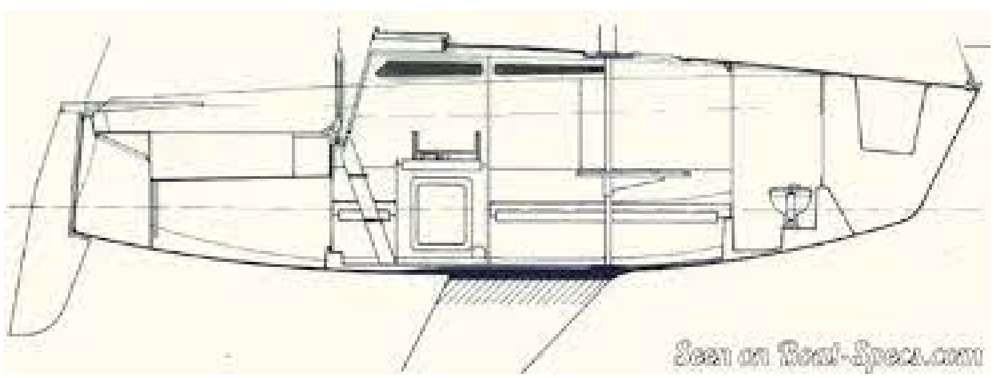
Sailboat rudder design report

by
Julien HAMELIN
Engineering student in mechanics at Ecole des Ponts et Chaussées



July 2021

Introduction

This summer 2021, while I was sailing off Trébeurden in Brittany, my rudder broke down. Fortunately I managed to bring my boat back in the harbor with my outboard engine without sustaining any other damage. However, I had to design and build a new rudder on my own : the part is not available on the market.

For information, the boat was a Jouët 24 designed and built by Yachting France in 1980. All specifications are available on the technical sheet in the appendix[2].

(a) The broken rudder

(b) The original part

Contents

Part I
Specification

My project aimed to design and build a new rudder. Firstly I had to precise the specification. To do so, I relied mainly on the fabulous book *Théorie du navire*[1].

Environment and case of use

I first decided to have a short reflection on the environment my rudder would work in.
Its mission is simple. It is a two dimensional board linked to the boat by hinges used to steer the boat. The orientation given to the board makes the boat turn right or left. Thus, it interacts with the seawater in two ways. First this board generates a lift that make the boat drivable and then it generates a drag that breaks the boat down. One issue of the design is to maximize lift and minimize drag.
The other issue raised is the question of the mechanical resistance. Indeed, the lift generated by the rudder's shape constrains the part and could break it again if it is not strong enough. The mechanics sizing is thus a major part of the design as well.
Finally, the part will work in a marine environment. This environment forced me to make it fully marine-proof.

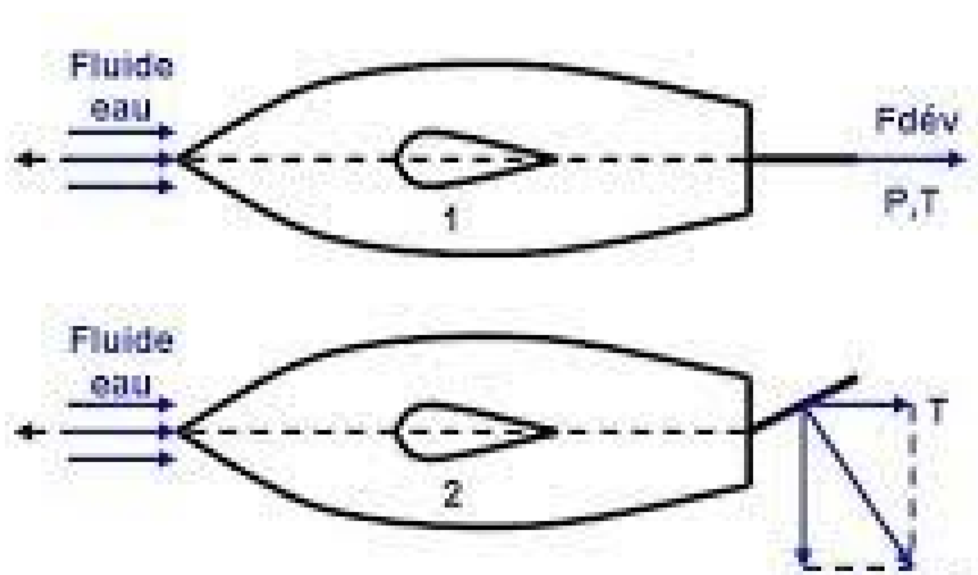


Figure 2: Functional scheme of a rudder

1 Sizing

First and foremost, the rudder must be big enough to have enough lift to drive the boat.
It is a major point because if the rudder cannot control the boat, my very job would have been useless. To clarify this point, I used an article from Voiles et Voiliers[3]. It is commonly admitted that a ship designer must choose a rudder surface up to between 1 and 1,5% of the close-hauled sail surface. In my case, my close-hauled sail surface is 30,7 m^2. So my rudder must have a surface between 0,31 and 0,46 m^2.

Figure 3: On the right, the close-hauled sail configuration. On the right, the downwind sail configuration.

2 Hyrodynamics

The main issue is the same, to minimize drag while maximizing lift. In this work, we chose a NACA 0012 profile as many references incited me.

3 Mechanics

When my rudder broke, the situation could have been much more dangerous for me. That is why this point is of great importance in this study. Here one only

cares about the flat side of the rudder. The thick side is never a problem as long as the profile minimizes the drag sufficiently not to strengthen too much this side. On the contrary, when the helmsman is turning, there is a lot of pressure on the flat side, especially when the boat is going fast and the helmsman is turning strong. It is a case of use that can happen so we have to design the rudder consequently.
In a nutshell, the rudder must resist to the pressure of the sea if the helmsman turns the part 90 degrees at a boat speed of 10 knots. Because it was handmade, I will take a safety coefficient of 1.5.

Part II
Design

1 Sizing

While I was doing my research on the sizing, I realized that one must add a compensation surface on a rudder. Otherwise, if all the surface is behind the axis of rotation, the lift generates a moment that will make the handling of the helm really hard.To avoid these problems, one adds a surface in front of the axis of rotation that generates a little torque which compensates the first moment.

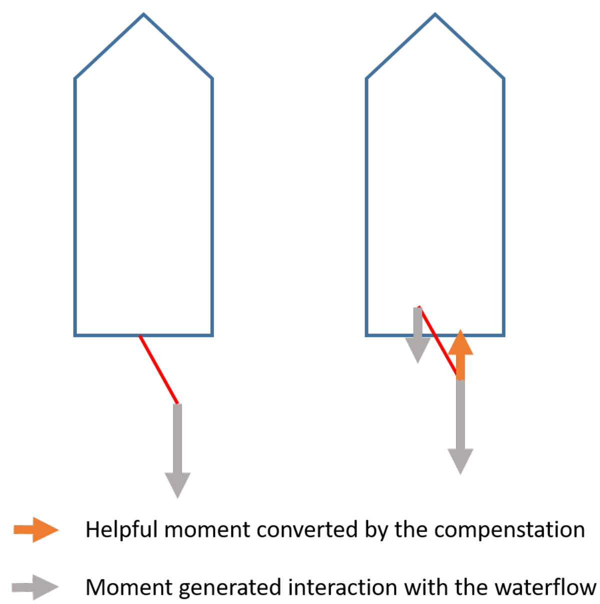


Figure 4: Functional scheme of the utility of a compensation

To avoid these unexpected issues, I decided to copy the sizing of my previous rudder. But because the other part of the rudder rests in peace at the bottom of the sea, I needed to analyze an image of the part I took during the fairing. I used the software Mesurim to draw a scale pixels-cm (based on the size of the fitting that I knew) and then to obtain the sizing of the rudder. With this process, I avoided every problem regarding the rudder surface and compensation surface.

Fortunately, the surface measurement of the previous rudder matched with our specification which was a good news (I could validate this design).

NB : One must notice that before beginning to craft my new rudder, I contacted a Jouët 24 owner I met on the Internet who took the dimensions of his

Figure 5: Results of the image dimensions analysis.

original rudder and sent me a paper pattern of it. I received it far too late to base my design on this pattern but a posteriori, the dimensions of my rudder were perfect. It validated the method of the image analysis.

2 Hydrodynamics

Then, I took the odds of a NACA 0012 profile from the website airfoiltools.com and I ajusted all the dimensions with a chord of 480mm. I put all the points coordinates on CATIA to design the profile. I had to correct some points to make the rudder thick enough to carry the wooden structure (3cm thick) and to make it more hydrodynamic. Indeed, The naca is the perfect profile when solicited by direct front water flow. Then, I projected this profile on 9 layers, each 10 cm apart. I managed to translate the profiles and to adjust their sides using the tool "affinity" (on the X and Y coordinates) to match with the rudder's dimensions. I used the generative shape design workshop on CATIA V5R18 to design the rudder.

3 Mechanics

The purpose of this section was to determine the number of glass fiber's layer required and to identify the weak points of our structure.

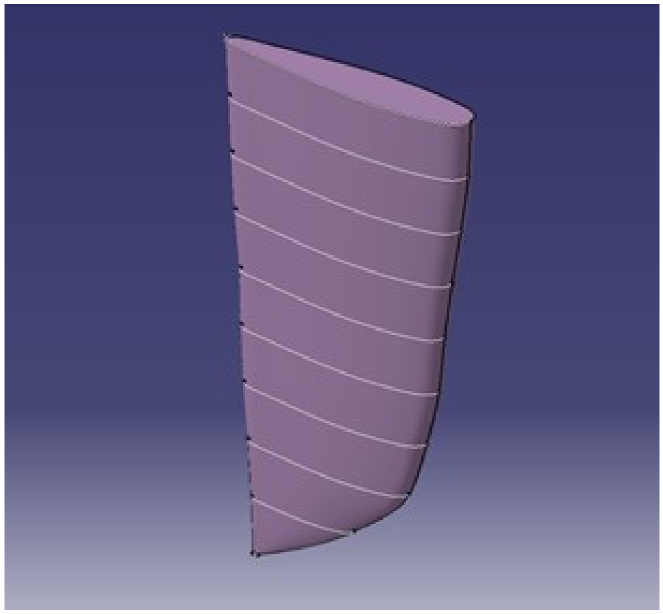


Figure 6: Rudder's shape done on Catia V5

First and foremost, one needs to estimate the interaction between the sea and the rudder depending on the orientation of it. The Joessel formula[1] provides this information :

$$F = \frac{k.S.V^2 sin(i)}{0,2 + 0,3sin(i)}$$

With S the rudder's surface (m^2), V the boat speed ($m.s^{-1}$), i the rudder's orientation and k a coefficient equal to 41,35 in seawater.

That represents a pressure on the on water part equal to :

$$\sigma = \frac{k.V^2 sin(i)}{0,2 + 0,3sin(i)} \qquad (1)$$

Then I plotted the constraint as a function of the boat speed.

On this graph, one can see that the maximum pressure on the rudder is about 850 Pa. That is far beyond the resistance of a basic composite sheet. For a security concern, we will put 5 layers of composite. In fact, the previous dynamic study only considers a rudder going in a water flow at a certain speed. The reality is much more complex because the rudder is fixed to a 1.6 tons boat which has a huge inertia and that constrains even more the rudder in flexion. The constraint is moreover in flexion and torsion because the pressure on the rudder's surface is not equally divided. That is why I oriented the fibers in different directions between each layer (but I will explain in more details later in this report).

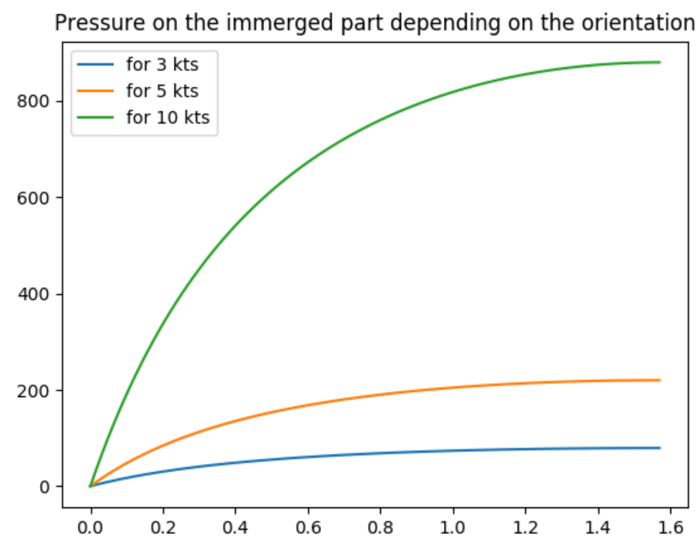


Figure 7: Constraint on the rudder as a function of the boat speed.

Part III
Production

Method

I chose to design my rudder in 3 different parts. One is expected to reduce the drag and improve the lift (it is the hydrodynamic part). An other is expected to ensure the cohesion of the structure and transmit the helmsman command (it is the wooden structure). The last one is expected to make it strong enough so it would handle the strength of the sea (it is the glass fiber stratification). I chose this construction strategy as it is really common in naval engineering.

Here is my method. First, I will shape a NACA 0012 (as said in the specification) in a polystyrene block. That was indeed less expensive and less heavy than wood. Then, I would make the wooden structure and stick it to the profile. Finally, I would wrap the complete structure with stratification of fiberglass epoxy. The different parts of the assembly are shown in the following picture. One may notice that there are two extra wooden parts on top of the rudder. They were here only to make an extra thickness at the top (which the profile does not model because it is above water). Moreover, fittings will be added to ensure the link between the rudder and the boat. And it is better to tighten them on a wood structure tan on a sandwich glass fiber-polystyrene.

To conclude, my strategy was quite simple. The wooden part ensures the cohesion of the structure. The polystyrene part gives the rudder its hydrodynamic properties. The fiberglass part strengthens the rudder and gives it its mechanic properties. Those 3 parts of the assembly defines the 3 steps of my fabrication process.

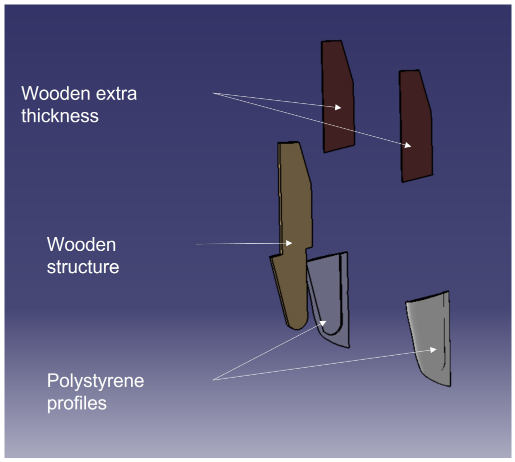


Figure 8: Here one can see every different part of the rudder assembly.

1 Hydrodynamics profiles

To realise the hydrodynamic part of the specification, I shaped the NACA 0012 profile with a CharlyRobot milling machine. I generated a Gcode with CATIA V5 and then sent it to the machine to mill my very profile in a polystyrene block. Nothing to notice at this point, everything went well and I finally had my two semi-rudder with a hole on both side to admit the wooden structure.

2 Wooden structure

The main constraint of the wooden structure was the dimension of its part that went inside the polystyrene profile. Once I drew the exact dimension with the milling machine, I cut a 30mm thick marine plywood. Then I stuck together the wood and the polystyrene, using a wood glue. The small space between the polystyrene profiles and the wooden structure was filled with polyurethane foam.
Then I added the two extra thickness wooden parts, tied together with wood glue as well.

Also, I did something I did not plan in my design. I drilled 3 holes in my polystyrene profile in the thickest place. When the helmsman is turning, the wooden part (hard) is transmitting a command to the glass fiber part (hard) through the polystyrene part (soft).On the thinnest part of the polystyrene

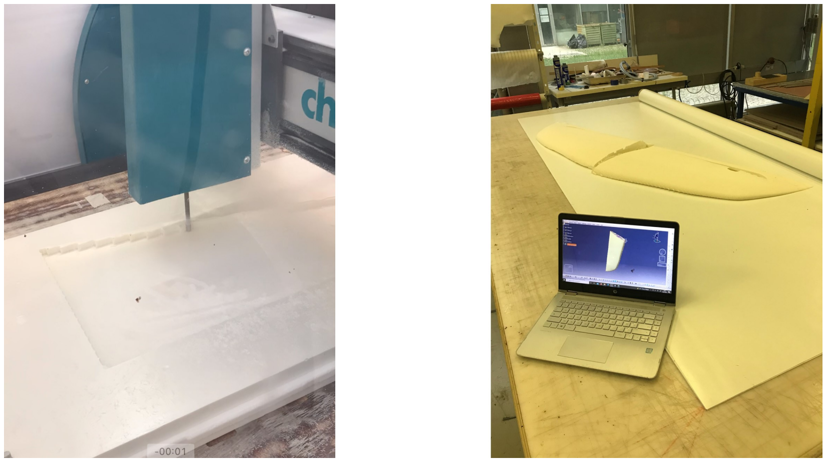


Figure 9: On the left one can see the polystyrene parts while milling. On the right, the result.

profile, there are no problems because there are no much polystyrene between the glass fiber and the structure. On the contrary, on the thickest place, there is much polystyrene that could deform if the water pressure on the rudder is high. This is why I drilled 3 holes on both sides of the profile and filled it with mat and epoxy. Thanks to this, one has hard points to rely on to transmit the command to the glass fiber while reducing the deformation of the polystyrene.

3 Glassfiber stratification

For the glass fiber stratification, I used a 430 g/cm^2 bidirectional glass fiber and an epoxy resin. I made 5 layers : 3 with vertical and horizontal fibers (to have a right flexion resistance) and 2 diagonal fibers (to have the right torsion resistance). I applied the resin on the glass fiber with a paint roller specially made for this kind of application. Thus I avoided having air bubbles caught in my stratification. Between each layer, I waited until the fiber was dry to put an other layer.

After all these layers, I cooked the rudder at 40°C with a powerful air flow for 2 hours to finish drying it.

An important thing to notice is that the epoxy resin is a marine proof product. Thus, with this kind of stratification, the rudder is theoretically waterproof.

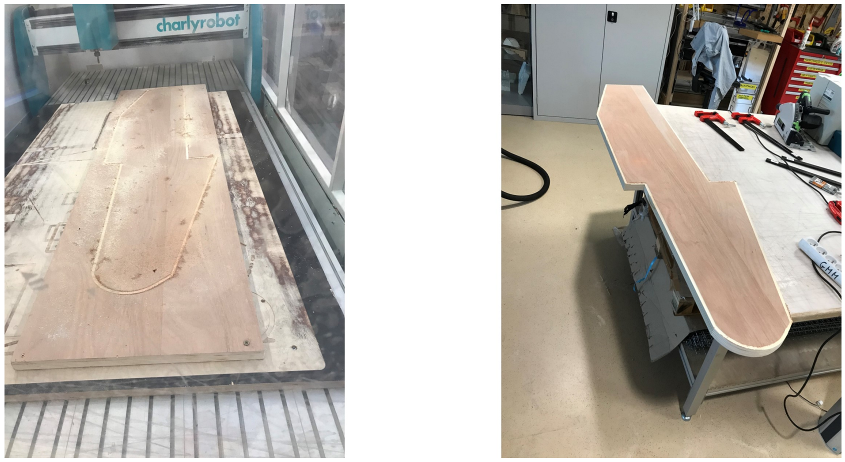


Figure 10: Fabrication and result of the wooden structure

4 Finition

The finishing was about making sure of the "marineproofness" of the rudder and smoothing its surface. To do so, I used an epoxy coating. I firstly sanded down the rudders surface and then I applied the coating side after side and cooked the rudder between each layer (at 40°C until it is fully dried). I also managed to fill the defaults of the stratification with the epoxy coating. Moreover, as long as the epoxy coating is marine proof, I strenghened the resistance of the rudder against the sea. Then I painted the rudder with a specific marine painting.

At this stage, I had finished the rudder but I still had to link it to the boat. I reused the previous fittings and just made holes to tighten them on the rudder with screws and bolts. I drilled the rudder and stuck the fittings. To not damage the marineproofness of the rudder, I used a Sickaflex mastic and put it inside the holes before screwing the fittings.

Conclusion

In conclusion, I would say that it was a great experience to build by own rudder in a limited time (2 weeks). And this allowed me to apply my engineer's skills acquired at Ecole des Ponts ParisTech.
I want to thank the departement of mechanical and material engineering for the material support !

Figure 11: On the right one can see the drilling of the 3 "stratified holes" and on the left the result when it was fully stratified.

References

[1] J. Pollard et A. Dudebout. "Théorie du navire". In: Architecture Navale tome III (2020).

[2] bateaux.com. Jouët 24's technical sheet. URL: `https://www.bateaux.com/plaisance/voiliers/jouet-24-REFha2KLfTUL2I,`.

[3] Pierre-Marie Bourguinat. The first 3D printed House with earth | Gaia. URL: `https://voilesetvoiliers.ouest-france.fr/industrie-nautique/chantiers/tout-ce-que-vous-avez-toujours-voulu-savoir-sur-votre-safran-sans-jamais-oser-le-demander-df9457f5-8fc4-b048-bd6c-c6f5e38f275d`.

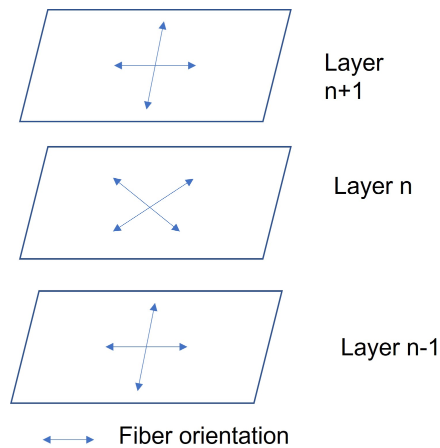


Figure 12: Explanations of the different layer's fiber orientation.

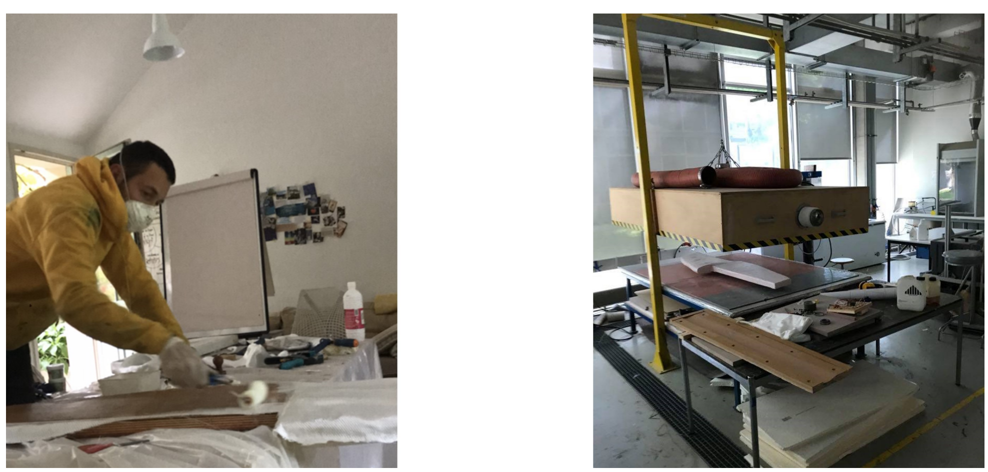


Figure 13: Application and cooking of the rudder's stratification.

Figure 14: Final touches and me beside the new rudder.