Delft University of Technology

Model HAWT
Documentation

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Contents

1 Introduction

This document serves to document part specifications and additional information around the model horizontal axis wind turbine built by PhD candidate Erik Fritz in the first half of 2023. The final assembly in the OJF can be seen in Figure 1.

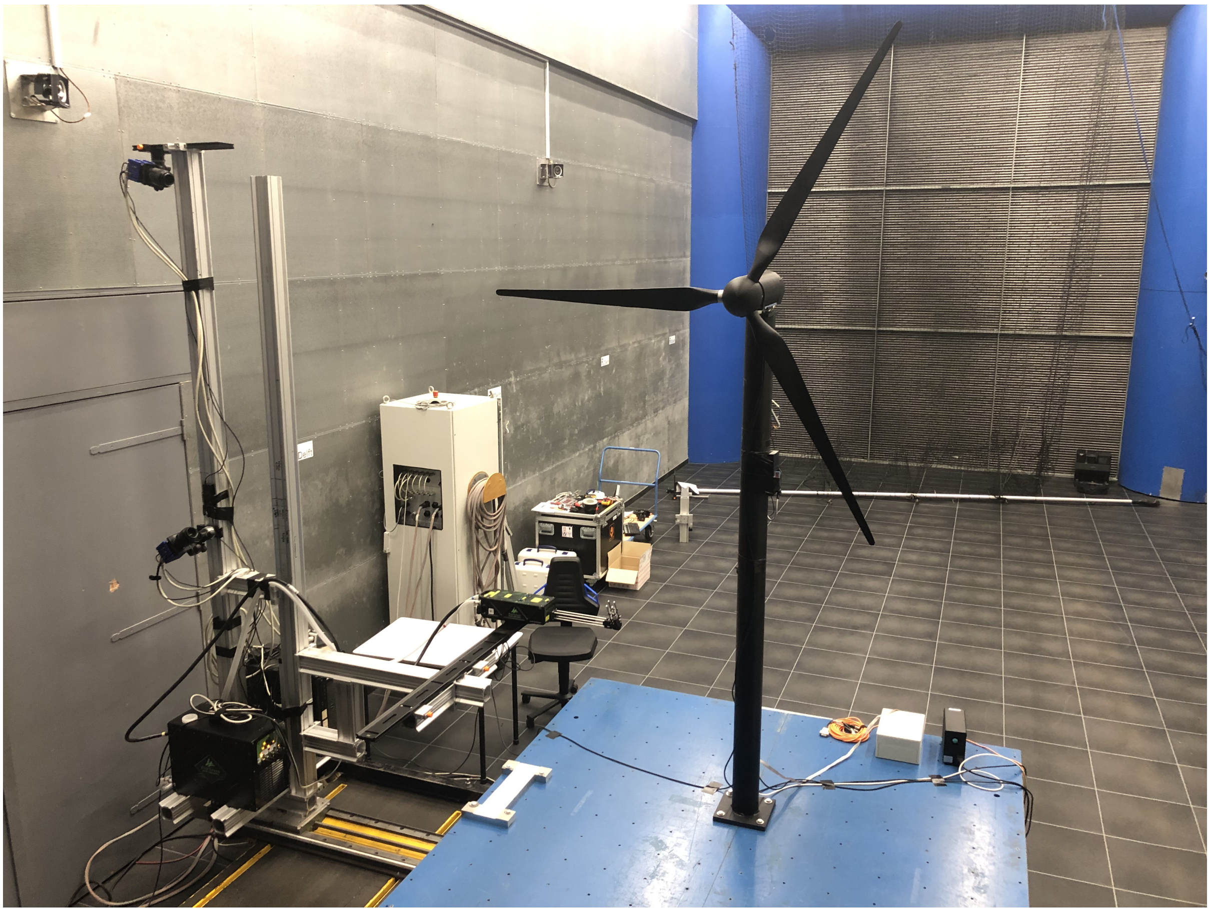

Figure 1: Model HAWT in the OJF

For details on the performed experiments, the reader is referred to the following two publications:

- E. Fritz, A. Ribeiro, K. Boorsma, C. Ferreira, *Aerodynamic characterisation of a thrust-scaled IEA 15 MW wind turbine model: experimental insights using PIV data*, Wind Energy Science **9**, 5 (2024)
- E. Fritz, K. Boorsma, C. Ferreira, *Experimental analysis of a horizontal-axis wind turbine with swept blades using PIV data*, Wind Energy Science **9**, 8 (2024)

I want to acknowledge that this report is far from perfect. I am writing this about one year after the experiments were completed and a lot of information details are already lost again. Keeping this in mind, I encourage anybody who works with this turbine in the future to add to this documentation. In my opinion, this report and, even more so, future researchers would benefit from a detailed description of electronic connections.

2 Components

2.1 Blades

2.1.1 Blade geometry

For the derivation of the blade geometry, the reader is referred to reference 1 mentioned in Section 1. Figure 2 gives the chord and twist distributions.

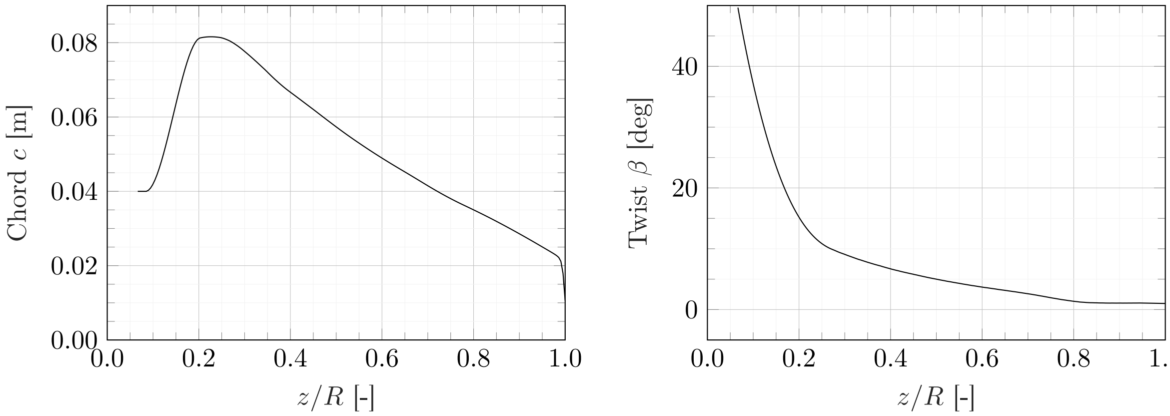

Figure 2: The model blade's chord and twist distribution

Based on the CAD design the radial position of the blade's center of gravity was estimated as

$$r_{cg} \approx 0.25\,m \ , \tag{1}$$

and the mass was estimated to be

$$m_{blade} \approx 0.45\,kg \ . \tag{2}$$

2.1.2 Blade foam plug and steel insert

The carbon fibre blades have a plug made from high density polyurethane that keeps the fibres from collapsing in the thicker region close to the root. A steel insert is glued into this foam plug which contains threaded holes for a screwed connection to the steel blade connector part.

This glued connection was tested on a tensile stress machine to see whether it can withstand the expected loads during the experiment. These loads are dominated by centrifugal loading which was estimated at around 200 N. Instead of the actual foam plug geometry, which would have been difficult to mount on the tensile stress machine a dummy foam plug was created. This dummy plug had the correct dimensions of the cylindrical part that forms the blade root. The steel insert used in the tensile stress test was identical with the one used in the actual turbine. The test geometry with its sub-components is shown on the left of figure 3, the part in the machine is shown in the middle and the broken part is shown on the right.

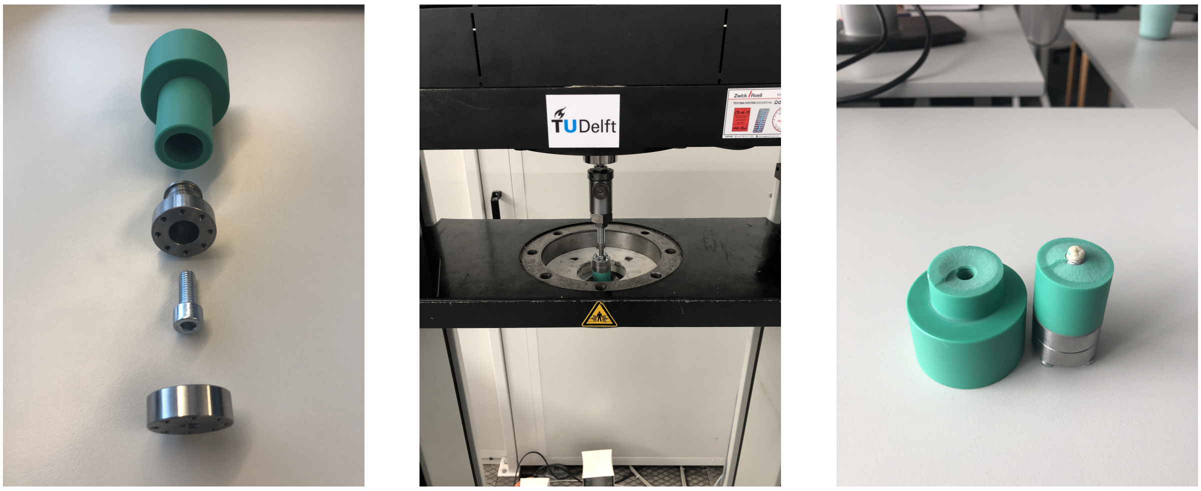

Figure 3: Tensile stress test geometry and setup

The results of this tensile stress test are depicted in figure 4. It can be seen, that the expected force of 200 N is far exceeded. At an ultimate tensile load of approximately 6.4 kN the glued connection has a safety factor higher than 30.

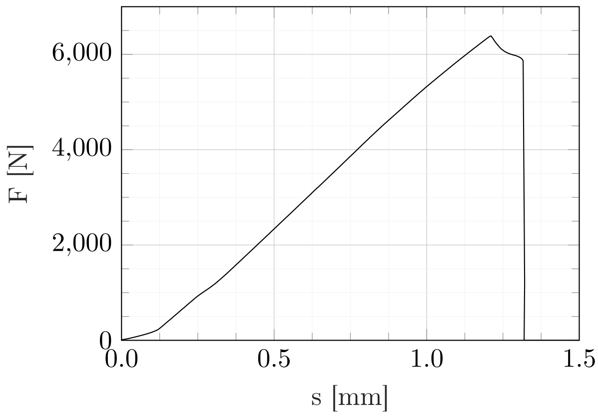

Figure 4: Tensile force over distance moved by tensile stress machine

For the actual blade plug, it is elemental that the orientation of the steel insert which has five screw connections, is known. This ensures that the foam plug is aligned correctly in the blade moulds and that it has the correct orientation in the final blade so that the pitch angle can be set. To achieve this, Ed Roessen (DEMO), built an alignment block which had one surface flush with a surface of the RAKU tool block that the blade plug would be cut from. The alignment block had one screw hole such that the steel sinsert would be oriented correctly with one screw hole rotated vertically downwards, see the left of figure 5. In this position, the steel insert was glued into the RAKU tool block. After curing, the glued assembly could be mounted in a milling machine. The final geometry of the blade plug is shown on the right of figure 5.

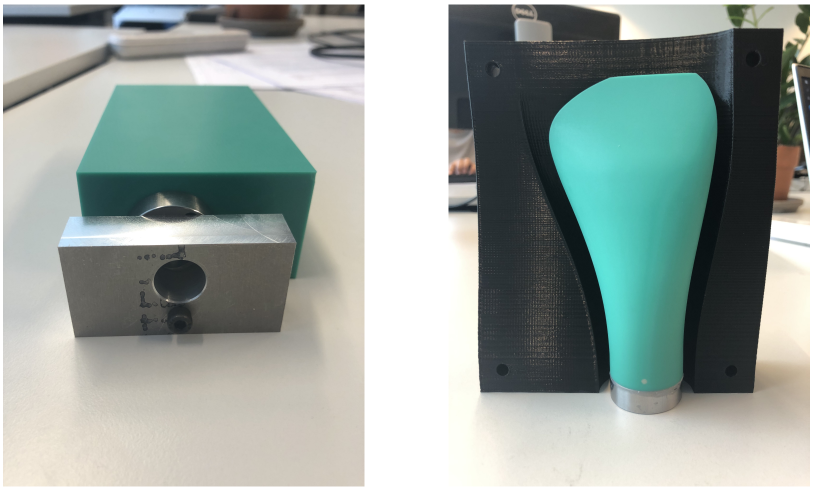

Figure 5: Alignment used for gluing steel insert and blade plug raw material (left) and final blade plug with alignment jig for better interpretation (right)

2.1.3 Blade moulds

The blade moulds were designed and manufactured by JulesDock (contact was Jeroen van der Vlis, j.vandervlis@julesdock.nl). The moulds are shown in Figure 6.

Figure 6: Blade moulds

Before use, the moulds were sanded to achieve the desired surface finish. After that, they were sealed with multiple passes and release agent was applied before every use with multiple passes.

2.1.4 Alignment jig in mould

To place the foam plug at the right angle in the mould, an aluminium alignment jig was placed at the blade root and connected with the foam plug, see Figure 7.

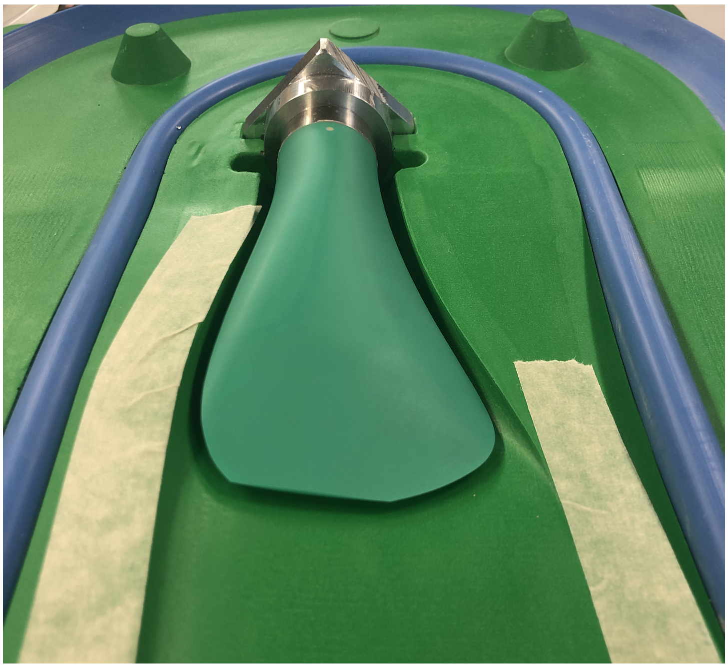

Figure 7: Alignment jib in mould

Comment:
Make sure to smear all surfaces and screws with release agent and seal the screw holes with tape or release agent before the vacuum infusion. If resin gets in there, it is a nightmare to get the screws out.

2.1.5 Blade manufacturing

The following were calculations I did prior to ordering the resin, hardener and carbon-fibre material. The actually used quantities likely deviated from these calculations (I never actually checked), but they can serve as a starting point.

Planning of resin:

- The **volume** of the blade that will actually be filled with carbon fibre composite material is $V_{straight} = 218209\,mm^3$ / $V_{swept} = 219179\,mm^3$.
- As conservative estimate, we consider that we have a fibre volume ratio of 40%. This leaves 60% volume for the resin, thus, approximately $V_{resin} = 131507\,mm^3$. Considering that we will produce eight blades (six used blades plus two throwaways), the **total amount of resin** required is $V_{resin,tot} = 1052059\,mm^3 \approx 1\,l$.
- The **cure time** of resins is estimated at around 18-24 h, while the **pot life** with a slow hardener is 80-100 mins. If the resin and hardener are stored properly and separately, they can be reused.
- Considering excess resin that will be lost in the process, two to three kg of resin/hardener (**1 kg of resin ≈ 1 l of resin**) should be enough for the manufacturing of these blades.
- One straight and one swept blade can be manufactured in parallel, considering one day of downtime between blades charges due to the curing cycle, about **eight working days** should be counted for the manufacturing procedure. (*In hindsight, I think 1.5 - 2 days per blade is more realistic, given that there is also a lot of work to be done post vacuum infusion, see below*)

Planning of carbon fabrics:

- Each blade has **5 UD layers** with a thickness of 0.2 mm, amounting to 1 mm and **10 woven layers** with a thickness of 0.4 mm, amounting to 4 mm. Combined the layers achieve the 5 mm thickness at the blade root.
- Straight blade:
  - The **UD layers of the straight blade** can be arranged on a 0.5 m fabric role such that one blade requires 1 m of fabric.
  - → For four straight blades, at least **4 m** of UD fabric are needed.
  - The **woven layers of the straight blade** can be arranged on a 1.27 m fabric role such that one blade requires 0.9 m of fabric.
  - → For four straight blades, at least **3.6 m** of woven fabric are needed.
- Swept blade:
  - The **UD layers of the swept blade** can be arranged on a 0.5 m fabric role such that two blades requires 2.5 m of fabric.
  - → For four swept blades, at least **5 m** of UD fabric are needed.
  - The **woven layers of the swept blade** can be arranged on a 1.27 m fabric role such that one blade requires 0.9 m of fabric.
  - → For four swept blades, at least **3.6 m** of woven fabric are needed.

Actual manufacturing:

For the vacuum infusion process, many small tips and tricks were given by Victor (head of composite labs). If, like me, one has little to no experience in vacuum infusion, it is very much a learning-by-doing process. So make sure to have some extra time for trials and failed attempts.

The carbon-fibre layers were stacked first on the blade's suction side, then the foam plug was inserted and then the carbon-fibre layers on the pressure side were stacked, before closing the mould.

The layers were stacked using the stacking order given in Table 1.

Table 1: Fibre layup

Suction side (SS)	Orientation	Pressure side (PS)	Orientation
SS woven layer 1	0/90	PS woven layer 15	0/90
SS unidirectional layer 2	0	PS woven layer 14	0/90
SS woven layer 3	-45/45	PS woven layer 13	0/90
SS unidirectional layer 4	0	PS woven layer 12	0/90
SS woven layer 5	0/90	PS woven layer 11	0/90
SS unidirectional layer 6	0	PS unidirectional layer 10	0
SS woven layer 7	-45/45	PS woven layer 9	0/90
SS unidirectional layer 8	0	PS unidirectional layer 8	0
SS woven layer 9	0/90	PS woven layer 7	-45/45
SS unidirectional layer 10	0	PS unidirectional layer 6	0
SS woven layer 11	0/90	PS woven layer 5	0/90
SS woven layer 12	0/90	PS unidirectional layer 4	0
SS woven layer 13	0/90	PS woven layer 3	-45/45
SS woven layer 14	0/90	PS unidirectional layer 2	0
SS woven layer 15	0/90	PS woven layer 1	0/90

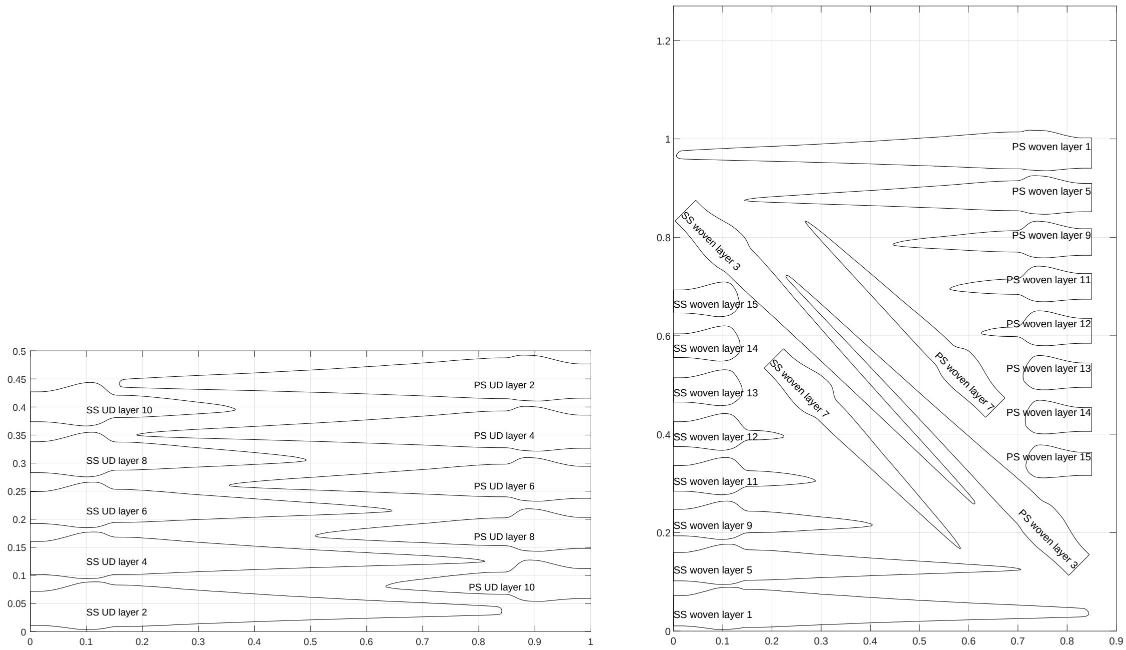

Figure 8: Carbon-fibre layers and their arrangement for the cutting machine

The shapes of the individual layers and how they were approximately arranged on the cutting machine are shown in Figure 8.

An impression of what the layup procedure looked like in real life is given in Figure 9.

Once the mould was close, two vacuum pumps were attached. One pump generates the outer vacuum that is used to shut the moulds, the other vacuum pump generates the vacuum, which sucks the resin from the blade root to the tip. To help with the outer vacuum we added clamps that would help keep the mould sealed. The vacuum infusion setup is shown in Figure 10.

After opening the mould, we usually discovered that there had been resin spillage and fibres that were sucked/pushed out of their desired position. Definitely a lot of room here to improve the vacuum infusion technique. In multiple steps, the blades were brought into their final shape:

1. Various grinding machines were used to get rid of the spilt resin, the out-of-place fibres, and the resin "doughnut" at the blade root, which was used to distribute resin all around the blade.

Figure 9: Carbon-fibre layup in the blade mould

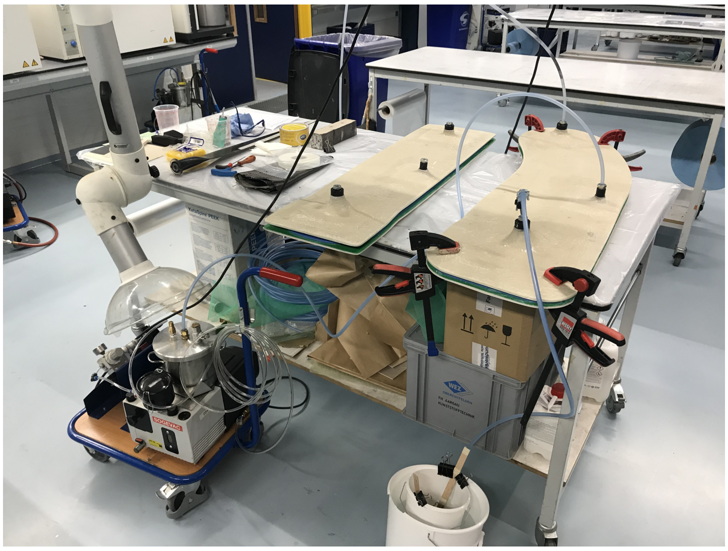

Figure 10: Vacuum infusion setup

2. Sandpaper was used on the trailing and leading edge to get the desired sharpness or roundness, respectively. This was done in multiple steps going from coarser to finer sand paper.
3. Holes left in the blade due to air inclusions were filled up. This procedure could definitely still be improved. We used a resin/chopped fibre mix, which gets extremely hard once cured and thus very difficult to shape into the desired smooth blade surface. Other filler materials (e.g. polyester plamuur) should be explored.
4. Finally, the blades were spray-painted matt black to avoid reflections during PIV measurements.

Different stages of this process are shown in Figure 11.

Figure 11: Blades during different manufacturing stages

2.1.6 Alignment jig after vacuum infusion

An alignment jig was 3d printed that enables to keep the blades in the correct pitch when screwing on the blade connectors. This way, we assumed that it could be assured that the pitch angle is the default angle of $\beta_{pitch} = 0°$ or any other desired pitch angle. Postprocessing of the experimental data revealed that there were offsets in the pitch angles. An improved methodology should be found for setting this angle.

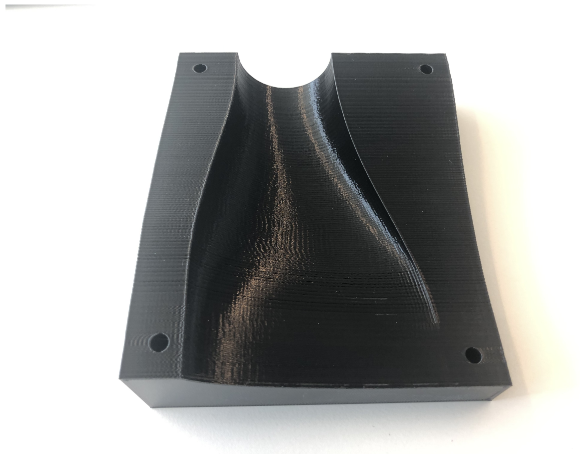

Figure 12: Lower half of the 3D printed alignment jig used for setting the pitch angle

2.2 Tower

The tower was produced by DEMO from a steel tube. The base plate can be screwed to the blue table in the OJF.

Figure 13: Tower

2.3 Nacelle

The parts that made up the nacelle were ordered at and manufactured by DEMO in the Aerospace Faculty. These parts were:

Base plate	1	Aluminium
Motor support	1	Aluminium
Torque sensor support	2	Aluminium
Bearing + brake support	1	Aluminium
Bearing support	1	Aluminium
Main shaft	1	Steel
Blade/shaft connection plates	2	Steel
Blade connectors	6	Steel

In addition, multiple left-threaded nuts were manufactured by DEMO. The nacelle assembly excluding the break and the blade connectors is shown in Fig. 14.

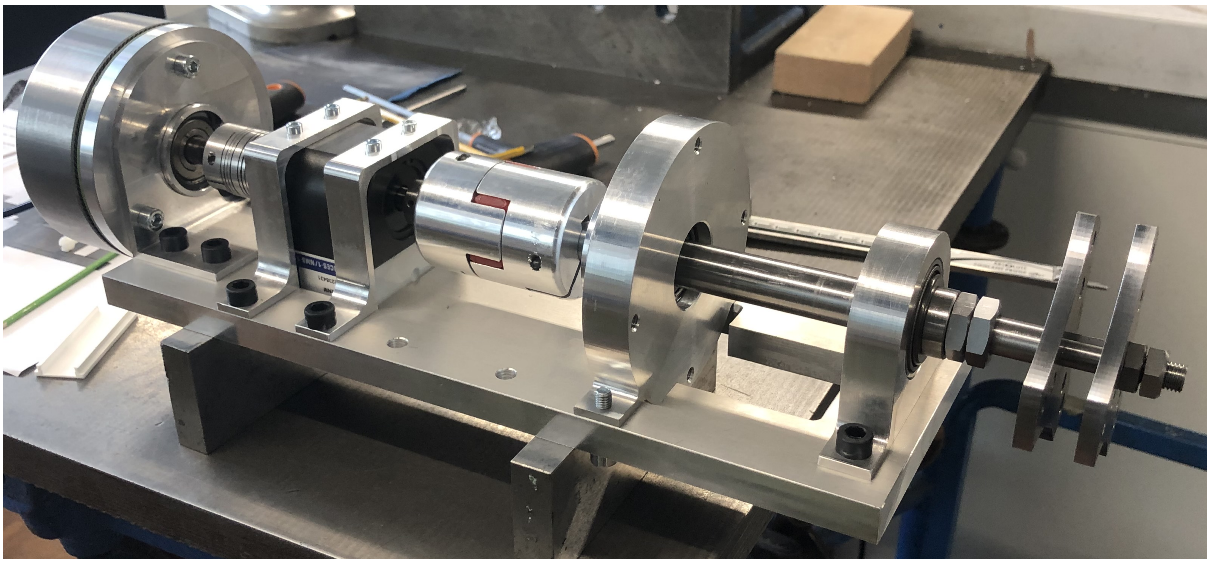

Figure 14: Nacelle assembly

Aerodynamic covers for nacelle and hub (and their holding mechanisms) were 3D printed by the technicians in the OJF, see Figure 15.

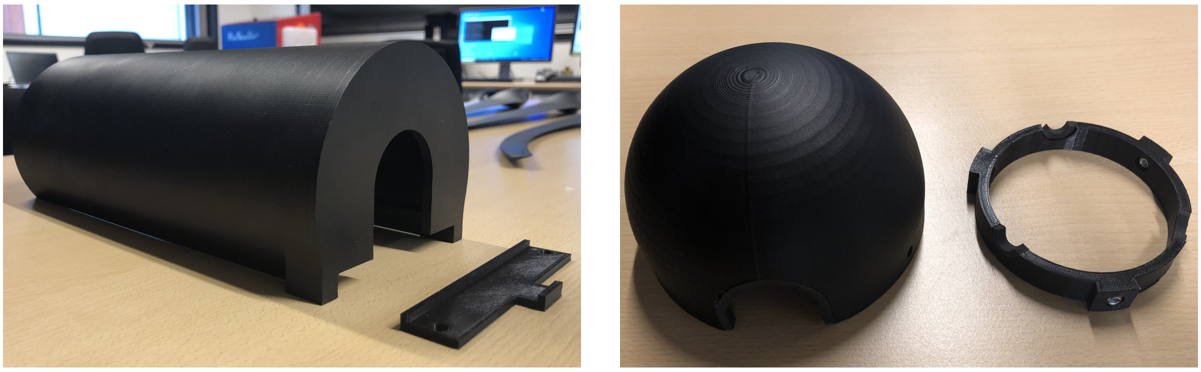

Figure 15: 3D printed aerodynamic covers for nacelle and hub

2.4 Motor and motor accessories

Part	EC90 flat
Manufacturer	maxon
Link	https://www.maxongroup.com/maxon/view/category/motor?etcc_cu=onsite&etcc_med_onsite=Product&etcc_cmp_onsite=EC+flat+Program&etcc_plc=Overview-Page-Brushless-DC-Motors&etcc_var=%5bcom%5d%23en%23_d_&target=filter&filterCategory=ecfla
Ordered at	David Bensason had one available

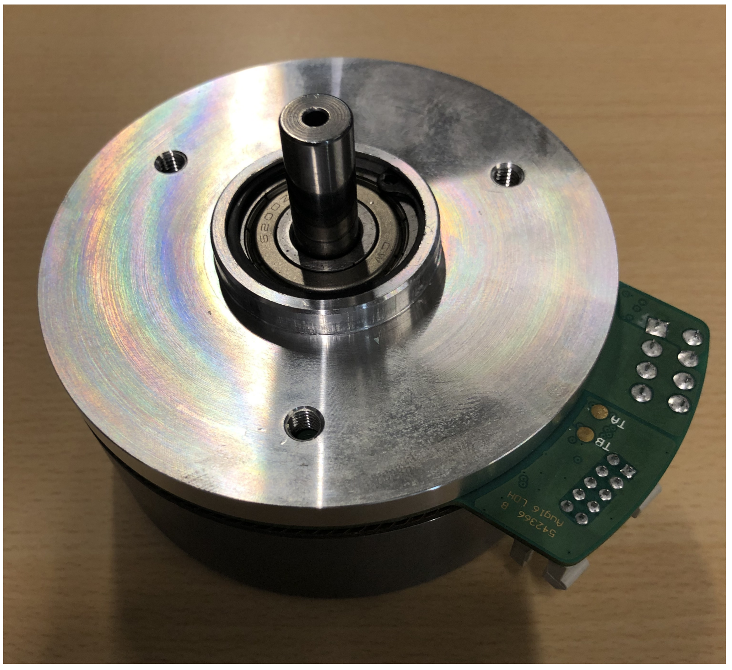

Figure 16: Motor

The motor was controlled using a maxon ESCON 50/5 409510 controller.

2.5 Torque sensor

Part	T22
Manufacturer	HBM
Link	https://b2bstore.hbm.com/myHBM/app/displayApp/(cpgnum=1&layout=7.01-16_153_6_9_70_34_65_73_134_6&uiarea=6&citem=FA650A4E39A8FC4DE1000000AC109934A01D4895C9E81EE4BA84242A9A161EA1&carea=FA650A4E39A8FC4DE1000000AC109934&xcm=hbm_b2boccasionalcrm&rdb=0&cpgsize=0)/.do?rf=y#
Ordered at	HBM webshop

Comments
The torque sensor was ordered for these experiments and installed along the drive train. However, data was not actually acquired since not enough time was left to program the data interfaces.

2.6 Brake

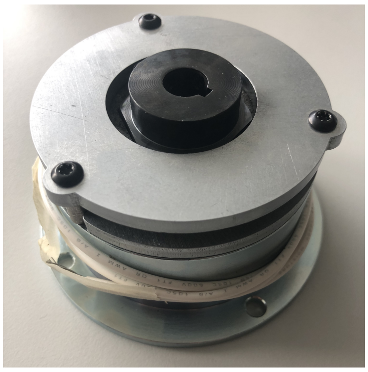

Figure 17: FSB035 electromagnetic brake

Part	FSB035
Manufacturer	WARNER ELECTRIC EUROPE
Link	https://nl.rs-online.com/web/p/electromagnetic-brakes/2677630
Ordered at	RS-online

The FSB035 is an electromagnetic brake that releases when power is supplied. Off the shelf, the inner diameter is too small for the desired setup of the model HAWT. The inner bore of the mounting flange was drilled open to match the main shaft diameter of $d = 15\,mm$.

Related calculations

Moment of inertia per blade:

$$I_{Blade} = m \cdot r^2 = 0.45\,kg \cdot (0.25\,m)^2 = 0.0275\,kg\,m^2 \tag{3}$$

Torque per blade:

$$M_{I,Blade} = \frac{1}{2} I_{Blade}\,\omega^2 = \frac{1}{2} \cdot 0.0275\,kg\,m^2 \cdot (40\frac{rad}{s})^2 = 22\,Nm \tag{4}$$

Braking moment:

$$M_{Brake} = 3.95\,Nm \tag{5}$$

Braking time:

$$t_{Brake} \approx N_{Blade} \cdot I_{Blade} \cdot \frac{\omega}{M_{Brake}} = 0.8354\,s \tag{6}$$

Braking time equivalent rotation:

$$N = 5.2909\,rev \tag{7}$$

Comments

We ran out of time to extend the cable length and to install an emergency button in the control room. So in the end, the brake was not mounted on the main shaft. Dennis should be able to build this emergency button for the next campaign and the brake should work (already tested in dry dock).

2.7 Bearings

Figure 18: FAG 30202-A tapered bearing

Part	FAG 30202-A
Manufacturer	FAG
Link	comparable to https://www.skf.com/group/products/rolling-bearings/roller-bearings/tapered-roller-bearings/single-row-tapered-roller-bearings/productid-30202
Ordered at	RS-online

2.8 Optical trigger for PIV setup

An optical trigger was installed in the nacelle to allow phase-locked PIV measurements. On the shaft, a disc with a single slot was mounted, while an optical gate was mounted on the nacelle base plate. Every time the slot passed the gate, the sensor sends a pulse signal which can be used as input for the PTU in the PIV setup. Dennis ordered the sensor and made sure the connection to the PIV setup worked.

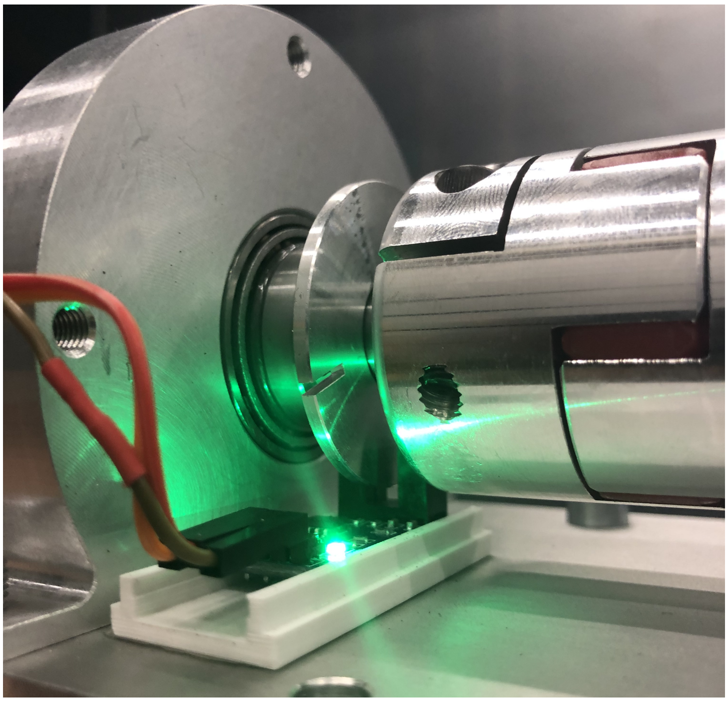

Figure 19: Optical trigger setup

2.9 Six-axis load cell

Part	ATI mini40 w/ SI-40-2 calibraation
Manufacturer	ATI
Link	https://www.ati-ia.com/products/ft/ft_models.aspx?id=mini40
Ordered at	ATI website, after contect with sales department

Comments
While the six-axis load cell was ordered for these experiments, it was not actually used since not enough time was left to program the data interfaces. During the experiment it was replaced by an aluminum dummy of the same dimensions. The load cell has since been used by Clem Li.