Report of a towing test campaign of a scaled wind turbine

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Abstract. For the full physical testing of FOWTs in combined wind and waves, it is necessary to generate good quality wind in order for the modeled wind turbine rotor to deliver the desired scaled down thrust. Limiting the turbulence to an acceptable level for steady wind tests can only be done at the price of important loss of output wind speed for fan based generator. It is not precisely known what is acceptable for the level of turbulence during the testing of FOWTs? Also, it is very difficult to generate a uniform wind field in a basin. The idea at the origin of this work was to think of a way to avoid or minimize these issues. MARIN carried out towing tests of a turbine made with the same rotor as it has been used for testing in combined waves and wind conditions. These data could be compared with the results of previous model tests in the Offshore Basin with the same rotor in a generated wind field. In this way, the effects of turbulence and slight non-uniformity of the wind field on the performance of this scaled down rotor in a fan generated wind field could be evaluated.

1. Introduction
To simulate the motions and loads of a floating wind turbine correctly it is important that the performance characteristics of the wind turbine, especially the horizontal thrust, in the basin are in-line with full scale. When the wind and a rotor are modelled in a wave basin, keeping the same geometry of the blades as at full scale will result in much lower aerodynamic loads due to strong Reynolds effects on the flow (Robertson et al. [1]). Therefore, in a Froude scaled wind, it is necessary to redesign the rotor in order to preserve the thrust of the rotor (Ridder et al. [2]). Manufacturing a quality Froude scaled wind in a basin is not an easy task. When the loads are scaled according to Froude and the tip speed ratio is preserved at scale 1/50, the wind speed is low (1 m/s in the basin for a 7 m/s prototype wind); increasing the complexity of modelling the aerodynamic loads on the rotor. The swirl and turbulence intensity inherent of fan generated wind need to be dissipated. This requires a dedicated wind generator ((Ridder et al. [3])) where screens are often used. This is done at the cost of important loss of output wind speed. The generation of wind in a confined volume also brings some challenges. Namely, the recirculation of the air flow and the shear with the water surface, the walls and the ceiling of the basin can alter the uniformity of the wind. Towing a turbine in still air is an easy way to avoid the issues encountered with fan generated wind in a basin. Even if the apparent wind during a towing test will also present some imperfections as the air flow need to go around the moving carriage, it was thought to be steadier and more uniform than in a fan based generated wind. Therefore, the same turbine that was tested in fan generated wind has been towed in the Shallow Water Basin of MARIN.
2. Froude performance scaled rotor
In 2013, MARIN has designed and evaluated a new rotor blade for a scale model wind turbine used for combined wind and wave basin tests (Ridder et al. [3]). The main parameters used to evaluate the performance of a wind turbine rotor are the thrust coefficient $CT$ and the power coefficient $CP$. These coefficients are defined as:

$$CT = \frac{F}{0.5 \rho A u_{w}^{2}}$$  \hspace{1cm} \text{(1)}$$

$$CP = \frac{Q \Omega}{0.5 \rho A u_{w}^{3}}$$  \hspace{1cm} \text{(2)}$$

$T$ denotes the total thrust applied on the turbine (N), $A$ the turbine swept area ($m^2$), $u_{w}$ the wind speed (m/s, shear not taken into account), $\rho$ (kg/m$^3$) is the density of the air, $Q$ the torque exerted by the aerodynamic forces around the wind direction at the hub (Nm) and $\Omega$ the rotational speed (rad/s).

3. Experimental set-up
The turbine is made of a very rigid tower, a 3-bladed rotor, a collective blade pitch mechanism and an engine. It is equipped with a 6 component force frame and an accelerometer. The turbine can be hinged around its foot to different trim angles (figure 1). The 3 identical blades have been designed to resemble the 5 MW NREL rotor at scale 1/50. More details over the turbine can be found in (Ridder [2]). The model tests were done at scale 1/50, applying Froude scaling laws for the speed, loads and accelerations. The same rotor was used in the test campaign of the OC5 semisubmersible in 2013 at the same scale (Kimball [5], Goupee [6] and Helder [7]). Back then, the turbine was placed in a wind field generated with a battery of fans. In the present experimental study, the turbine was towed. These tests have been carried out in the Shallow Water Basin of MARIN. This basin is located in a large building with sufficient length to tow the turbine for long enough time at speeds equivalent to the wind velocities of interest at this scale. It is equipped with a moving carriage, ahead of which a sub-carriage was assembled (see table 1 for the characteristics of the towing basin). The turbine was mounted on this sub-carriage (figure 2). The large cross section area of this basin and the position of the turbine have been chosen to limit possible blockage effects due to the ceiling and walls. The basin has been emptied for these tests to offer more space for the flow to circulate around the moving carriage and to facilitate the access to the wind turbine. Figure 3 shows a picture of the main carriage (in light blue), the sub-carriage (in grey) and the turbine (inside the red circle) once assembled together. Despite all this care, the flow may not be as good as wished. Therefore, extra wind measurements were done on both sides of the turbine at the rotor’s height with 2 speedometers located next to the turbine (-3.22 m, + 3.33 m).

| Characteristics of the towing tank @MS. |
|------------------------------------------|
| Length (m)  | 220 |
| Width (m)   | 16.9 |
| Height (m)  | 7   |
| Carriage maximum speed (m/s)            | 4   |
Figure 1. Drawings of the turbine (dimension in mm @ MS).

Figure 2. Top view of the towing test set-up (dimensions in m @ MS).
4. Presentation of the experiments

This chapter describes what the different types of model-tests carried out in this experimental study were.

4.1. Tests at fixed rotor speed

The aim of these experiments is to determine the rotor characteristics in a very low turbulent wind. To this end, the operating turbine is towed through the still air. The duration for which the rotor thrust and torque can be measured is directly related to the length and speed of the towing motion. When the turbine operates at a fixed rotation speed, the measurement of a steady state can be executed on the part of the trajectory for which the carriage has reached the requested speed and is holding it. This part is called the effective length; before, the carriage needs to accelerate; and after, the carriage needs to break. The effective length depends on the requested wind speed. Table 2 gives the values of the effective lengths for the speeds investigated in this campaign. A typical history of the carriage’s speed is shown in figure 4. The speed of the carriage is regulated to reach a target speed. The achieved velocity is very stable on the effective length of the towing test. The rotation of the blades is also controlled to reach a given velocity and stay at this requested speed. However, both the carriage’s speed and the rotor’s speed vary slightly. Therefore, the value of TSR for such a test is not absolutely constant but exhibit small variations. Figure 4 shows the history of the carriage speed during a test.

![Figure 3. Documented photography of the towing test set-up (dimensions in m @ MS).](image)

| Requested wind speed (m/s) @FS | Carriage speed (m/s) @MS | Effective length (m) @MS |
|-------------------------------|--------------------------|----------------------------|
| 7.0                           | 0.99                     | 151.0                      |
| 11.4                          | 1.61                     | 140.6                      |
| 13.0                          | 1.84                     | 135.7                      |
| 17.0                          | 2.40                     | 121.6                      |
representing a wind speed of 13 m/s (i.e. towing at 1.84 m/s at MS). The histories of the resulting thrust and power coefficients as well as the corresponding TSR are given on figure 5 for a rotor’s RPM of 11.8. CT and CP are plotted as a function of TSR on figure 6. Table 3 gives the values of CT and CP for this fixed RPM towing test.

For simplicity, all values given in the rest of the paper are in full scale, except when explicitly mentioned to be at model scale by MS.

Figure 4. Full scale carriage speed for 13 m/s wind speed test.

Figure 5. History of CT, CP and TSR for 13 m/s wind speed test.

Figure 6. CT and CP for a fixed RPM towing test when carriage speed (red square) is used and wind measurement (blue line) is used.

Figure 7. Range of TSR covered by towing tests at different speeds.

Although the carriage speed was very stable and precisely known, the wind measurements on both sides of the rotor did not agree with the carriage velocity (Table 3). The wind speedometers measured some low frequent variations of the wind speed and a higher average speed (by 3 to 5%) during the effective duration of the tests. Similar discrepancies were noticed during a test with the rotor feathered. The low frequent variation could partly be attributed to the flexibility of the support (subcarriage and pipes) on which the speedometers were mounted. The higher value of wind speed is more difficult to explain without additional measurements. One likely reason could be that the carriage while moving in a confined volume pushed the air around. This could create a local increase of the apparent wind above (and below) the carriage. Even if the turbine was placed 5.5 m meter ahead of the
main carriage (and even 7 meters from pieces of equipments that are big enough to effectively block the flow), it looks as if the flow is disturbed. Unfortunately, the program of this test campaign did not allow for a better characterization of the flow around the moving carriages. Including the actual wind speed measurements in the determination of the rotor’s characteristics gave different results than when only the carriage speed was used (figure 6). This difference comes mainly down to a shift towards lower TSR of ½ unit and an 8% decrease of CT and a 16% decrease of CP.

Table 3. Results for a constant towing speed (13 m/s) and fixed RPM (11.8).

| TSR = 6 | Mean | Standard deviation |
|---------|------|--------------------|
| CT (-)  | 0.51 | 0.01               |
| CP (-)  | 0.06 | 0.00               |
| Carriage speed (m/s) | 13.00 | 0.01               |
| Wind speed 1 (m/s) | 13.58 | 0.24               |
| Wind speed 2 (m/s) | 13.48 | 0.29               |

4.2. RPM sweep tests
In order to obtain CT and CP for a range of TSR rather than a single value, it is possible to vary the rotation speed of the rotor while the carriage speed is kept constant. However, such RPM variation cannot happen too quickly in order to obtain enough load measurements for a given range of TSR. Several acceleration levels of the rotor’s rotation were tried before 0.01 rpm/s was chosen. Figure 7 shows the range of TSR covered for each investigated towing speed. The intervals represent the tests with varying rotation speed, whereas the circles stand for the fixed RPM tests. With 0.01 rpm/s, the range of TSR explored for the wind speed of 17 m/s is very narrow, whereas it is very broad for 7 m/s. Smaller rates than 0.01 rpm/s only enable to explore a narrower range of TSR and would require more towing tests. Such tests are called “rpm sweep tests”.

Results of sweep tests for different starting value of RPM can be combined to obtain the characteristics of the rotor for a broader range of TSR. Also, towing tests at different speeds can be combined. For large differences between towing speeds or blade’s rotation velocities, the aerodynamic loading may be caused by different phenomena (e.g. when stall occurs) and such combination may not be useful anymore.

5. Model-test results
The main results of this experiment campaign are presented and discussed in this chapter.

5.1. Results for zero blade pitch angle and zero trim angle
Four towing speeds were investigated for a rotor with 0 deg blade pitch and no trim:
- 7 m/s,
- 11.4 m/s,
- 13 m/s,
- 17 m/s.

Fixed RPM tests and RPM sweep tests were carried out. The rotor characteristics (CT and CP) coming from all these tests are plotted together (figure 8). The graphic at the top shows the thrust curves obtained from all tests, the graphic at the bottom shows the power curves. For TSR lower than 7, the thrust curves are similar independent of the towing speed. For TSR higher than 7, bigger differences arise. CT for the lowest speed, 7 m/s, is lower than the rest. The differences in CP between different speeds are more pronounced. CP for 7 m/s is significantly lower than for 11.4 m/s and 13 m/s for TSR larger than 6.5. The highest speed is only used to obtain results for low TSRs. This graphic shows that the rotor performs differently at low wind speed, like 7 m/s or below, resulting in deficits in
thrust and power. The same observation had already been done in a fan based generated wind (Helder et al [7]).

Figure 8. Measured rotor’s CT and CP curves for zero blade pitch and a vertical rotor (all rpm sweep tests combined).

5.2. Results for other blade pitch angles and zero trim angle

The turbine was also tested with different blade pitch angles. CT and CP for the turbine with all 3 blades pitched with the same angle are plotted for a series of values from -2 deg to 20 deg. The towing speed for all these tests was 11.4 m/s. These results are plotted together with measurements for the same rotor completed in the Offshore Basin in fan generated wind (Ridder et al. [2]). Those results were obtained from tests at constant RPM. Therefore, they are represented as a succession of points in figure 9 (marked as triangles). The sweep tests of the present campaign are plotted as lines in figure 9. Comparing data for different pitch angles is not trivial as the initial pitch angle, “pitch zero”, cannot be determined with precision and is therefore likely to be different in the first campaign and the second campaign. Only the pitch variation with respect to the initial pitch angle is known accurately (i.e. “5 deg” is “pitch zero” + 5 deg). These graphics demonstrate the large sensitivity of the thrust and power curves to the blade pitch angle. It is noted that the results for -1 deg and 1 deg are noticeably different. The agreement of CT between these two test campaigns is reasonable for all pitch angles, whereas deviations on CP are more important for small pitch angles than for bigger angles.

Figure 9. CT and CP curves for different blade pitch angles and a vertical rotor.
5.3. Results for a trimmed turbine

As visible in figure 1, the turbine’s tower was assembled to the frame with a hinge that enables to trim the turbine. The turbine was towed with different trim angles:
- 0 deg
- -1 deg
- -4 deg
- -6 deg
- -7 deg

The towing speed for all these tests was 11.4 m/s. Figure 10 contains the thrust curves and power curves obtained from these tests. CT and CP don’t appear to be very sensitive to the trim angle.

![Figure 10](image)

**Figure 10.** Results for different trim angles of the turbine.

5.4. Comparison with results of tests in a fan generated wind field

One of the main goals of this experimental study was to check if the aerodynamic loads on the rotor are comparable during a towing test or in a fan generated wind field for the same speed. This is done in two ways:
- A direct comparison of the CT-curve and CP-curve from both experimental set-ups.
- The comparison of the loads measured at the nacelle for two experiments with the same velocity history at the nacelle.

During these two campaigns, the rotor was identical but the towers were not. The tower was much more flexible in the set-up of the Offshore Basin to resemble a real turbine. A second 6 component load frame was installed at the foot of the turbine, whereas only one was present and located right under the nacelle in the towing tests. The accelerations and the loads under the nacelle were measured in the same way and at the same locations in both set-ups.

![Figure 11](image)

**Figure 11.** CT- and CP- curves from towing tests and from tests in a wind field (dashed bright green line).

Figure 11 presents the results of the towing tests of the turbine with the addition of the CT- and CP-curves obtained by Helder ([7]) in a fan generated wind field. The CT- and CP-curves of the towing tests of figure 11 were determined with no trim and a blade pitch angle of 0 deg. It is noted again that the initial blade pitch angle is not precisely determined because the blade are initially assembled by hand. Therefore, it is possible that the results of the two campaigns have been measured with slightly different initial blade pitch angle, considered as the 0 deg blade pitch angle. Keeping in mind that the
blade pitch angle has a large influence on CT and CP, the results obtained from these two set-ups are comparable. However, a slight shift of CT and CP towards lower TSR can be observed (of about $\frac{1}{2}$ TSR). This shift can be related to the apparent wind velocity that was actually bigger than the carriage speed (used for the determination of these curves) as seen earlier for the fixed RPM towing test. Nevertheless, the amplitudes and global shapes of CT are similar between these two campaigns. The differences in the shape of the CP-curves are bigger than for the CT-curves. It is known that the wind field generated by fans exhibited a strong shear in the lowest part of the swept area of the rotor. During the towing tests, the wind is believed to be more uniform; although it is still yet to be proven by detailed measurements. This difference in the wind profile is thought to be the main reason behind the differences observed in figure 11. It may also indicate a difference in the inflow factor between these two experimental set-ups. A better characterization of the wind flow in both kinds of experiment is required to decide on this matter.

A pitch decay of the same rotor put on top of the OC5 semisubmersible floater in the Offshore Basin of MARIN was used as a reference case. In this test, the floating turbine was released after being hold under a pitch offset while the wind generator was blowing a steady wind of 11.4 m/s (Helder [7]). The velocity of the nacelle during this pitch decay test was used to impose the velocity of the carriage during the towing test. In this process, the velocity was first filtered with a low pass band with cut-off frequency of 0.3 rad/s. The acceleration at the nacelle (AX) and the loads perpendicular to the rotor plane (FX) for both model tests are compared in figure 12. Except for more high frequent noise content for the OC5 pitch decay, the accelerations AX look the same for the pitch decay and the towing test. This proves that the velocity of the pitch decay is imposed correctly during the towing test. The loads measured in the direction perpendicular to the rotor plane are also similar except for the higher frequency content of FX of the OC5 pitch decay. Thus, the pitch decay has been successfully mimicked by adjusting the towing velocity to the one experienced at the nacelle during the pitch decay. By this mean, the aerodynamic load FX on the rotor operating in the wind field of the Offshore Basin is reproduced by a towing test in the Shallow Water Basin.

![Figure 12. Comparison of pitch decay in wind (left) and its emulation in a towing test (right).](image-url)
6. Conclusion
The performance scaled rotor of MARIN was towed in the Shallow Water Basin of MARIN. This set-up enables to determine the rotor characteristics, thrust and power curves, for different configurations (blade pitch angles, rotor’s RPM). The results were found to be comparable to previous tests of the same rotor in a fan generated wind field. This demonstrates that towing tests are a valid alternative solution to determine the characteristics of a scale rotor for floating offshore wind turbines. The effect of the trim angle of the turbine on the thrust and power was found to be small. By towing the turbine in the still air, the apparent wind velocity profile was supposedly uniform and constant. Actually, the apparent wind velocity showed some variations in space and time during a towing test at constant speed. For instance, its time average value was slightly bigger than the towing speed (3 to 5%). A more thorough measurement of the apparent wind profile is necessary to fully understand what the causes of this larger apparent wind speed are. One possible explanation is that the carriage may have interfered with the flow upwind where the turbine was located while it was moving. This finding adds on the uncertainty on the CT- and CP-curves coming from towing tests. In previous tests in a fan generated wind field, the turbine was placed in a wind shear and some inherent turbulence (estimated to 3-5 %). The CT- and CP-curves obtained from the towing tests looked slightly shifted towards higher TSR (by +½ unit) with respect to those of the wind field generated with fans. Keeping in mind what the effect of the uncertainty of the apparent wind during a towing test is, the CT- and CP-curves between these two testing methods were found to be rather similar. A shift of ½ TSR and a small difference in amplitude for CT and a larger difference for CP were expected. This shift may also indicate that these methods give a slightly different induction factor. As it is unsure if the apparent wind during these towing tests was better than the wind generated with fans in the Offshore Basin, it is not possible to give recommendations on achievable improvements on this wind generator by further reducing the turbulence or increasing the uniformity of the flow in the swept area of the rotor.

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