RETROFITTING OF FLETTNER ROTORS – RESULTS FROM SEA TRIALS OF THE GENERAL CARGO SHIP "FEHN POLLUX"

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SUMMARY

In 2018, a German- Dutch project consortium under the scientific direction of the Emden/Leer University of Applied Sciences retrofitted and commissioned the latest rotor development of the Eco-Flettner type on the test ship *Fehn Pollux* of the Leer-based shipping company Fehn Ship Management. Main design features are both upper and lower endplates with large diameter for improved aerodynamic performance and modular manufacturing. The retrofitting concept is groundbreaking in terms of easy transferability to other ships. Upscaling to a significant share of the world merchant fleet could make a substantial and realizable contribution to climate protection in the short term and potentially reduced transport costs in the long term. The most frequently asked question in connection with modern sail drives is about the performance potential and the associated fuel savings. Transparent performance data is required to enable an economic prognosis for the use of Flettner rotors on ships. The Faculty of Maritime Sciences at Emden/ Leer University of Applied Sciences has developed an automatic control and monitoring system for Flettner rotors that also records extensive operating and environmental data. The data shows that all previous assumptions and model calculations are basically correct. With regard to the performance potential, the first series of measurements show even higher rotor forces compared with model calculations. This is a further benefit for Flettner rotor efficiency and could help the technology achieve a breakthrough as a building block for low-emission shipping.

NOMENCLATURE

[Symbol]	[Definition] [(Unit)]
AWA	Apparent Wind Angle (deg)
AWS	Apparent Wind Speed (kn)
C_L, C_D	Lift and Drag Coefficient [-]
C_X, C_Y	Coefficients for forces in ship fixed x- and y-direction [-]
COG	Course over ground (deg)
F_X, F_Y	Forces in ship fixed x- and y-direction (kN)
PB	Break power of ship's main engine (kW)
RPM	rotational speed (revolutions per minute)
ROT	ship's rotational speed (deg/min)
SOG	Speed over ground (kn)
TWA	True Wind Angle (deg)
TWS	True Wind Speed (kn)

1. INTRODUCTION

The IMO's Initial Greenhouse Gas Strategy aims to reduce CO2 emissions of international shipping by at least 50 percent by 2050. In this way, shipping would make a significant contribution to the climate target, even if the IMO remains below the demands of the high ambitious states that want to achieve 70 to 100 percent decarbonization in this period. Even though many details of the initial IMO strategy are still open, it is already clear that new technological approaches are needed. A renaissance of wind energy for ship propulsion seems to be obvious, the high potential at sea is well known. Today's shipping needs technologies that meet all the important requirements of modern ship operation. Flettner rotors have already proven their fundamental suitability in various projects. In June 2018, a German-Dutch project consortium under the scientific direction of the Emden/Leer University of Applied Sciences retrofitted and commissioned the latest rotor development of the "Eco-Flettner" type on the test ship *Fehn Pollux* of the Leer-based shipping company Fehn Ship Management. The retrofitting concept developed by the maritime companies and scientific institutions involved is groundbreaking in terms of easy transferability to other ships. Upscaling to a significant share of the world merchant fleet could make a substantial contribution to climate protection.

Figure 1: *Fehn Pollux* outbound for sea trials (Source: MariGREEN)

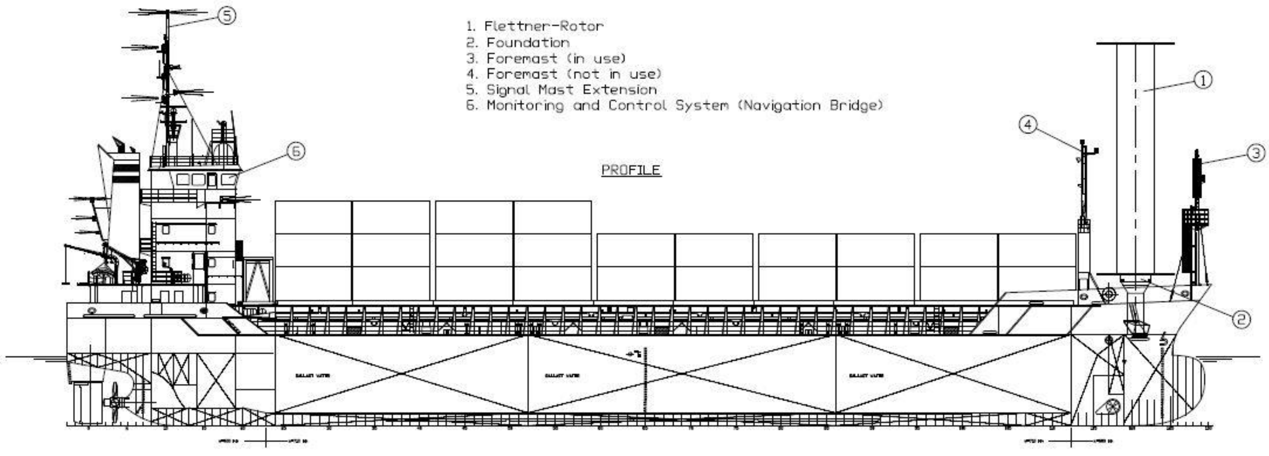

Figure 2: Arrangement drawing for retrofitting *Fehn Pollux* (Source: ABH Ingenieurtechnik GmbH, Emden)

The following report is intended to provide information on important aspects of planning retrofits or newbuildings with Flettner rotors and is based on the results of the sea trial and the first phase of testing under normal operating conditions. In order to comply with all existing regulations regarding the use of this new technology, various areas of ship technology and navigation had to be illuminated, e.g. proof of safe manoeuvring characteristics and sufficient stability. The most frequently asked question in connection with modern sail drives, however, is about the performance potential and the associated fuel savings. Transparent performance data are required to enable an economic prognosis for the use of Flettner rotors on ships. The Department of Maritime Sciences at Emden/Leer University of Applied Sciences has developed an automatic control and monitoring system for Flettner rotors that also records extensive operating and environmental data. The data show that all previous assumptions and model calculations are basically confirmed. With regard to the performance potential, the first series of measurements show even higher rotor forces compared to the model calculations. This would have a positive effect on the economic efficiency of Flettner rotors and could help the technology to achieve a breakthrough as a building block for low-emission shipping.

2. RETROFIT CONCEPT

An important development objective for the Eco-Flettner within the framework of the "MariGreen"[1] project is the transferability of the retrofitting concept to a larger share of the existing world merchant fleet in order to achieve significant reductions in fuel consumption and emissions. The structural features of the multipurpose freighter *Fehn Pollux* provide an ideal basis for this, as there are a large number of ships worldwide with a similar arrangement of holds and superstructures.

By installing a wind propulsion system supporting the main engine, the potential for average fuel savings in the order of 10 percent was to be demonstrated on the test ship. In previous analyses, the Flettner rotor was technologically favoured because it combines high sailing performance with minimum space requirements and the advantages of a fully automated system. Furthermore, the construction is robust and insensitive to wear, which offers further advantages compared to other sailing systems, e.g. based on textile sails adapted from the field of yachting.

The central question of the choice of the installation location on the ship was preceded by a detailed analysis of all relevant factors. In order to avoid an impairment of the existing operating procedures, a rotor position outside the cargo area had to be found. The only installation site available was the foreship in front of the cargo holds. The aerodynamic and hydrodynamic conditions were investigated using CFD flow simulations and model tests. The installation on a raised foundation and the use of a lower end plate not provided for in previous Flettner rotors ensure very favourable flow conditions at the rotor. The introduction of the sail forces in the forecastle deck leads to a reduction of yaw moments caused by side forces of the sail yielding a good steering behaviour of the ship during rotor operation. It is therefore advantageous over a midship or aft installation.

The advantages of the installation on the forecastle deck faced the following problems and questions:

- How can the rotor be protected from wave impact?
- How does the restriction of the view from the bridge and the radar performance affect nautical operation?

[1] www.marigreen.eu

- What influences on the manoeuvring behaviour can be expected from the rotor forces?

The rotor was reinforced in accordance with existing classification regulations to counteract the effects of wave impact, which led to a slight increase in the weight of the rotor. The DNVGL has checked and approved the compliance with the regulations regarding the visibility from the bridge and the radar visibility in advance.

Further investigations by the Department of Maritime Sciences of the University of Applied Sciences Emden/Leer included simulations on the full mission shiphandling simulator, the results of which were validated during the sea trial. The fulfilment of all regulatory requirements for manoeuvring behaviour was also investigated in a study on the shiphandling simulator and verified during the sea trial. Details are given below.

3. NAVIGATION ASPECTS

3.1 VIEW FROM THE BRIDGE

In the first step, arrangement plans had to be submitted to demonstrate that both the view from the bridge and the operating conditions of the radar meet the requirements of relevant regulations.[2] The rotor causes a visually blind sector of 2 degrees in the area of the midship line and thus remains clearly below the limit value of 5 degrees. To check the blind sector, the officer of the watch must change the position on the bridge at regular intervals. During the installation works, a special training programme was conducted for the staff including exercises on a full mission shiphandling simulator. A validation took place during the sea trials. The effect of the rotor on bridge visibility was not perceived as significant by the nautical experts involved in the test and is similar to that on ships with cranes in the midship line, as shown in Figure 3. Changing the position on the bridge by a few metres allows an unrestricted field of vision.

Figure 3: View from the bridge (source: Hochschule Emden/Leer, University of Applied Sciences)

[2] e.g. SOLAS Chapter V, Regulation 22

3.2 RADAR DETECTION

During planning of the rotor installation, a blind radar sector behind the rotor in the size of one degree was assumed according to verified plans. Due to the different locations of the two radar antennas, however, there is an unrestricted radar view when both antennas are used simultaneously. However, the blind sector could not be observed during the sea trials. A radar detection test was carried out with a small vehicle. Figure 4 shows that the vehicle could be observed on the radar at close distance in front of the ship, although it was completely covered by the rotor. Possible causes for the detection of the target in the blind sector of the rotor are its material properties (GRP) with respect to the transmission of radar waves and diffraction effects in the shadow area.

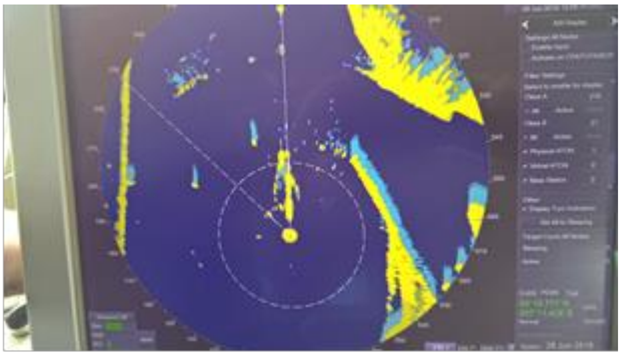

Figure 4: Radar image during a detection test with a small vehicle in the rotor shadow (Source: Hochschule Emden/Leer, University of Applied Sciences)

4. MANOEUVRING BEHAVIOUR

For the sea trials, a manoeuvring programme was drawn up in coordination with the DNVGL classification society to demonstrate conformity with IMO Resolution MSC 137 (76) "Standards for Ship Manoeuvrability" (IMO, 2002) and the DNV-GL guideline 'Certification and Classification Procedures associated with installation of a "Flettner" Rotor Unit onboard a classed vessel' (DNV GL, 2016). The main focus was on the influences on the steering and turning characteristics caused by the aerodynamic forces of the rotor. This had already been preceded by an investigation on the "susanNE" ship handling simulator at University of Applied Sciences Emden/Leer. In cooperation with the Leer based company Nautitec, a virtual model of the *Fehn Pollux* for manoeuvring tests on the simulator was developed. This model was used to predict the effects of rotor forces on the ship's manoeuvring behaviour. Furthermore, a "Familiarization Course" lasting several days was developed and conducted for the ship's command. The results of the simulator study by Kramer (2017) were validated during the sea trials.

4.1 COURSE KEEPING PERFORMANCE

The influence on the steering characteristics was tested with full rotor RPM on a course heading into the wind, thus generating a maximum of side forces. During the test runs, approx. 40 kN side force was achieved with moderate winds of strength 4, which corresponds to approx. 50% of the maximum permitted forces by design. The ship could easily be kept on course with autopilot control. The required rudder angles were below 5 degrees at a ship speed of approx. 10 knots, and below 10 degrees at slow speed of approx. 5 knots. The small effect on the course keeping capability of the test ship can be attributed to good rudder performance values and, in particular, to the fore ship installation close to the hydrodynamic centre of effort of the hull.

4.2 TURNING CIRCLE

Compliance with the minimum values for Advance and Tactical Diameter in the turning circle was checked by comparative turning circles at full speed (10 knots) with the rotor stopped and rotor running at moderate wind speeds (Beaufort 4). The differences were relatively small and showed a good alignment with the values determined beforehand in the simulator. The actually obtained values were far below the permitted maximum values of IMO Resolution MSC 137 (76) for the Advance of 4.5 times the ship's length and for the Tactical Diameter of 5 times the ship's length as can be seen in figure 5. The plot shows the ship's outline at the end of the turning circle with high rotational speed (ROT), high transverse speed (red and green vectors) and forward motion nearly stopped as the course over ground vector (COG, dashed line) is directed sideways. The rotor installation located on the fore ship has a favourable effect as the yawing moments caused by rotor side forces are comparatively smaller to an installation further aft in the ship.

4.3 STOP FUNCTION OF THE ROTOR

In order to stop the effect of the rotor forces on the ship as quickly as possible, e.g. in safety-relevant situations, an electrically acting brake was provided. After pressing the stop button on the bridge console, the rotor is stopped within approximately 5 minutes (Figure 6). The stop curve has a linear characteristic. It is recommended to stop the rotor beforehand in order to avoid any influence on the manoeuvring behaviour when carrying out port manoeuvres.

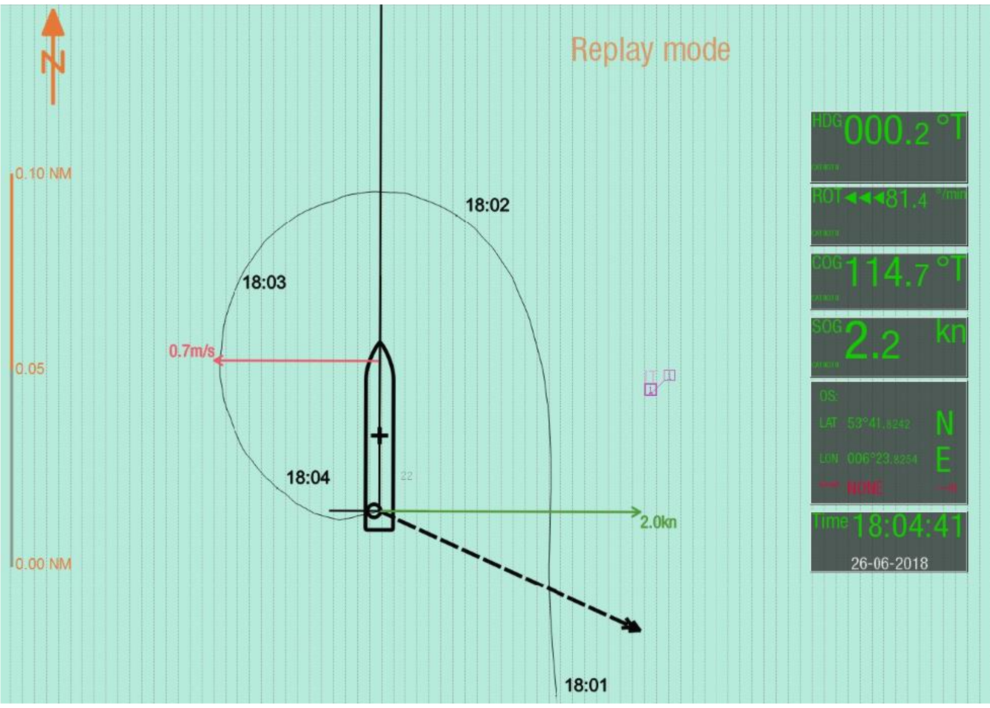

Figure 5: Turning circle plot

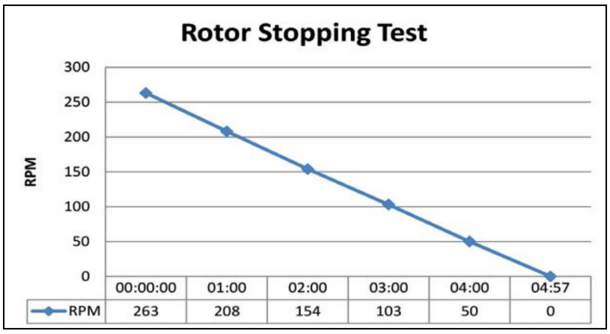

Figure 6: Test of rotor stop function

5. ROTOR PERFORMANCE

5.1 MODELING AND SIMULATION

For the prediction of the rotor's propulsion power and associated fuel savings, numerous model tests and simulations were performed using the wind tunnel of TU Hamburg-Harburg and numerical computational fluid dynamics (CFD) methods at the Center for Modeling and Simulation at Emden/Leer University of Applied Sciences (Strasser, 2015). The rotor's geometry including end plates was optimized. Lift and drag coefficients from wind tunnel model testing are presented in Figure 7.

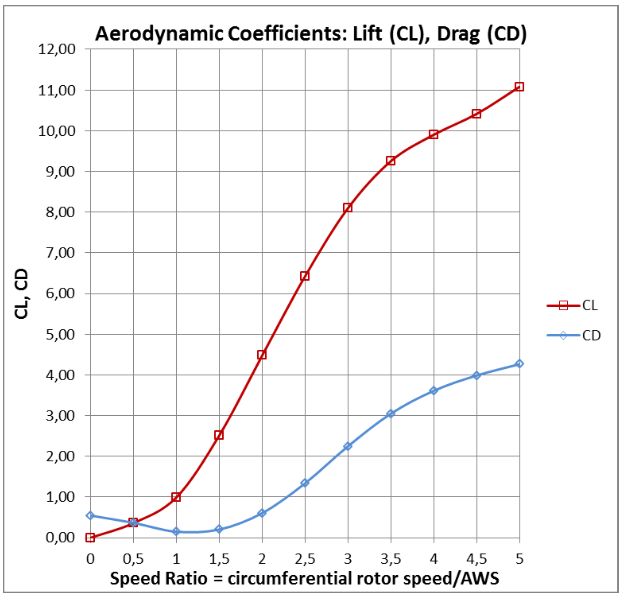

Figure 7: Lift and drag coefficients from model tests

The rotor's control and monitoring system developed and patented by scientists at the university displays the rotor forces and propulsion power in real time and comprises additional functions for performance optimisation (Müller *et al,* 2019). In addition to values from model calculation, force measurements are displayed in real time. The rotor force is measured in two axes (longitudinal and side force) by sensors specially adapted for onboard application.

5.2 MEASURMENT METHOD

The force measurement sensors were calibrated by means of a tensile test with load cells. Since certain inaccuracies cannot be excluded during the calibration, an additional measuring method for validating the rotor forces under real operating conditions was tested. For this purpose, a high-resolution measurement of the ship's heeling angle resulting from rotor side forces was carried out during the sea trials. The use of this principle is comparable with the well-known inclining test at the shipyard or for the support of ship's cargo operations to determine the initial stability of the ship. However, the test setup was carried out in the opposite way. The initial stability of the ship was determined precisely by a shipyard inclining test before the sea trials. With a known initial metacentric height, the angle of heel caused by rotor side forces was measured. Heeling moment and rotor side force were recalculated from the heeling angle. For the conduct of the test the ship was steered on a course against the wind, so that the rotor side force reaches a maximum and no crosswind influences the measurement. The rotor was switched on and off several times during the test period in order to measure the differential heeling angle generated by the rotor's side force. With almost smooth seas in protected waters only minimal ship's motion superimposed the measuring process, so that a clear result was obtained. As shown in Figure 8, the rotor forces recalculated from the heeling angle show a high correlation with the measured values of the force sensors and the values of the model calculation. The values of the rotor force both from the sensors (red) and from the heeling measurement (blue), however, are on average about 10% to 40% above the values of the model calculation (yellow). From this it can be concluded that a full scale Flettner rotor generates higher aerodynamic forces under real conditions than predicted by model calculations based on small-scale wind tunnel testing. This may be caused by the influence of the ship structures on the air flow, surface effects on the rotor as well as errors from upscaling the model test results. Since this project was the first to perform precise force measurements on Flettner rotors in real ship operation, no comparative results from other projects were available. Meanwhile recent experiments on Flettner rotors at critical and supercritical Reynolds numbers by Bordogna et al. (2019) indicate that Flettner rotors are significantly dependent on the Reynolds number which has not been duly regarded in the prediction of full scale rotor performance so far.

5.3 ROTOR PERFORMANCE IN SERVICE

The additional thrust generated by the Flettner rotor can be used either to increase ship's speed for saving voyage time or to reduce power and fuel consumption of the main propulsion system at constant speed. Therefore, in addition to the force measurement on the rotor, the ship's speed was measured with GPS and the fuel quantity was measured by a signal transmitter to record the fuel rack setting on the main engine. Since the electric drive of the Flettner rotor is fed from the shaft generator and thus directly from the main engine, the fuel measurement provides the correct total consumption including rotor operation. To evaluate the rotor performance, the ship's speed and engine power as well as fuel consumption with and without rotor was compared. However, as the ship's speed at given propulsion power depends on many factors, it is difficult to evaluate the data. To solve the problem, measurements were carried out over short periods under constant environmental conditions, during which the Flettner rotor was first switched on and then switched off again. If the main engine setting remained constant, the increase in ship's speed could be measured and a backward calculation of the rotor power could be made. If the vessel achieved the initial speed when the rotor was switched off, the influence of environmental factors on the ship's speed during the measurement could be excluded. Similarly, after switching on the Flettner rotor, the fuel rack setting of the main engine could be reduced and measured while maintaining a constant ship speed. The measurement results were used to validate the previous model calculations.

The following example shows the increase and decrease of the ship's speed by switching the rotor on and off with constant main engine setting. The diagram in Figure 10 shows the relationship between rotor's rotational speed (RPM), rotor's propulsive thrust (Fx) and ship speed over ground (SOG). The fuel rack setting of the main engine is initially constant and then reduced at the end of the measurement. The fluctuating fuel rack filling values result from the engine controller keeping constant propeller pitch and RPM under changing load conditions in rough sea. The ship steers a south course (180 degrees) with easterly winds of force 7 on the Beaufort scale (TWS about 30 knots), so the wind direction is from port abeam (TWA approximately 90 degrees, see Figure 9).

The measured values in the diagram show a clear correlation of the rotor thrust curve (Fx, red and yellow) and the ship speed (SOG, blue) with the rotor speed (green). When the rotor accelerates to 260 rpm (100%), the measured rotor thrust values (Fx measured, red) go up to a maximum of approximately 70 kN (70%). The ship's speed increases by 2.5 knots – from 7.6 to 10.1 knots – with almost constant main engine filling (fuel rack, brown). At full rotor speed the filling is then reduced by approximately 15% with only a minor influence on the ship's speed. When the rotor is switched off, the rotor speed and rotor thrust go back to zero within approximately five minutes, correlating with the reduction of the ship's speed. The measured rotor thrust (Fx measured, red) is significantly higher than the model calculation (Fx model calc, yellow), confirming the results of the sea trials.

To evaluate the rotor power, it can be compared with power from the main engine. In the test, the rotor was used to increase the ship's speed and compared with the equivalent power required for the main engine to achieve the same speed increase. This is based on model tests carried out in the towing tank of the DST research institute at the University of Duisburg-Essen in order to determine the required main engine power as a function of ship's speed. The resulting function curve must be corrected for added resistance and deviating draught/trim that occur under real conditions (service conditions). The measured ship's speed over ground must be corrected for the influence of the prevailing ocean current (here approximately +0.3 knots). Figure 11 shows the red speed-power curve for sailing under service conditions. The function curve is laid through the measuring point of the initial situation "Ship without rotor" (Rotor Off). The equivalent power of the main engine for the same speed increase as produced by the rotor (Rotor On) can be estimated by the red curve. The resulting propulsive power of the rotor is in order of 700 kW of power provided by the main engine, taking efficiencies of gearbox, shaft and propeller into account. This is above the main engine power of approximately 600 kW. In normal charter service of *Fehn Pollux*, the main engine power is limited to about 650 kW (Eco-Speed).

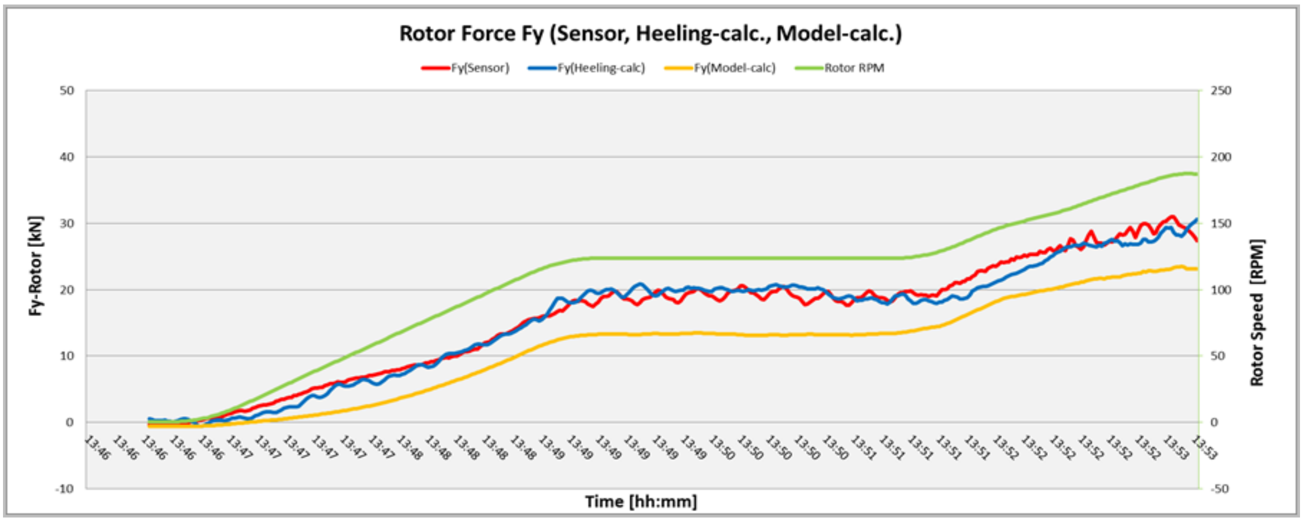

Figure 8: High correlation of rotor force values from force measurement (red), heel angle measurement (blue) and model calculation in real time (yellow). The rotor force is controlled by the rotational speed (green). The measurements show significantly higher values than the model calculation.

In summary, the following performance figures were recorded from the test:

- Rotor thrust approximately 70 kN,
- Rotor propulsion power approximately 700 kW equivalent to the main engine.

For assessment purposes it should be pointed out that these are high performance values that are close to the performance maximum. However, they are significantly higher than the previous assumptions based on model tests.

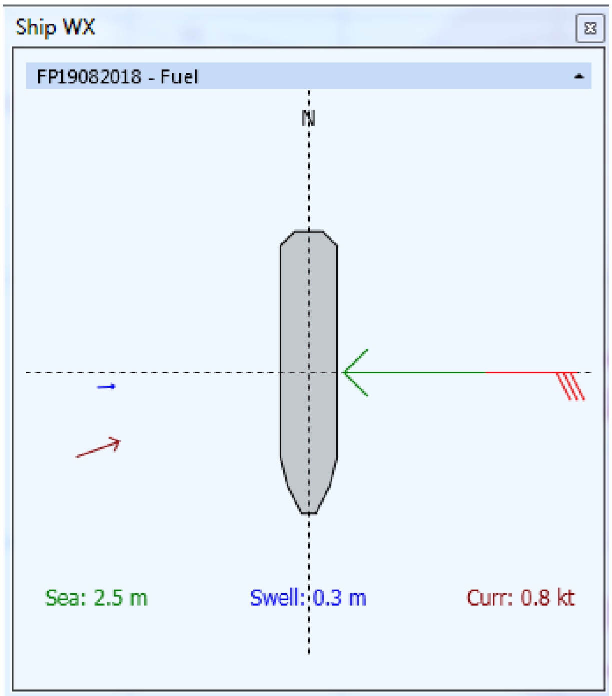

Figure 9: Wind, sea, swell and current conditions at the time of measurement (Source: SPOS MariGREEN-Version, Meteogroup)

6. TECHNICAL DATA

Vessel Data *Fehn Pollux*

Type	Multi-purpose freighter suitable for containers and grains
Year of Construction	1996
Length o.a.	89.77 m
Beam	13.17 m
Draught (S)	5.68 m
Deadweight Capacity (S)	4211 t
Tonnage	2844 GT
Main Engine	MWM Deutz SBV 9M 628, 930 kW
Speed	about 10 kn
Rudder	Becker type flap rudder

Rotor Data

Type	Eco-Flettner
Height of the cylinder	18.00 m
Diameter of the cylinder	3.00 m
Diameter of end plates	6.00 m
Projected area	54 m
Speed	263 RPM max
Drive	E-motor, max 75 kW, average power output depending on the wind conditions, e.g. 30 kW
Thrust	depending on wind conditions, limited to max 80 kN
Propulsive power	The savings potential depends on the wind conditions along the route and other factors. Under medium-to-good wind conditions, an annual average of approximately 2 kW main engine equivalent power can be saved per 1 m of projected rotor area (for guidance). Precise predictions are made by route simulations for the specific ship.

7. CONCLUSIONS AND OUTLOOK

The first test results of the *Fehn Pollux* showed that the retrofit concept of a Flettner rotor on the forecastle deck has advantages in terms of aerodynamic behaviour which have a positive effect on the propulsion performance and the manoeuvring characteristics. The disadvantages in terms of visibility from the bridge and radar detection are within acceptable limits and fulfilling all legal requirements. For the forthcoming transition of the world merchant fleet towards sustainable and low carbon marine propulsion it is important that a rotor installation on the foreship is transferable to a significant number of other vessels and can lead to considerable CO_2 savings without limiting other ways of saving.

According to validated performance models and route simulations, the annual average power potential of the Flettner rotor installed on the *Fehn Pollux* is in the range of approximately 100 kW to 150 kW in addition to the main engine power. These values naturally depend on the wind conditions along the route. In this case they apply to a trade along the coasts of northern and western Europe. Depending on the required ship speed and the actual power of the main engine, savings of approx. 10% to 20% can be expected on the *Fehn Pollux*. A reduction in speed leads to higher percentage savings, so a combination with slow steaming could lead to higher overall percentage savings. The recorded data and results from the first project phase already allow a relatively reliable prognosis of the achievable savings. Clear data transparency was provided during the project by validated measurements. This is essential to reassure shipowners, shipbuilders and investors about the validity of this new technology and to enable them to carry out economic appraisals of their own. The project can also be used as proof that converting fleets in this way can reduce CO_2 emissions, but that the process must be supported by appropriate measures in order to achieve important climate policy goals in good time.

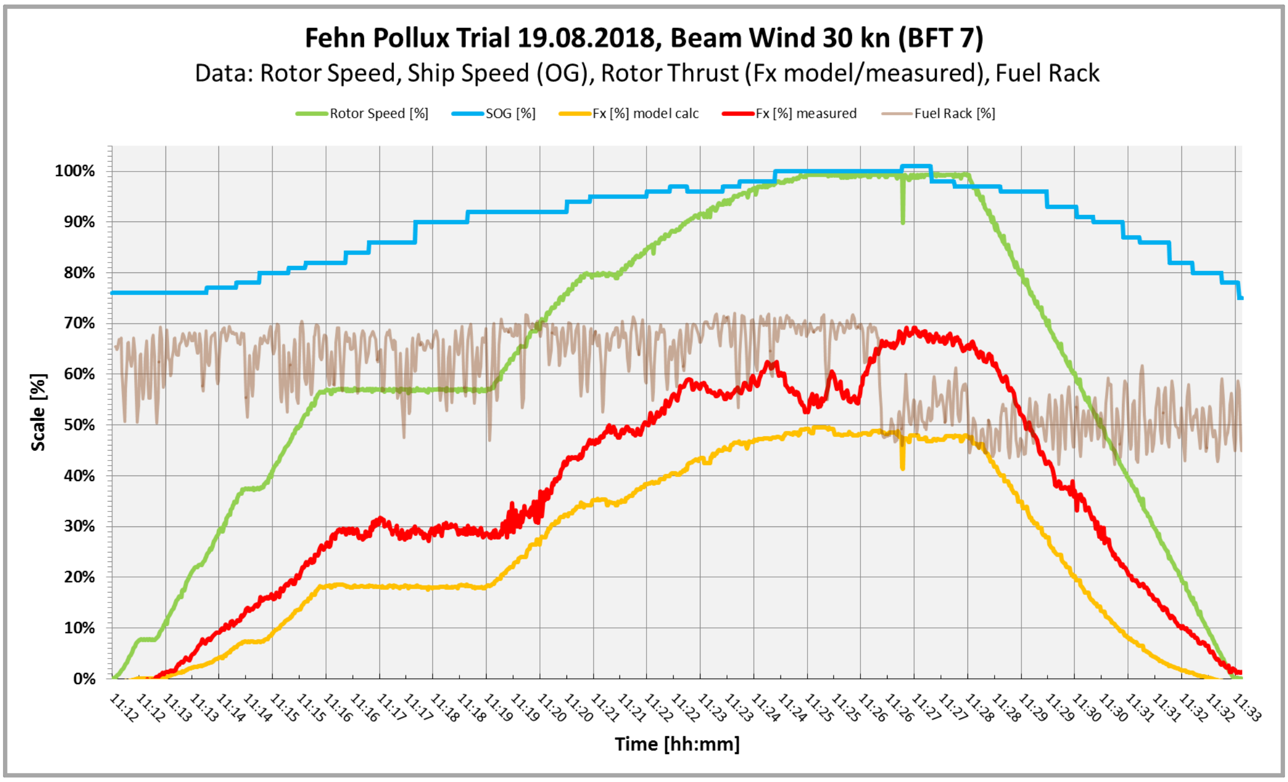

Figure 10: Graph showing the measured values of a performance test during regular service of the Eco-Flettner rotor on *Fehn Pollux*

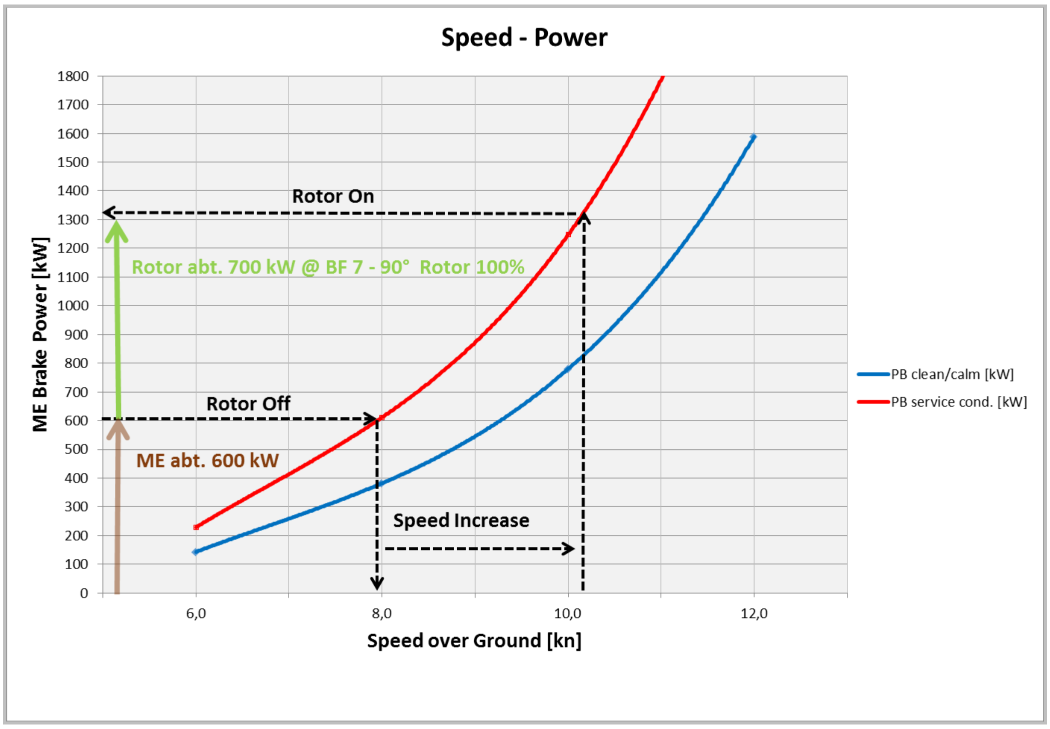

Figure 11: Propulsion power from the rotor and the main engine in relation to ship speed

First rough cost estimates indicate installation costs in the order of 10 kEUR per one square metre of projected rotor area with an average power savings potential of 2 kW/m . The payback time is 5 years or more on the example of *Fehn Pollux* depending on the ship's operational profile and the fuel price. Series production will lead to a significant cost reduction.

When considering the performance values of a Flettner rotor, it must be borne in mind that the installed sail area is decisive for the share of the total power of a ship. For newbuilding, more advanced concepts with better integration of the rotors into the ship's design are conceivable.

8. ACKNOWLEDGEMENTS

The development and testing of the "Eco-Flettner" wind drive was part of the MariGreen project, funded within the framework of the INTERREG V A programme Germany-Netherlands with funds from the European Regional Development Fund (ERDF) and through national co-financing from Germany and the Netherlands. Lead partner of the project was MARIKO GmbH in Leer.

The aim of the MariGreen project was to prepare the maritime industry, especially small and medium-sized enterprises, for the future requirements of environmental protection, climate protection and resource and energy efficiency in shipping through cooperation with universities and research institutions. An essential prerequisite for the realisation of the project was the cooperation in the German-Dutch border region in the field of Green Shipping that had developed in recent years. 13 companies and research institutions from Germany and the Netherlands worked together to develop the Eco-Flettner.[3]

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[3] http://marigreen.eu/projects/wind-windship-engineering-and-design/