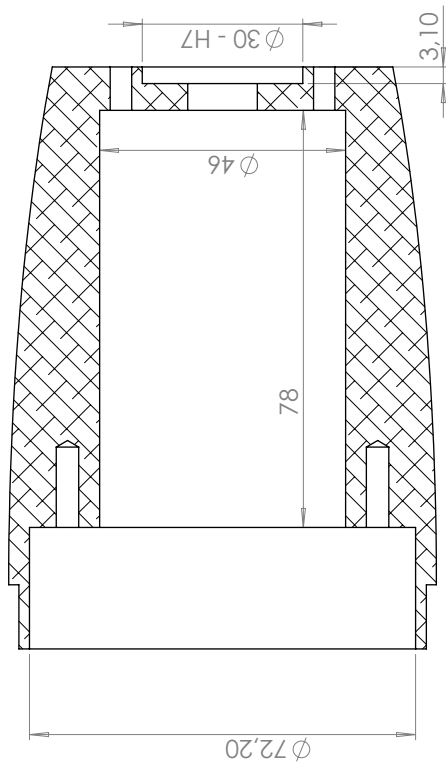
1 EXEMPLAIRE

ElipseNez2Part-A

1 EXEMPLAIRE

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Positions symétriques
par rapport à l'axe
central de la pièce

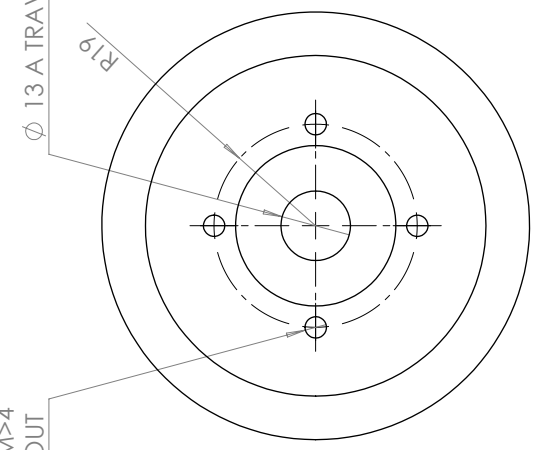
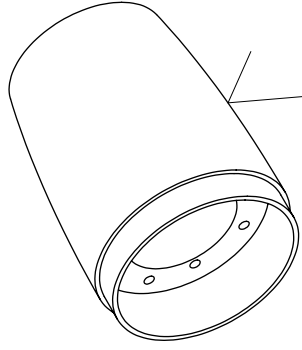
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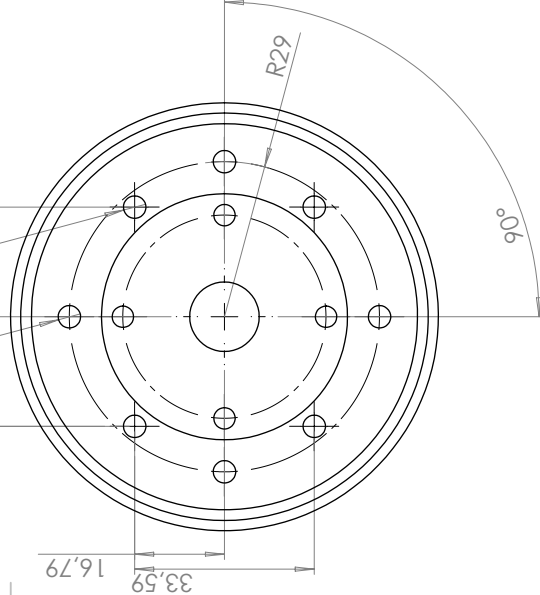
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Tourné
Ra 0.8



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41 20,50

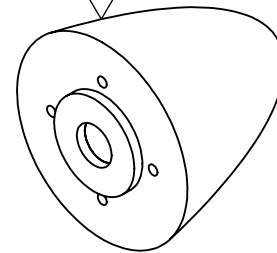


A A

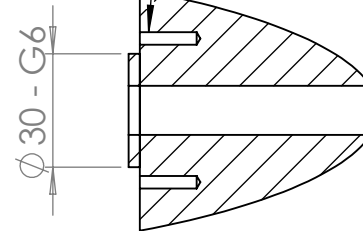
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						EllipseArriereCMini ^{A3}					
						ECHELLE: 1:2					
						FEUILLE SUR 1					

1 EXEMPLAIRE

Tourné
Ra 0.8



Taraud M4
longeur filet : 10mm



COUPE A-A

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R=19

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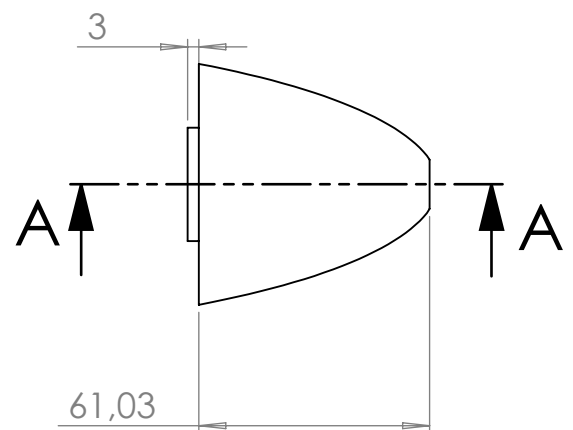
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$\varnothing 30$

20°

A

0.05 A



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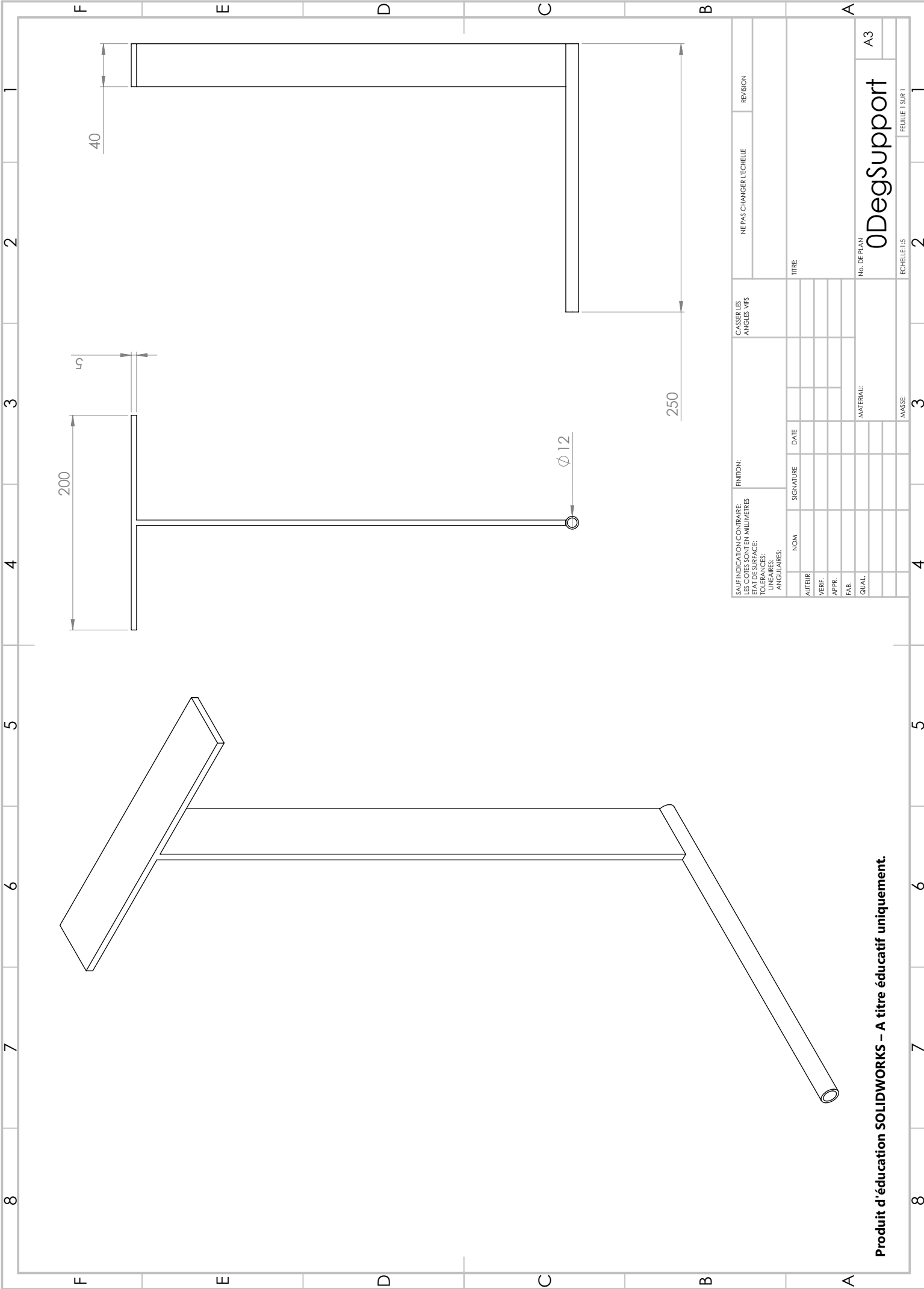
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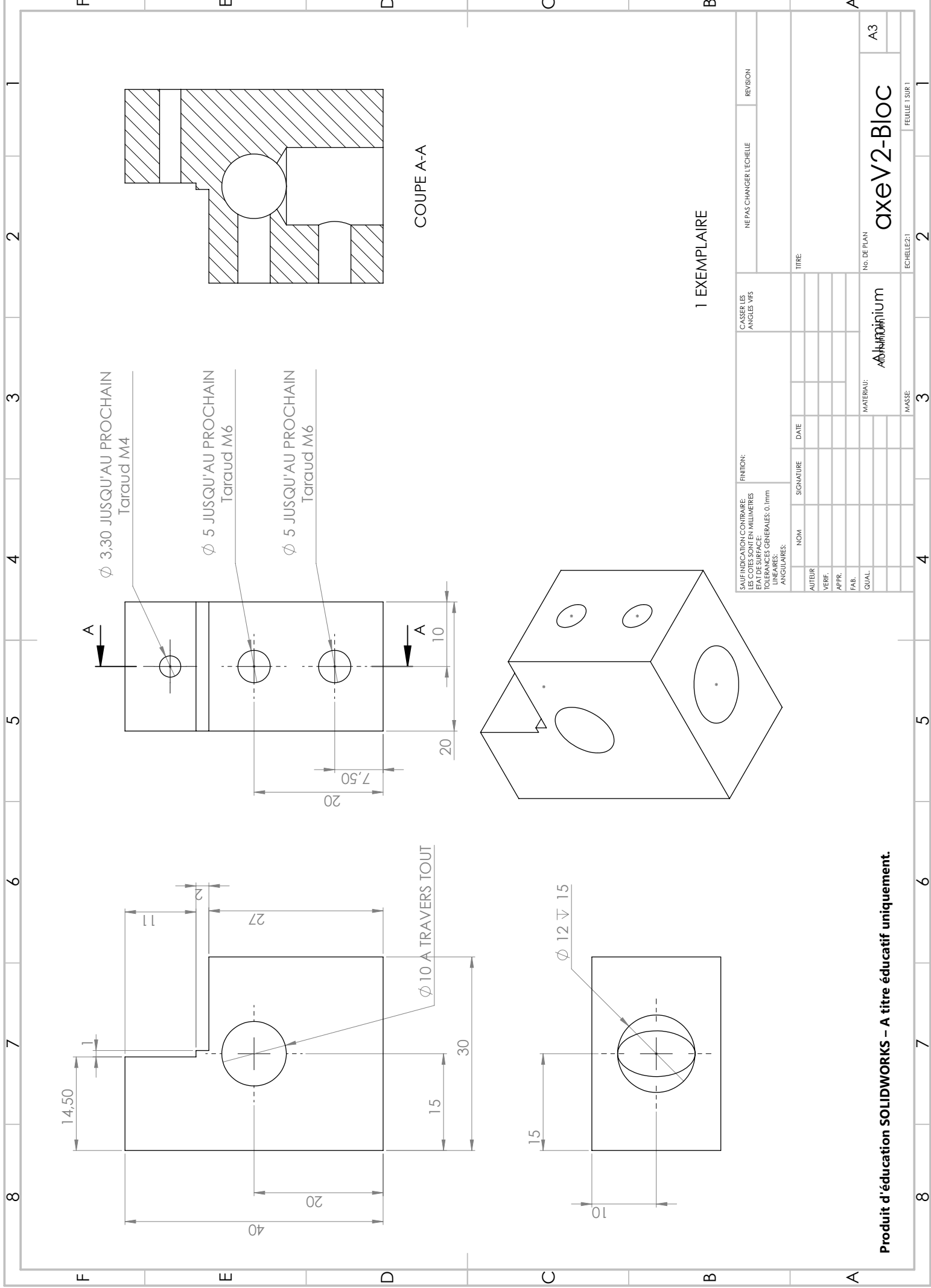
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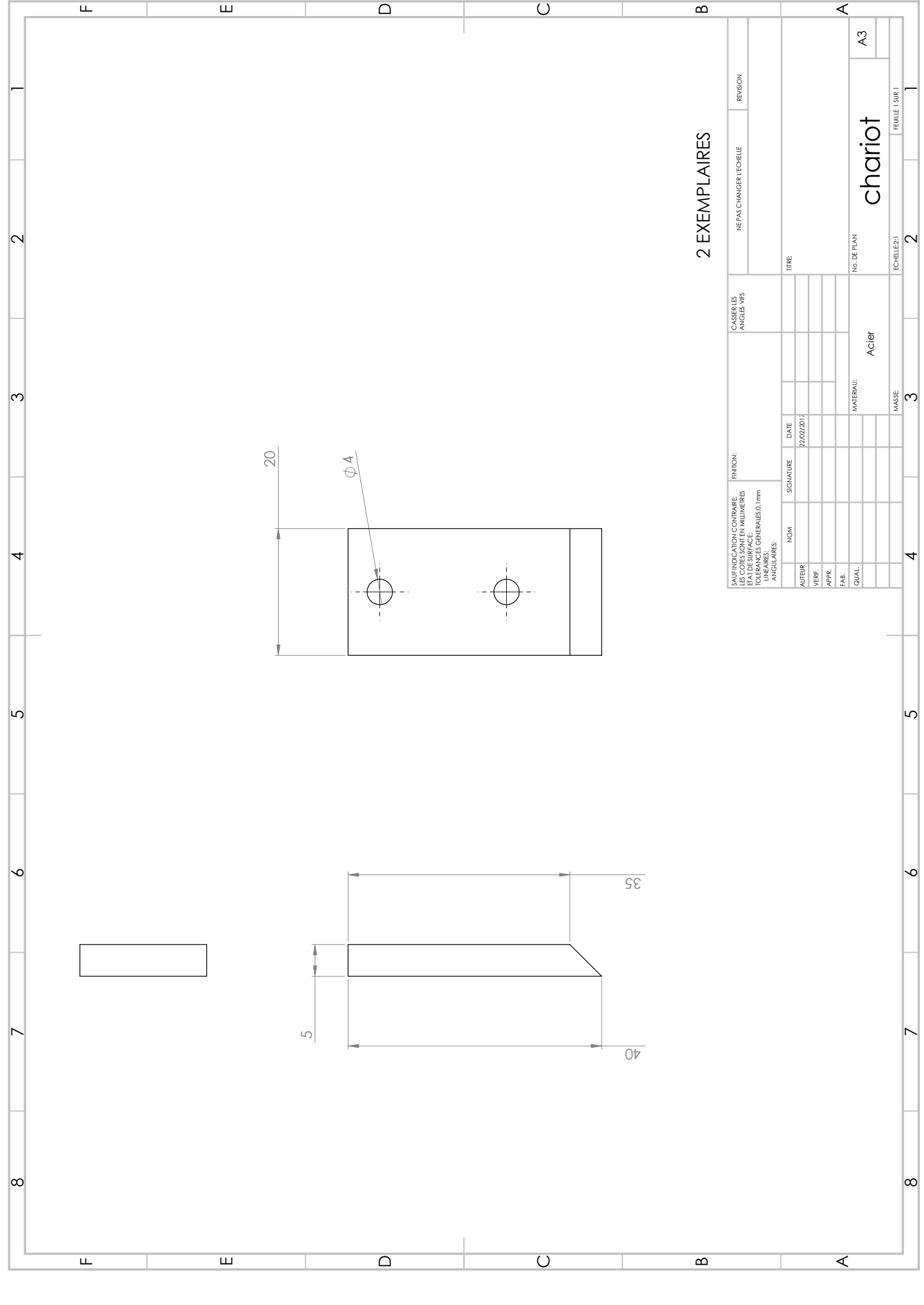
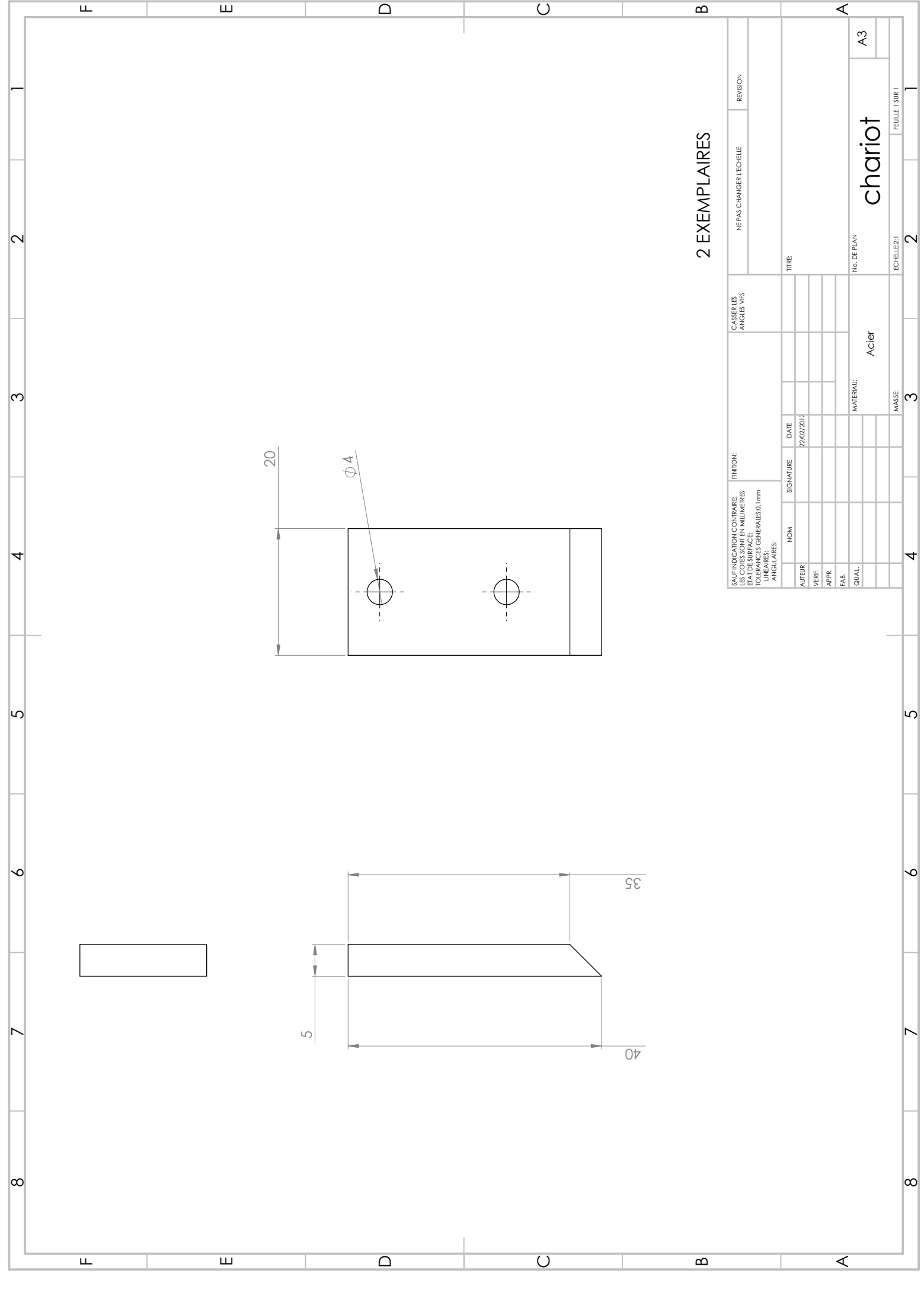
1 EXEMPLAIRE

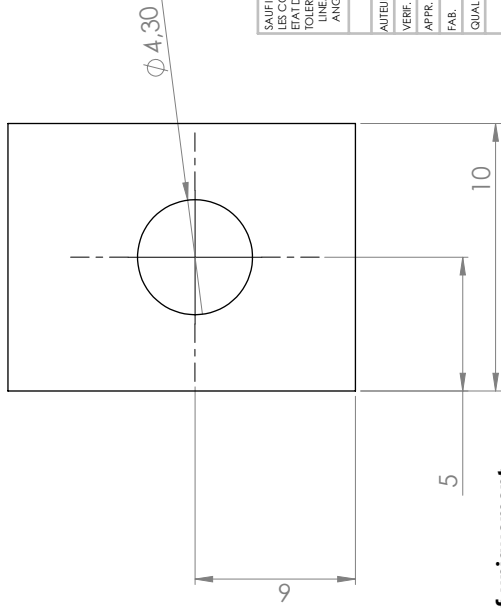
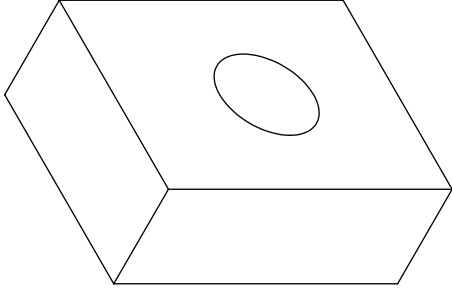
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1 EXEMPLAIRE

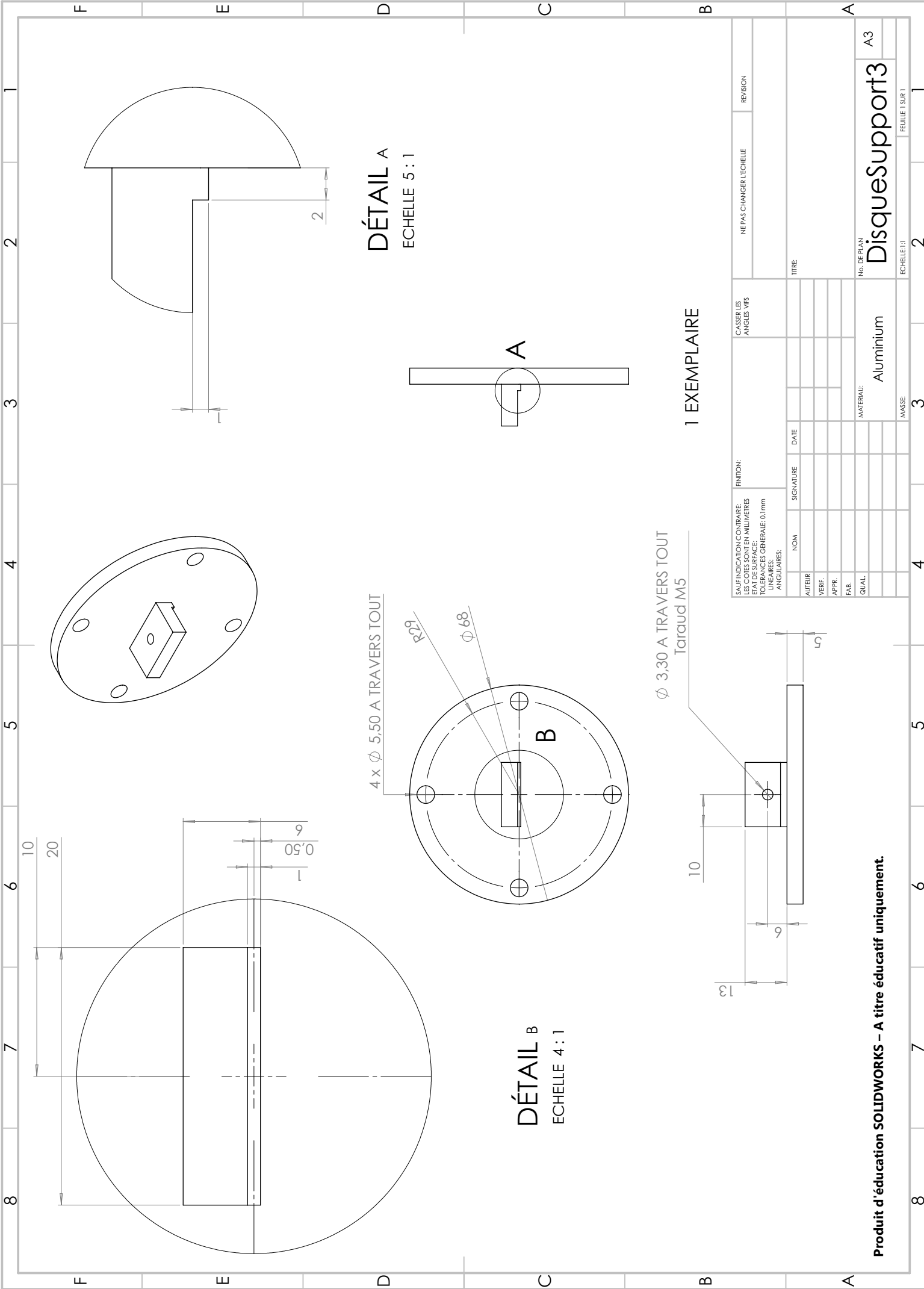
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QUAL.											
MATERIAU:						Aluminium		No. DE PLAN		A3	

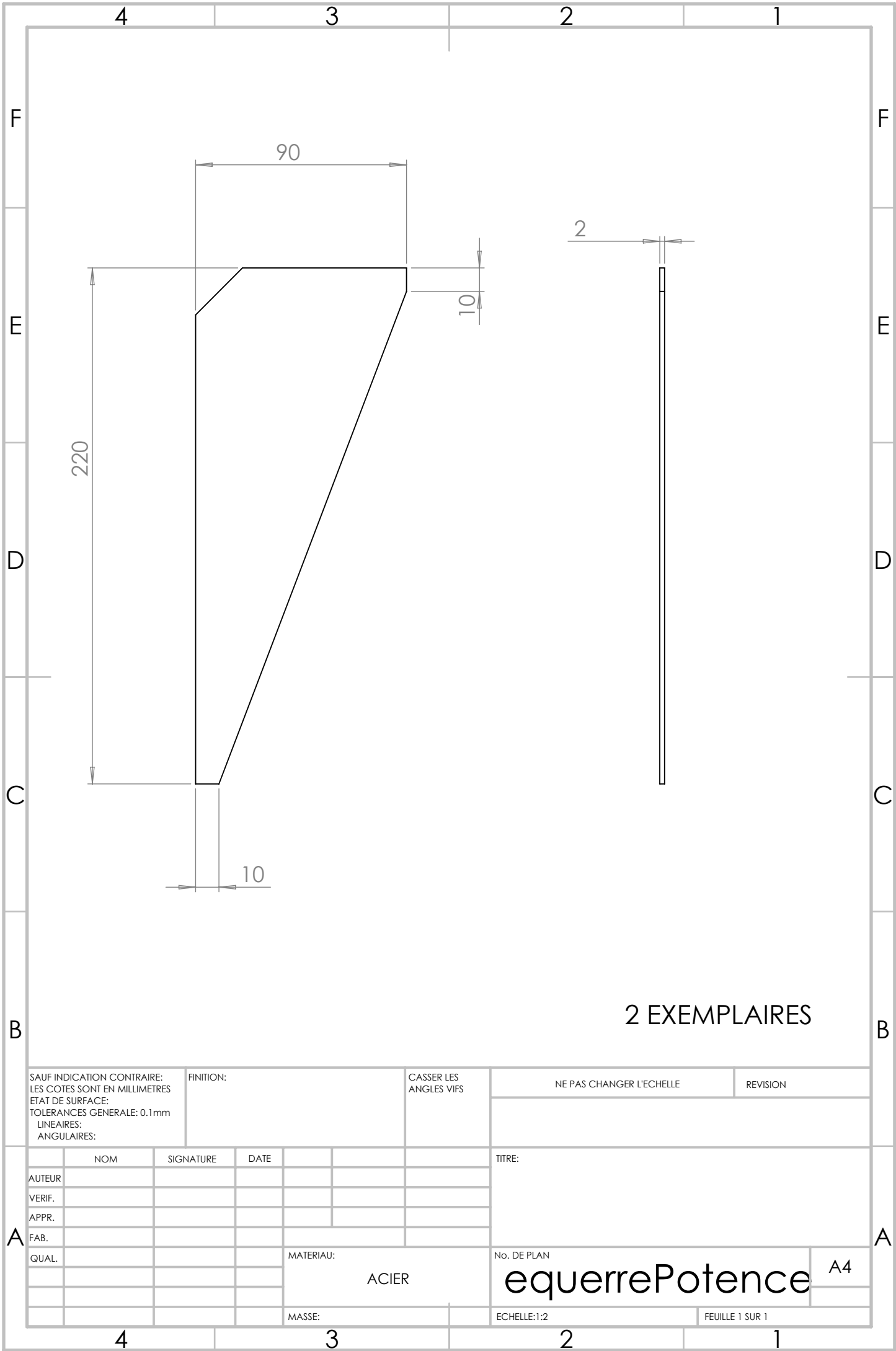
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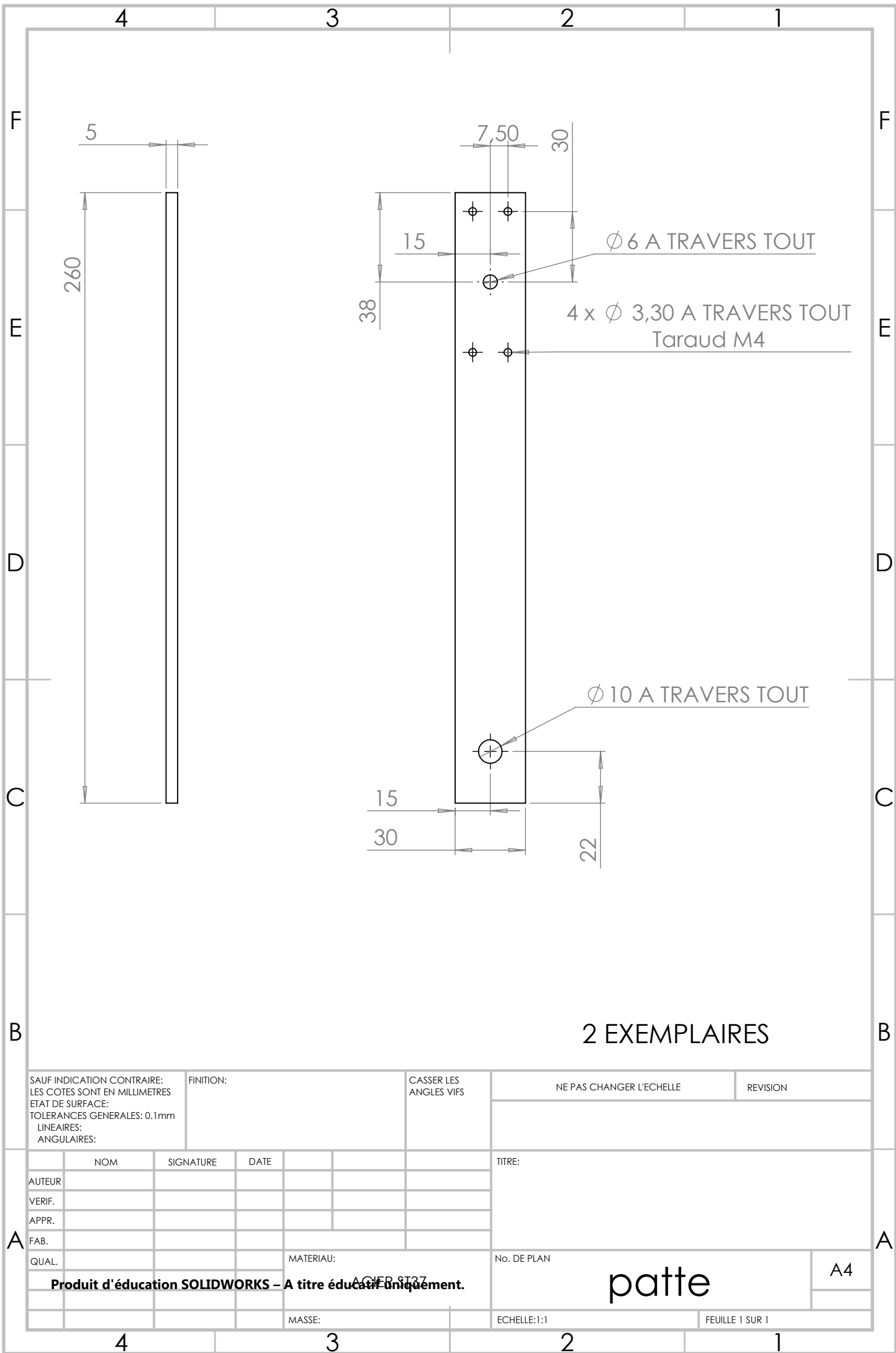


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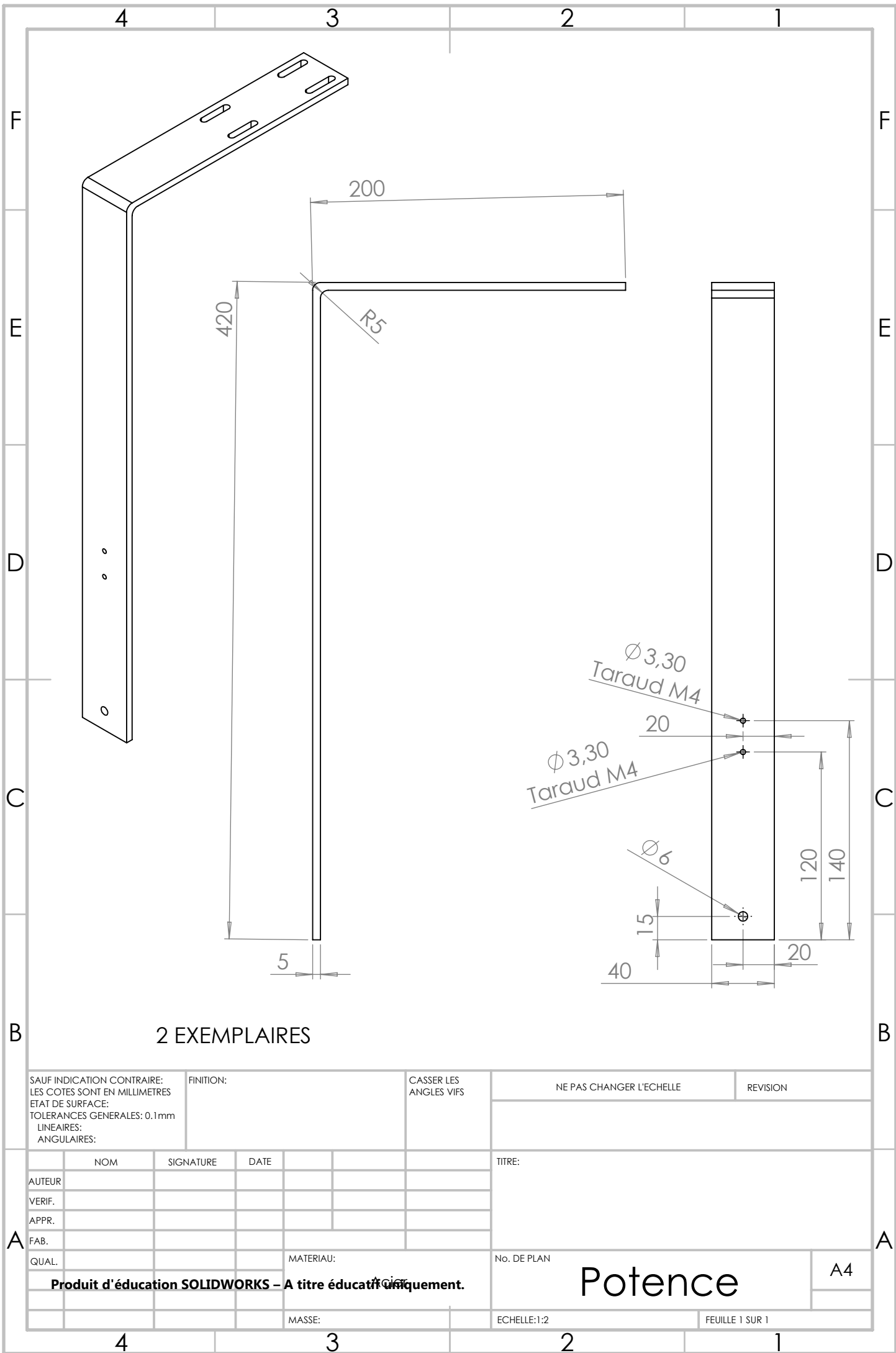
MASSÉ:	ECHELLE:5:1	FEUILLE 1 SUR 1
3	2	1







SAUF INDICATION CONTRAIRE: LES COTES SONT EN MILLIMETRES ETAT DE SURFACE: TOLERANCES GENERALES: 0.1mm LINEAIRES: ANGULAIRES:				FINITION:		CASSER LES ANGLES VIFS		NE PAS CHANGER L'ECHELLE		REVISION	
NOM						SIGNATURE		DATE		TITRE:	
AUTEUR											
VERIF.											
APPR.											
FAB.											
QUAL.											
Produit d'éducation SOLIDWORKS – A titre éducatif uniquement.						MATERIAU: ALUMINUM 6061-T6		No. DE PLAN		A4	
						MASSE:		ECHELLE: 1:1		FEUILLE 1 SUR 1	



2 EXEMPLAIRES

SAUF INDICATION CONTRAIRE: LES COTES SONT EN MILLIMETRES ETAT DE SURFACE: TOLERANCES GENERALES: 0.1mm LINEAIRES: ANGULAIRES:				FINITION: CASSER LES ANGLES VIFS		NE PAS CHANGER L'ECHELLE		REVISION	
NOM				SIGNATURE		DATE		TITRE:	
AUTEUR									
VERIF.									
APPR.									
FAB.									
QUAL.									
MATERIAU:									
MASSE:									
No. DE PLAN									
ECHELLE: 1:2									
FEUILLE 1 SUR 1									

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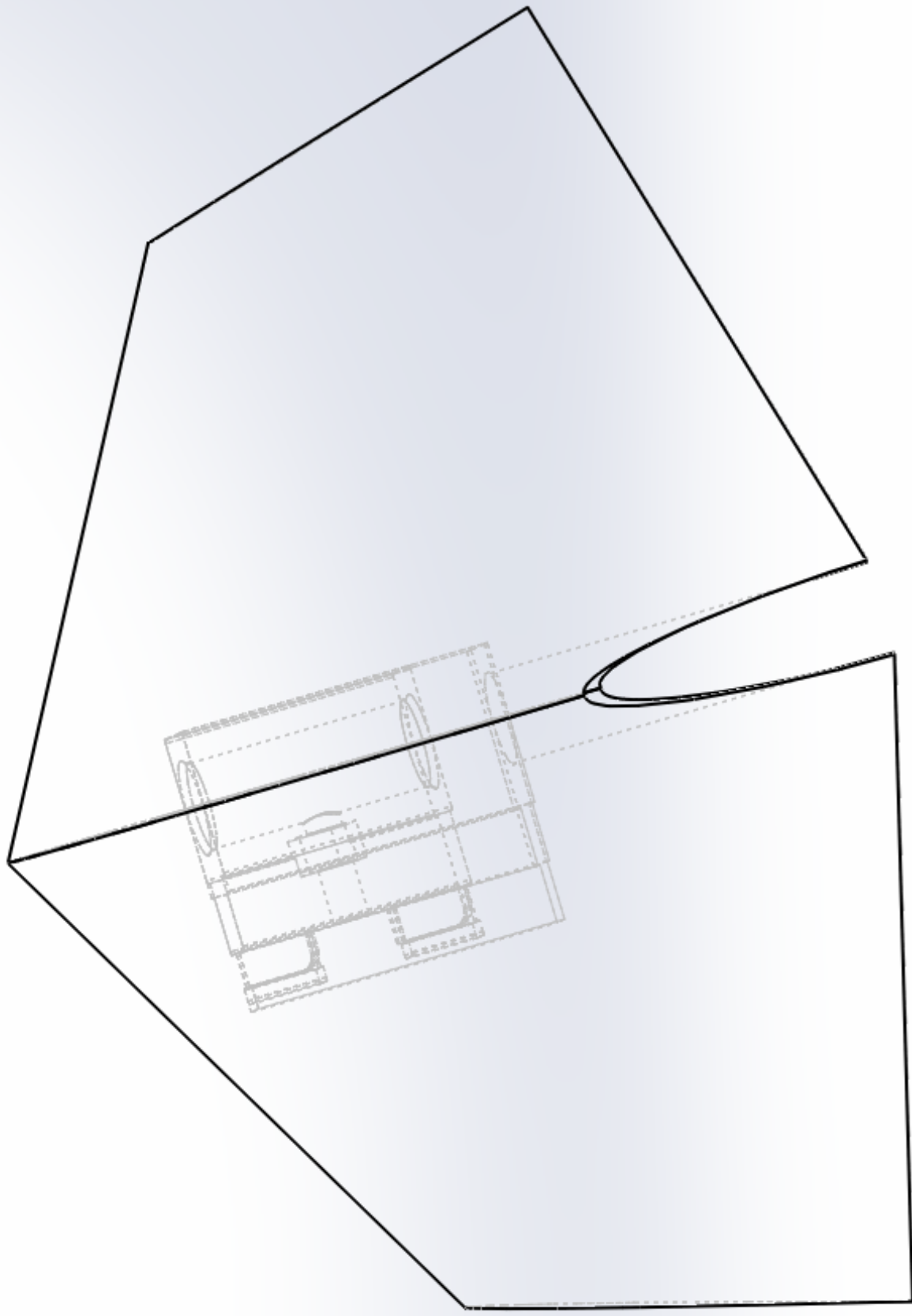
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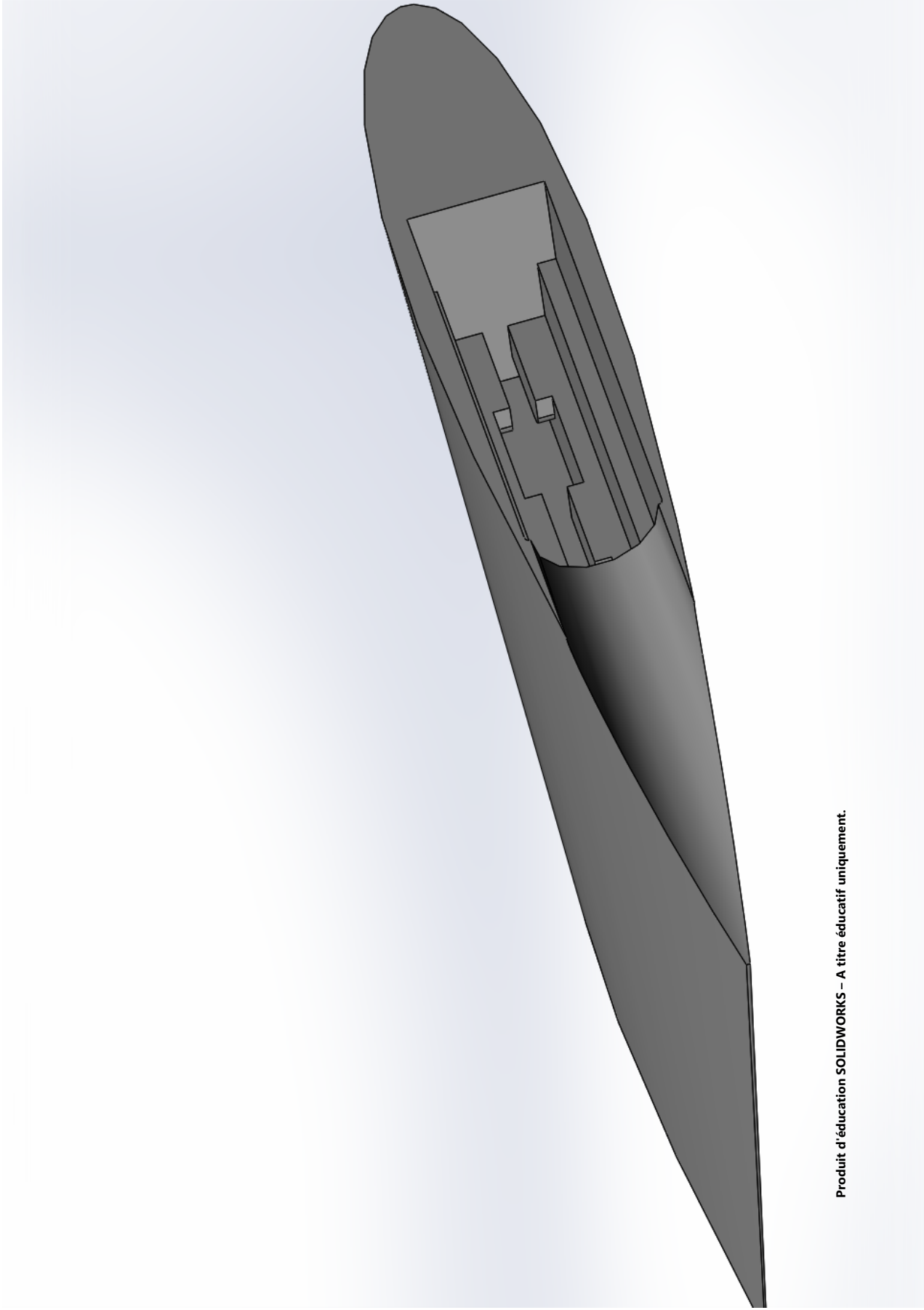
A4

	4	3	2	1			
F						F	
E						E	
D						D	
C						C	
B	1 EXEMPLAIRE					B	
A	SAUF INDICATION CONTRAIRE: LES COTES SONT EN MILLIMETRES ETAT DE SURFACE: TOLERANCES GENERALES: 0.1mm LINEAIRES: ANGULAIRES:			FINITION:	CASSER LES ANGLES VIFS	NE PAS CHANGER L'ECHELLE	REVISION
	NOM			SIGNATURE	DATE	TITRE:	
	AUTEUR						
	VERIF.						
	APPR.						
	FAB.						
	QUAL.						
	Produit d'éducation SOLIDWORKS – A titre éducatif uniquement.			MATERIAU: INOX		No. DE PLAN	
						transversale	
						A4	
			MASSE:		ECHELLE: 1:10		
					FEUILLE 1 SUR 1		
	4	3	2	1			

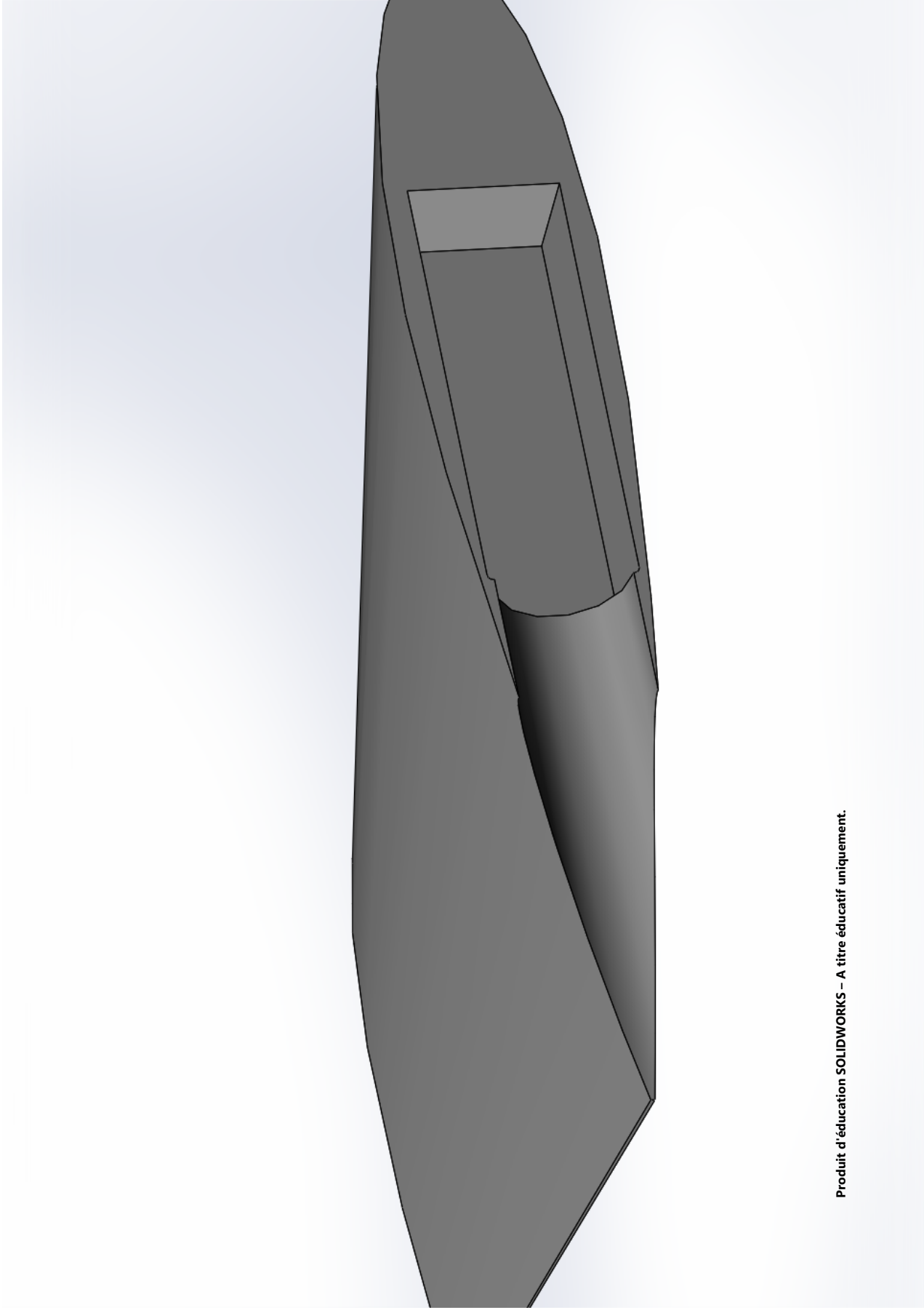
4				3				2				1							
F																			
E																			
D																			
C																			
B																			
A																			
4 EXEMPLAIRES																			
SAUF INDICATION CONTRAIRE: LES COTES SONT EN MILLIMETRES ETAT DE SURFACE: TOLERANCES GENERALE: 0.1mm LINEAIRES: ANGULAIRES:								FINITION:				CASSER LES ANGLES VIFS		NE PAS CHANGER L'ECHELLE				REVISION	
NOM		SIGNATURE		DATE															
AUTEUR																			
VERIF.																			
APPR.																			
FAB.																			
QUAL.																			
Produit d'éducation SOLIDWORKS – A titre éducatif uniquement.								INOX				No. DE PLAN				tube			
												ECHELLE:1:1				FEUILLE 1 SUR 1			
4				3				2				1							

B. Fin plans

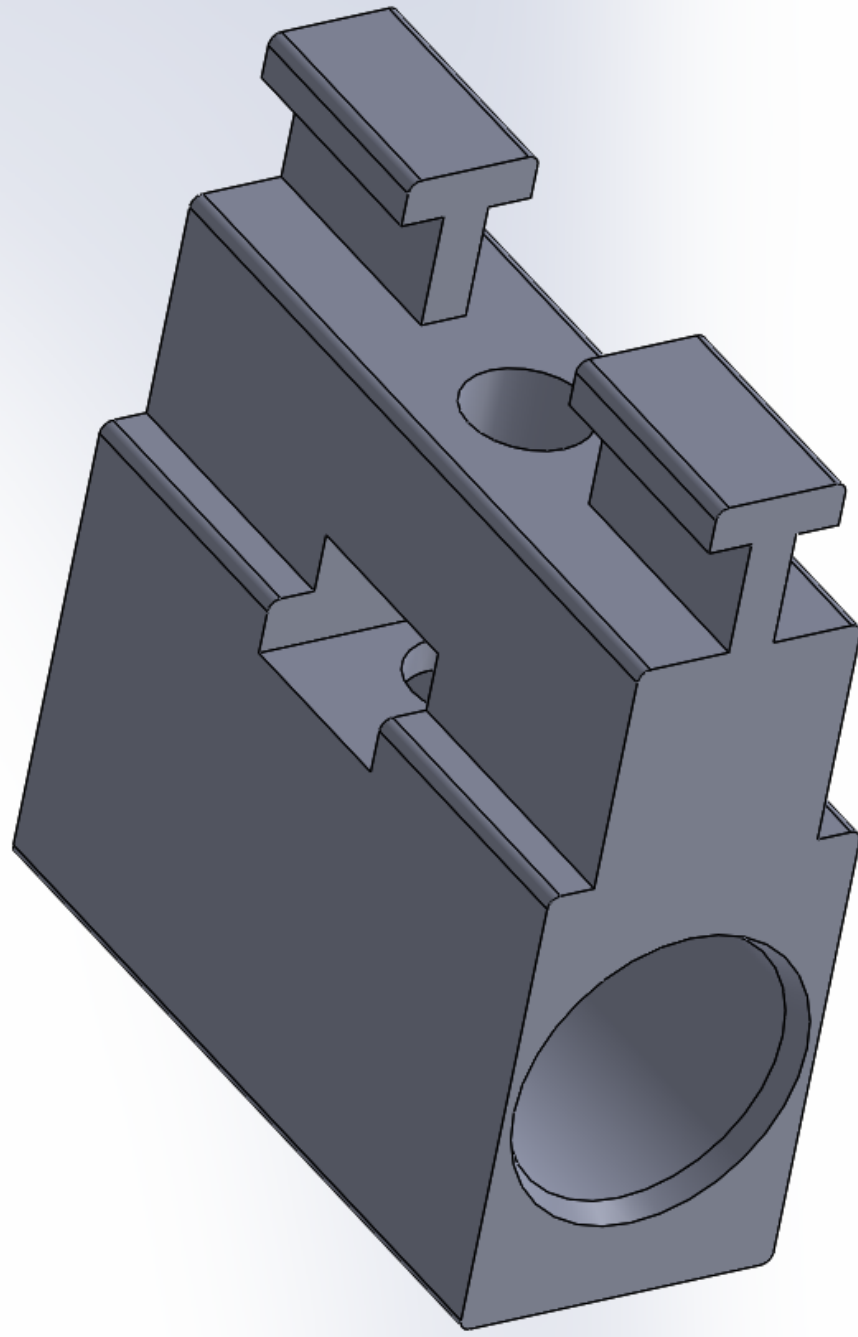




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C. PIV

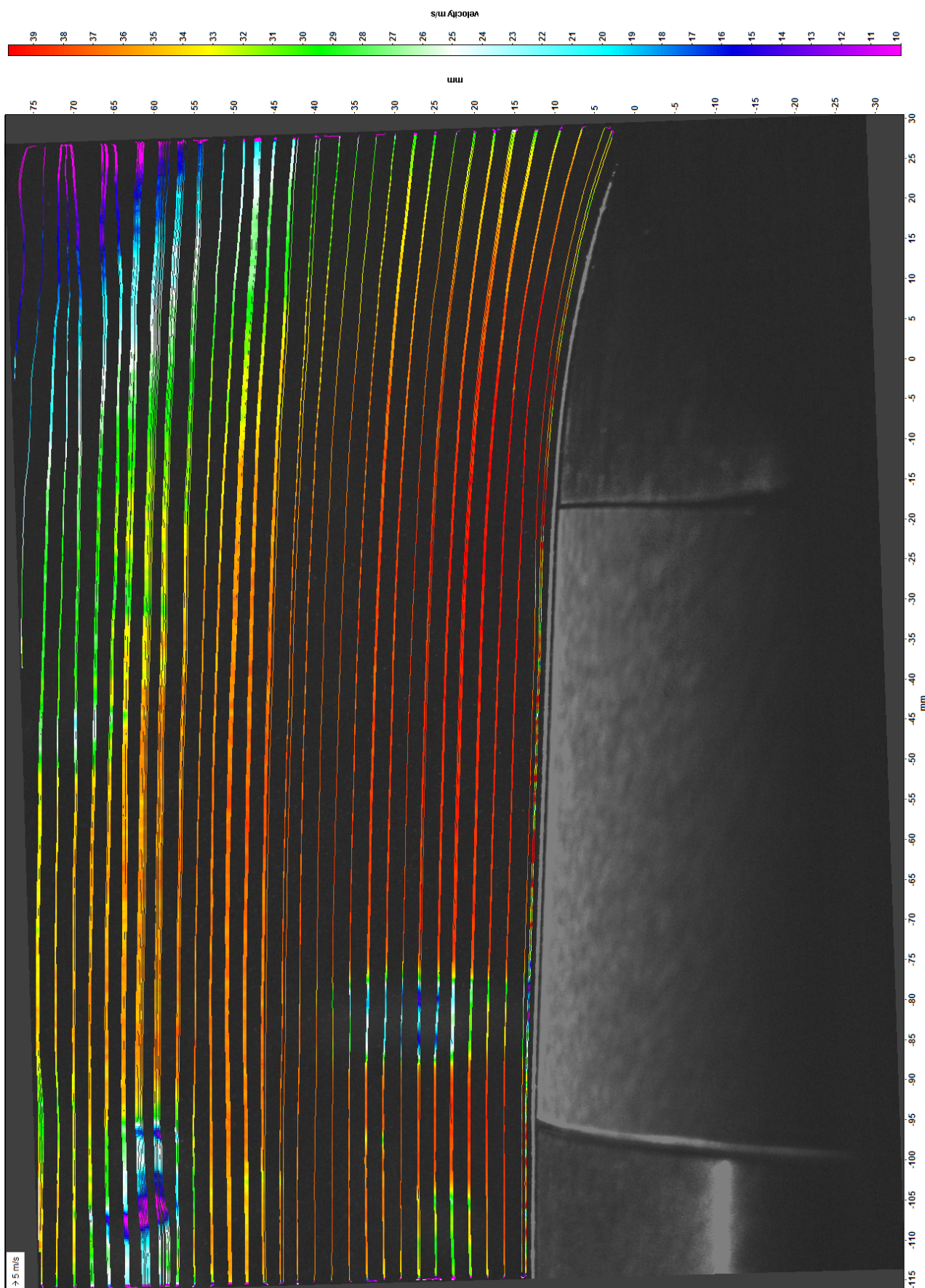


Figure C.1: EXP3 (Fins and no tripping disc in pitch + configuration) : Streamlines at 0^0 angle of attack

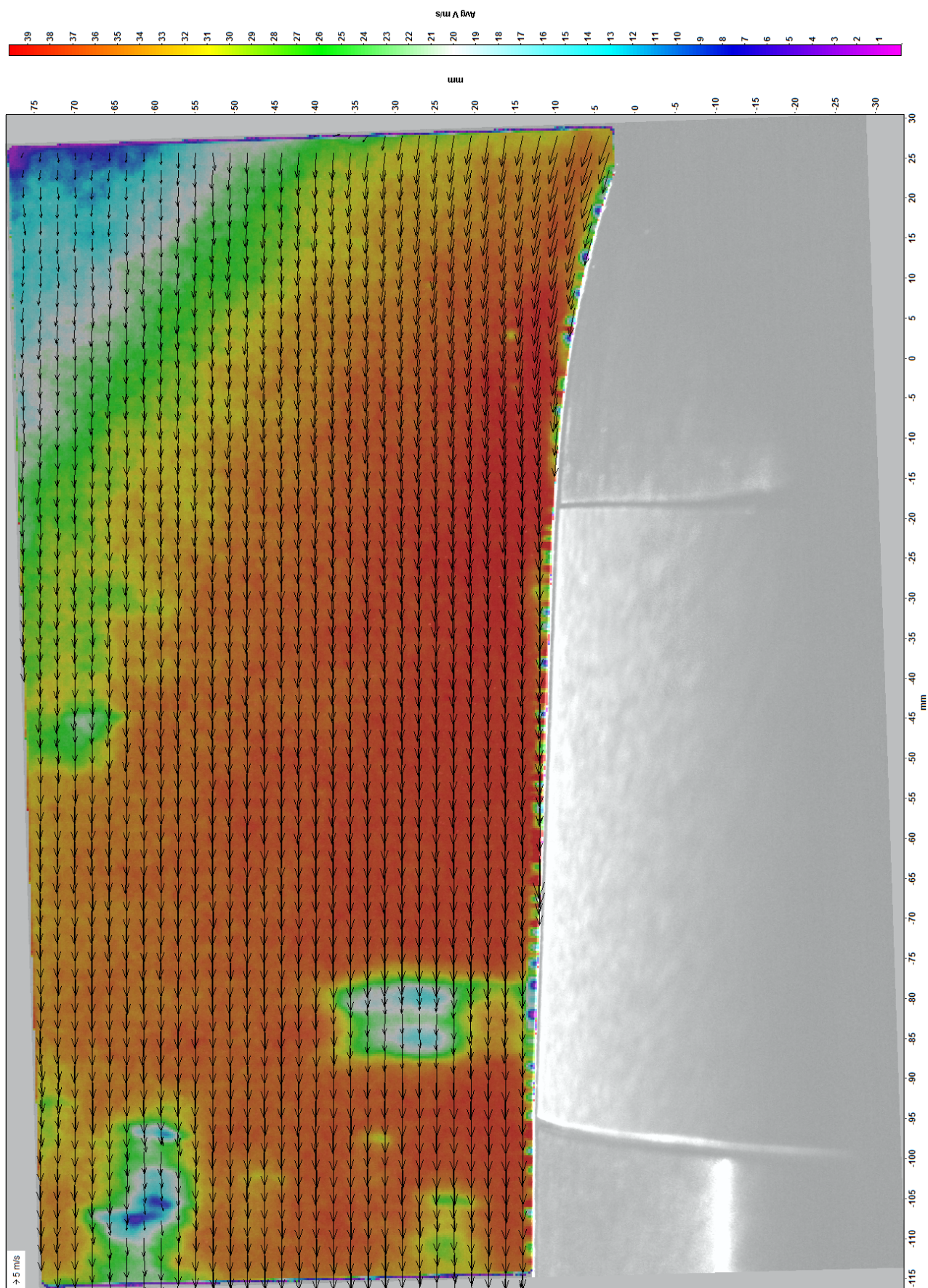


Figure C.2: EXP3 (Fins and no tripping disc in pitch + configuration) : vector fields at 0^0 angle of attack

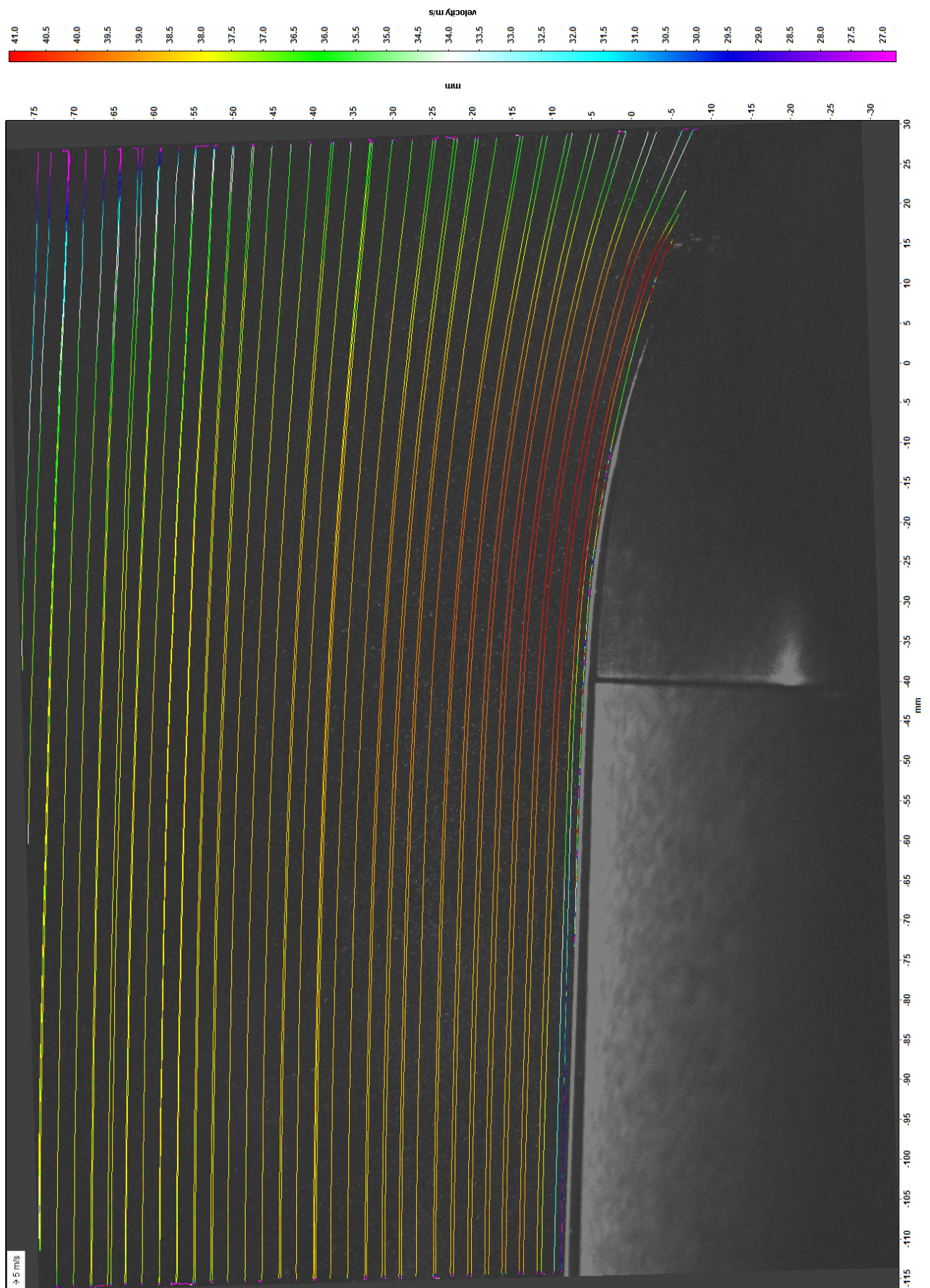


Figure C.3: EXP6 (Fins and tripping disc in pitch + configuration) : Streamlines at 0° angle of attack

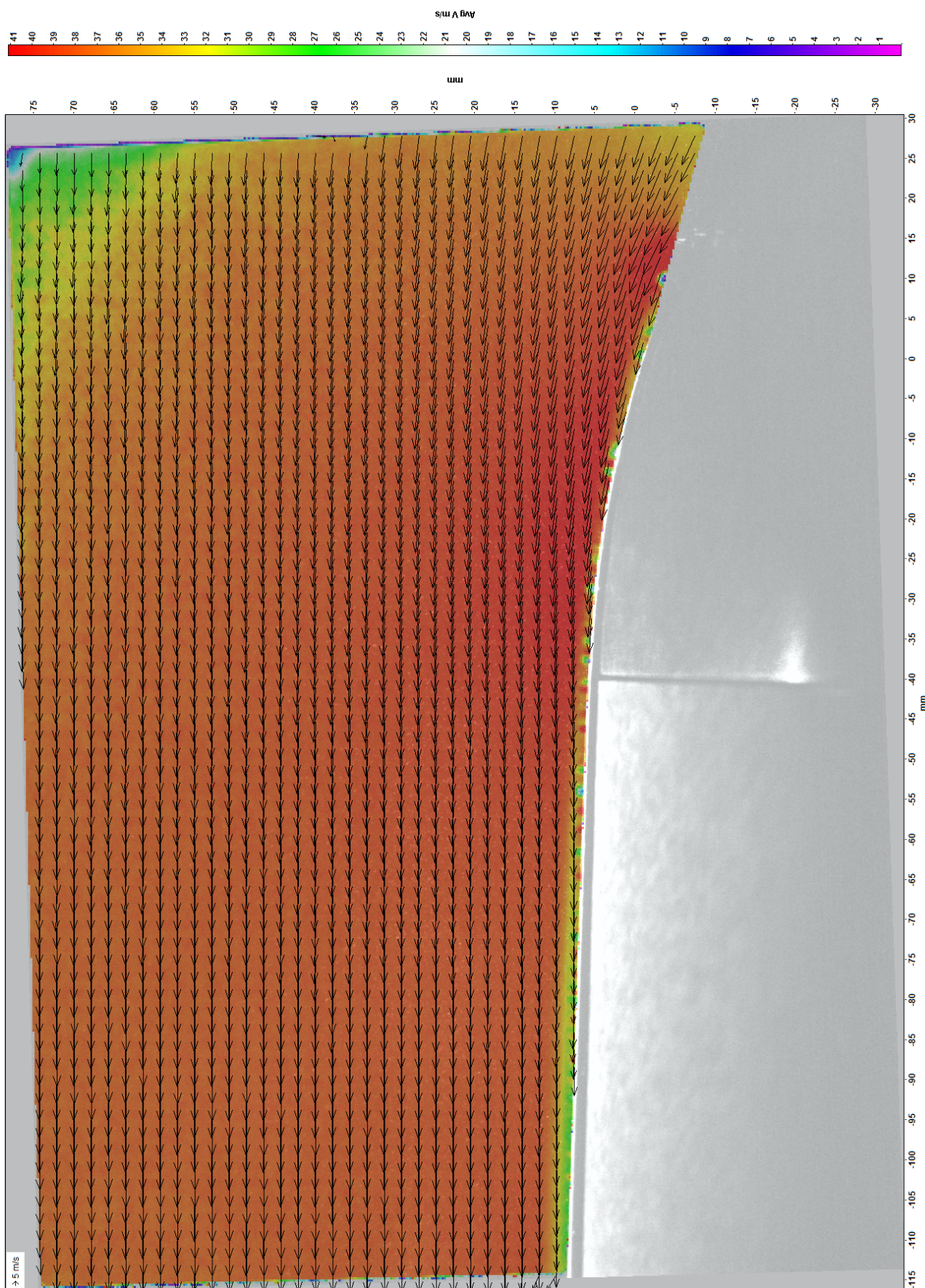


Figure C.4: EXP6 (Fins and tripping disc in pitch + configuration) : vector fields at 0^0 angle of attack

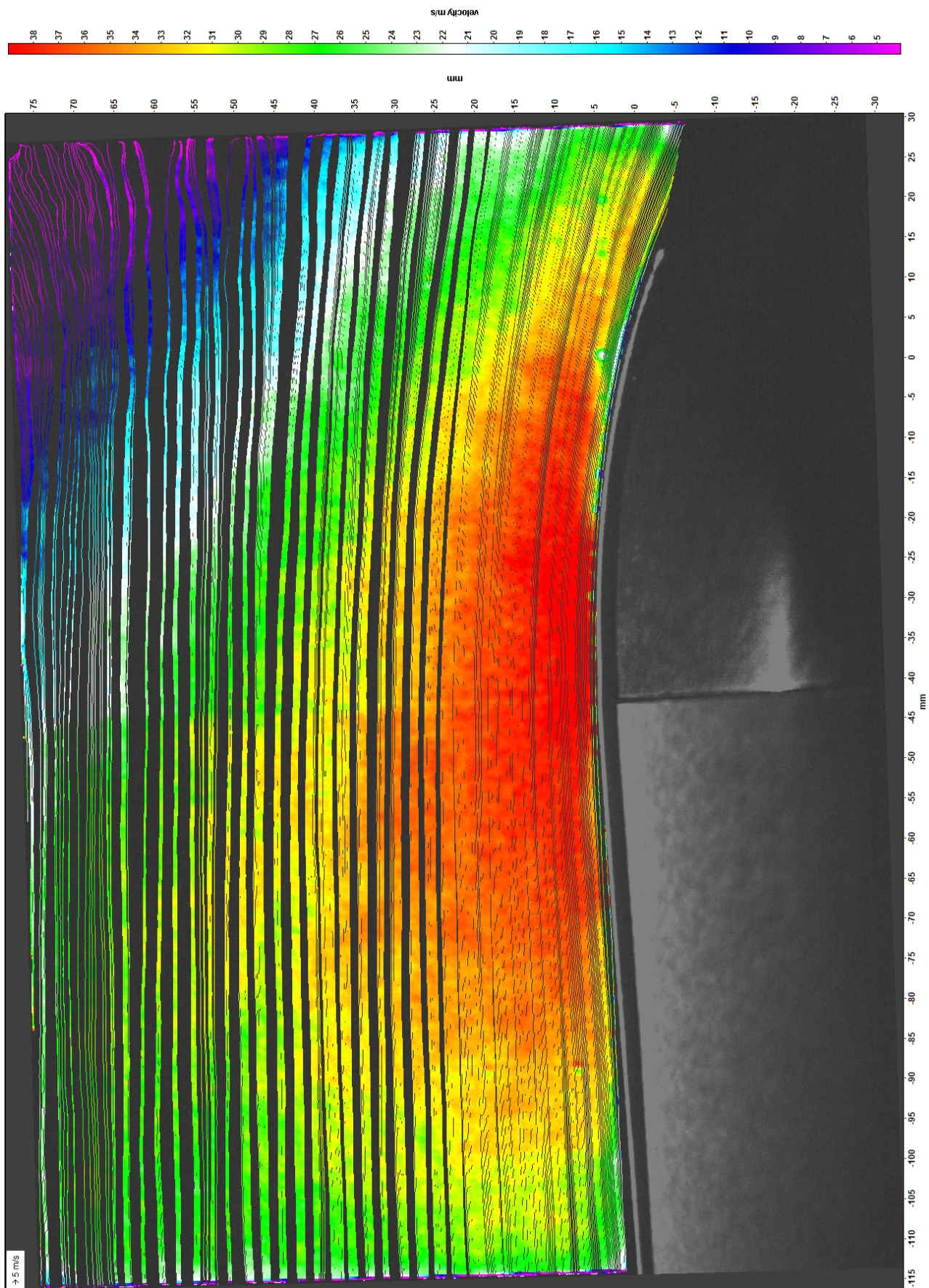


Figure C.5: EXP3 (Fins and no tripping disc in pitch + configuration) : Streamlines at 5^0 angle of attack

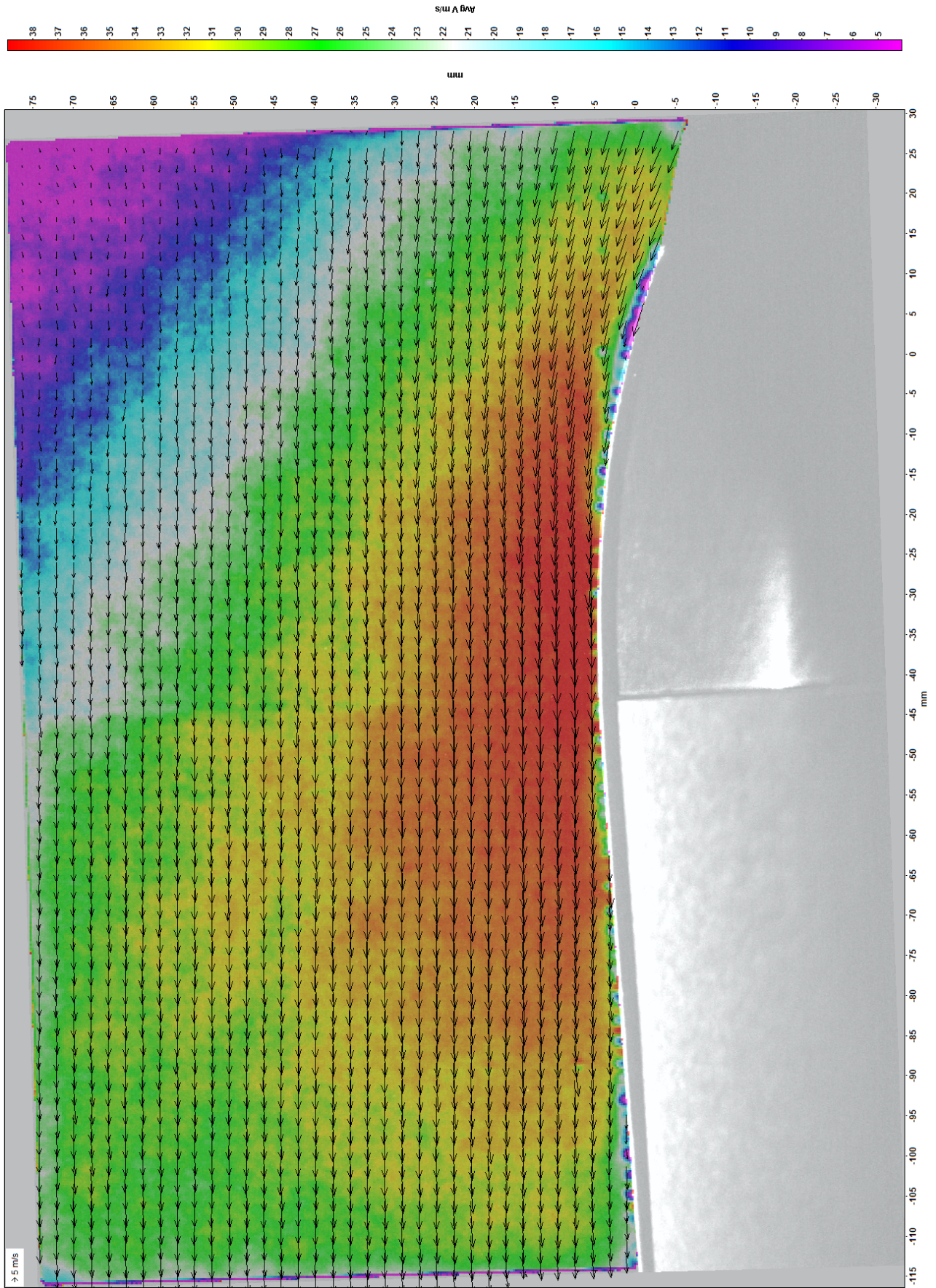


Figure C.6: EXP3 (Fins and no tripping disc in pitch + configuration) : vector fields at 5° angle of attack

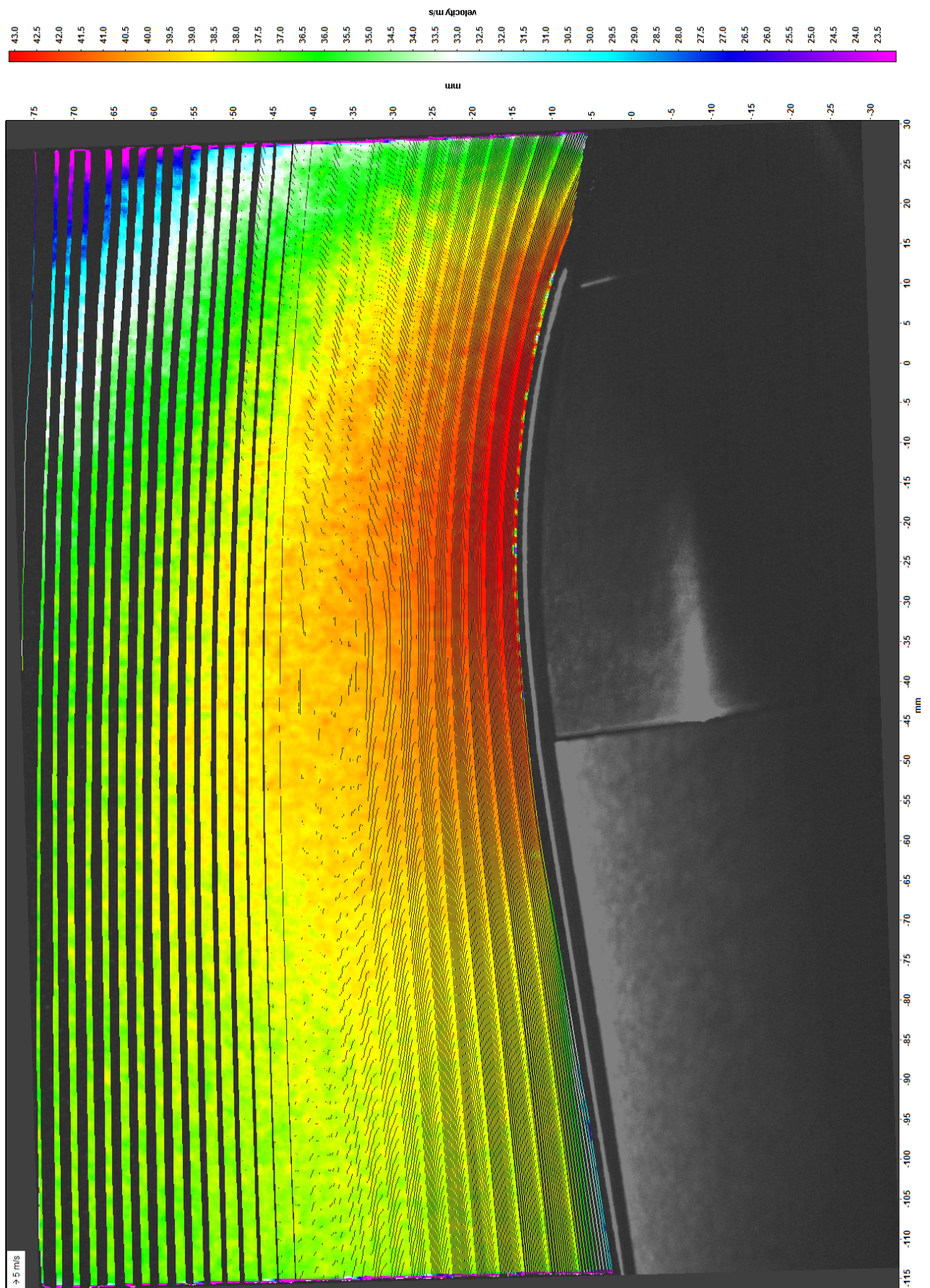


Figure C.7: EXP3 (Fins and no tripping disc in pitch + configuration) : Streamlines at 10° angle of attack

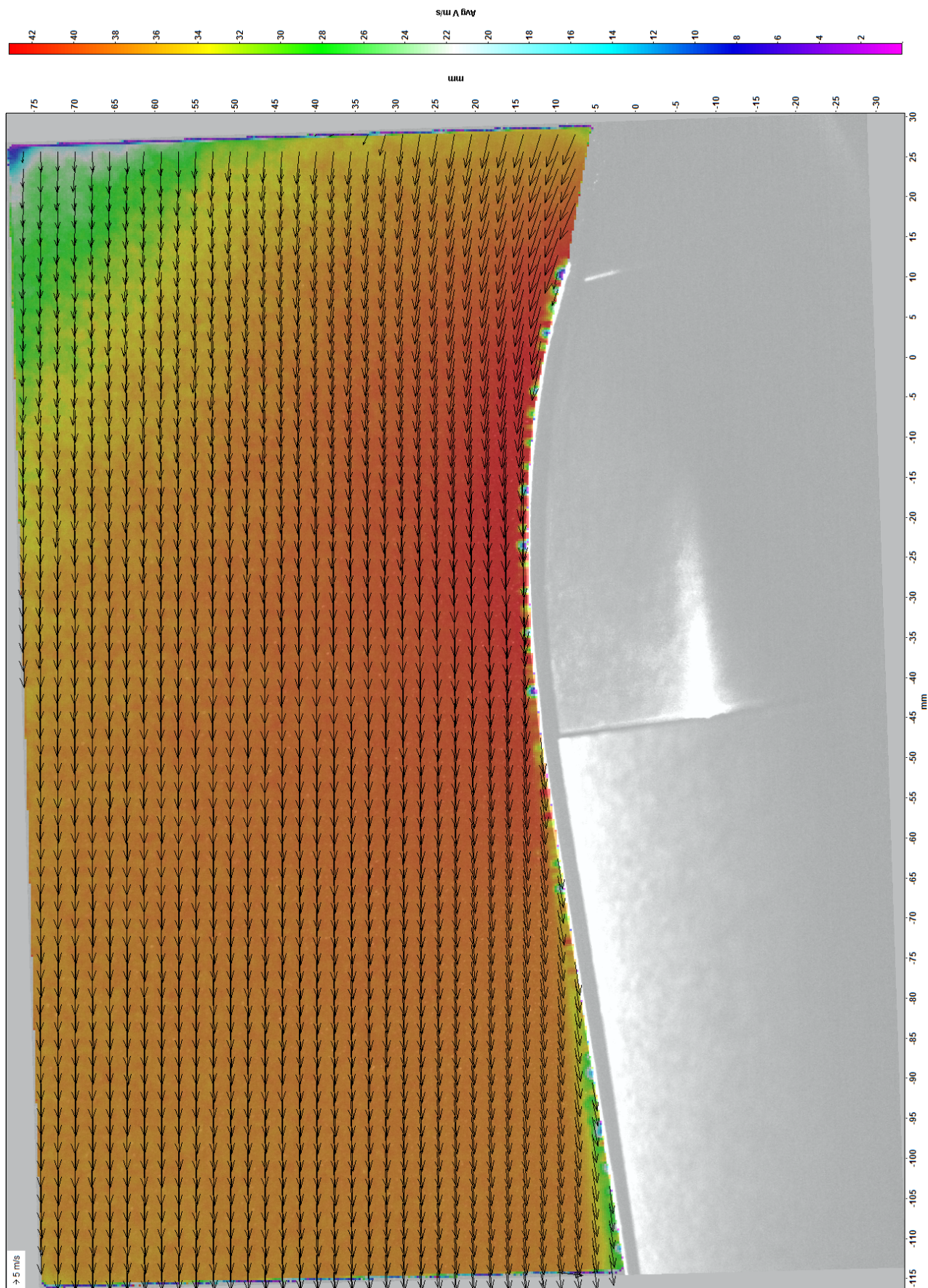


Figure C.8: EXP3 (Fins and no tripping disc in pitch + configuration) : vector fields at 10^0 angle of attack

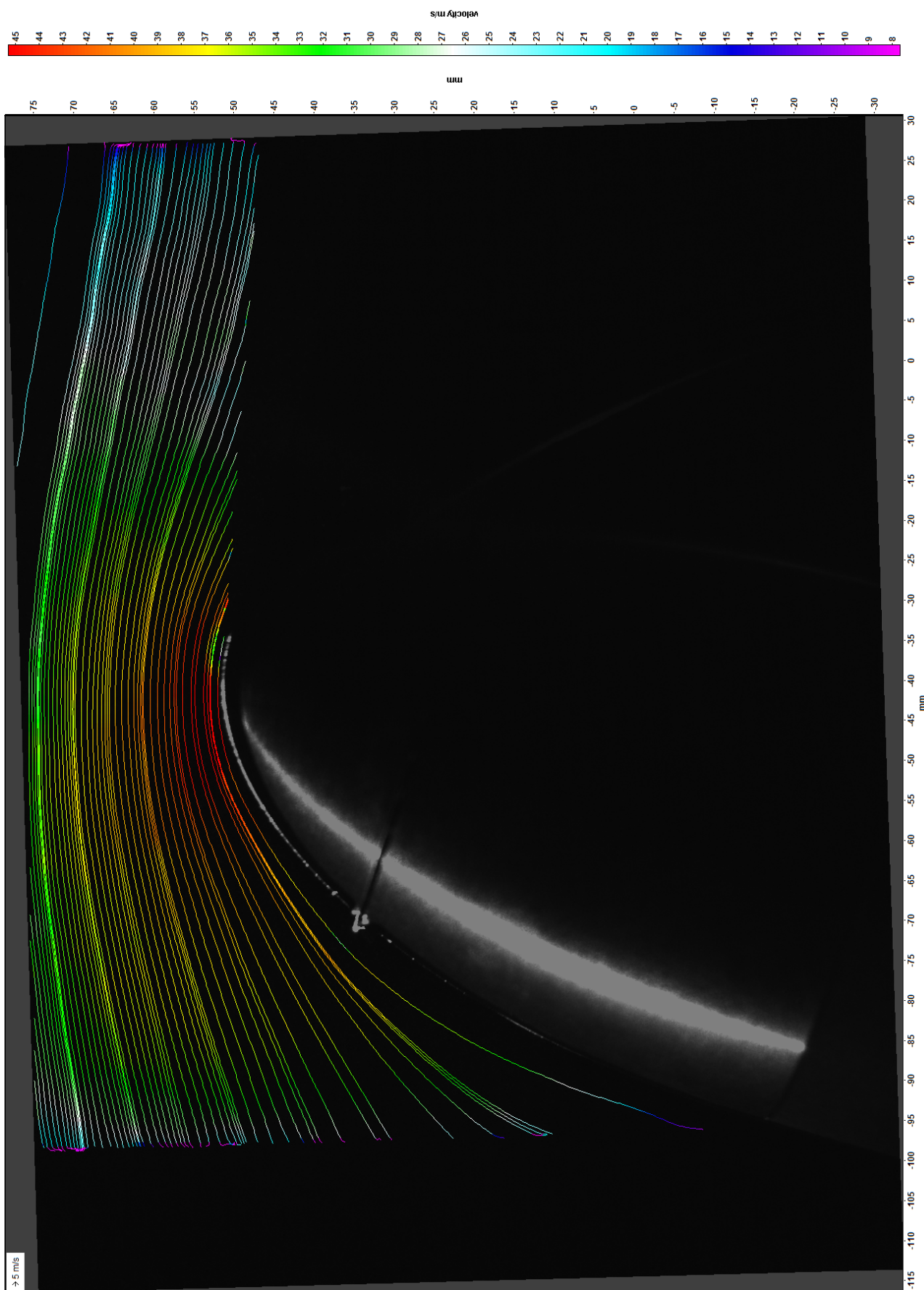


Figure C.9: EXP6 (Fins and tripping disc in pitch + configuration) : Streamlines at 75° angle of attack

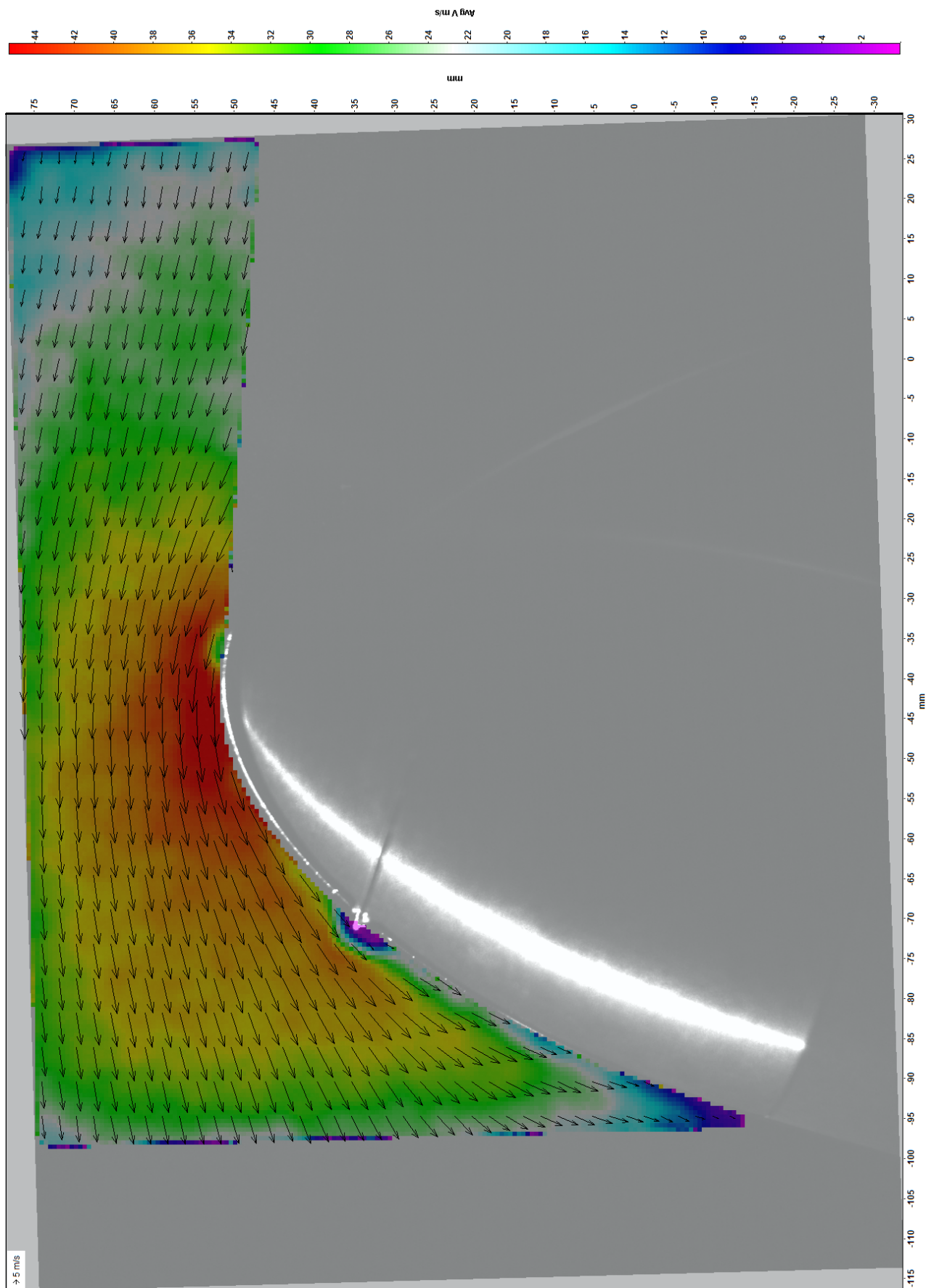


Figure C.10: EXP6 (Fins and tripping disc in pitch + configuration) : vector fields at 75° angle of attack

