Tanja Suominen

Rotor pilot project on M/S Estraden of Bore fleet

A thesis submitted for the degree of

Bachelor of Marine Technology

2015

samk
Satakunnan ammattikorkeakoulu
Satakunta University of Applied Sciences

ROTOR PILOT PROJECT ON M/S ESTRADEN OF BORE FLEET

Suominen, Tanja
Satakunnan ammattikorkeakoulu, Satakunta University of Applied Sciences
Degree Programme in Maritime Management
January 2015
Supervisor: Roos, Ninna
Number of pages: 32
Keywords: Flettner -rotors, SO_x regulation, bunker cost savings

---

In this work a completely new wind assisted propulsion technology for commercial shipping is introduced. The rotor sail solution by Norsepower Ltd. was installed on M/S Estraden from Bore Ltd fleet. Rotor sails are essentially improved Flettner - rotors with full automation. Although the basic principle of Flettner- rotors has been known for a long time, this was the first time that a rotor has been retrofitted on to a ship and made commercially available.

Since the beginning of 2015 the sulphur oxide (SO_x) emissions are regulated in the Baltic Sea, the North Sea and in the English Channel. Instead of the traditional heavy fuel oil (HFO), existing ships are now forced to use more expensive low - sulphur content HFO, change their engines to work with marine diesel oil (MDO) or to install scrubbers that eliminate the SO_x compounds from the exhaust gas. New builds can be made to work with environmentally friendly liquid natural gas (LNG).

The bunker costs will rise despite the method applied. Even before, with the traditional, cheaper HFO, the fuel costs were remarkably high, forcing the ship owners to search for savings on other operating costs. Thus it is essential to find a way to reduce the bunker costs. Already optimization programs are used to minimize the consumption by calculating optimal trim, selecting the best route based on weather and currents, adjusting the travel speed between the way points etc.

With the use of Flettner rotors it is possible to obtain notable savings, up to 8 % per rotor. They are completely independent, almost maintenance free and programmed to work without manual adjusting or crew members attending. They are fully automated and no special training or course is required from the user. Also, they can be installed on board during normal harbour stop without interruption or delays in the normal schedules. Their payback period is so short, that they can be installed even on older ships.

Some minor alterations have been made on this on-line version. The whole work is available in the SAMK library upon request.

Abstract

In this work a completely new wind assisted propulsion technology for commercial shipping is introduced. The rotor sail solution by Norsepower Ltd. was installed on M/S Estraden one of the Bore Ltd.s fleet. Rotor sails are essentially improved Flettner - rotors with full automation. Although the basic principle of Fletter- rotors has been known for a long time, this was the first time that a rotor has been retrofitted on to a ship and made commercially available.

Since the beginning of 2015 the sulphur oxide (SO_x) emissions are regulated in the Baltic Sea, the North Sea and in the English Channel. Instead of the traditional heavy fuel oil (HFO), existing ships are now forced to use more expensive low - sulphur content HFO, change their engines to work with marine diesel oil (MDO) or to install scrubbers that eliminate the SO_x compounds from the exhaust gas. New builds can be made to work with environmentally friendly liquid natural gas (LNG).

The bunker costs will rise despite the method applied. Even before, with the traditional, cheaper HFO, the fuel costs were remarkably high, forcing the ship owners to search for savings on other operating costs. Thus it is essential to find a way to reduce the bunker costs. Already optimization programs are used to minimize the consumption by calculating optimal trim, selecting the best route based on weather and currents, adjusting the travel speed between the way points etc.

With the use of Flettner rotors it is possible to obtain notable savings, up to 8 % per rotor. They are completely independent, almost maintenance free and programmed to work without manual adjusting or crew members attending. They are fully automated and no special training or course is required from the user. Also, they can be installed on board during normal harbour stop without interruption or delays in the normal schedules. Their payback period is so short, that they can be installed even on older ships.

Acknowledgements

This work has been done during the years 2014 - 2015 at the Satakunta University of Applies Sciences in close collaboration with Bore Ltd and Norsepower Oy Ltd. Finnish Merenkulunsäätiö is acknowledged for financial support.

I would like to thank my supervisor sea captain N. Roos, who tirelessly answered my questions, quite often outside the office hours. To CEO T. Riski from Norsepower Oy Ltd and technical manager K. Gestranius from Bore Ltd I would like to express my sincere gratitude for the opportunity to work within this pioneering project of a new technology. I also appreciate the fruitful discussions we had over the subject.

I would also like to mention the personnel from the school library and specially T. Salminen from the Maritime Management library of Satakunta University of Applies Sciences, who was always very quick and friendly at processing my requests for articles and references for this work. The crew of M/S Estraden in the summer 2014 is acknowledged for their open-mindedness towards me and this thesis.

To my family and friends, thank you for your patience, I promise not to study anything for a while.

Declaration

I herewith declare that I have produced this paper without the prohibited assistance of third parties and without making use of aids other than those specified; notions taken over directly or indirectly from other sources have been identified as such. This paper has not previously been presented in identical or similar form to any other examination board.

The thesis work was conducted from 2014 to 2015 under the supervision of N. Roos at Satakunta University of Applied Sciences and in collaboration with technical manager K. Gestranius from Bore Ltd and T. Riski from Norsepower Oy Ltd.

I made the literature review and theory introduction based on previous publications. System familiarization is based on my own experiences, documentation and discussions with the persons involved. I observed the quay side testing, and attended the transport, installation and the first week sea trials.

Tanja Suominen
January 2015, Pori

Contents

1

Introduction

In this work the installation of a rotor sail solution by Norsepower Ltd. to M/S Estraden of Bore fleet is followed. The rotor sail is based on a Flettner -rotor, a technology known nearly a hundred years. Due to the increased bunker prices and new emission control areas the possibility for auxiliary wind propulsion has become attracting option to obtain savings in bunker costs.

This work consists of four parts. First two are literature based, the introduction and the theory part. The introductory section covers a brief history of the Flettner -rotors and the sulphur regulation pros and cons are discussed from the environmental point of view. In the theory part a more detailed approach is taken to the rotor structure and basic theory is familiarized. Last two sections cover the the practical parts of the project, on land and at sea. These include rotor design, testing, classification, installation and the experiences from the first sea trials.

1.1 Bore and Norsepower

Bore Ltd is one of the oldest Finnish shipping companies, founded in 1897. Bore has modernized its fleet by acquiring new builds and selling old ships. At the time the fleet consists of 11 vessels, majority of them being ro-ro cargo ships operating on the Baltic and the North Sea areas. In this work deployment of the Norsepower rotor sail solution on ro-ro ship M/S Estraden is documented.

Norsepower Oy Ltd is a newcomer in the Finnish maritime industry. The personnel is formed by top specialists with a strong background in Finnish maritime industry and wind energy. Founded in 2012 the company focuses on the new method of retrofitting the existing ships with rotor sail solutions. Rotor sails are essentially improved Flettner - rotors with full automation. The key advantages are the "plug and play" installation, fully automated use, significant savings in bunker costs and thus relatively short payback period. Therefore even the older ships can benefit from their use and the marketing potential practically covers all the existing ships worldwide.

1.2 M/S Estraden

M/S Estraden is a ro-ro cargo ship, built in 1999 in Rauma, Finland. Description of the ship properties are collected in Table 1.1. The lane meter information is not accurate at the moment as hoistable car decks were removed when her contractor changed in the beginning of 2015.

Table 1.1: Main characteristics of M/S Estraden as given on board.

Indentification	IMO number	9181077
	Call sign	OJIL
	Flag state	Finland
Dimensions	Length	162.70 m
	Breadth	25.70 m
	Max draft	6.60 m
	Air draft	
Tonnage	Gross tonnage (GT)	18 205 t
	Net tonnage (NT)	5 462 t
	Dead weight (DWT)	9 700 t
Engines (x2)	Wärtsilä 8L46A	7 240 kW/500 rpm, total 14 480 kW
	Caterpillar 3508B	856 kW, total 1 712 kW
	Bowthruster (1)	900 kW
Other	Service speed	19 kn
	Lane meters	2300 m

At the time of installation she was operating on a line Turku(Finland) - Bremerhaven (Germany) - Harwich (UK) - Cuxhaven (Germany) - Paldiski (Estonia) - Turku (Finland). One round trip took one week and it was done via Kiel canal. From the beginning of 2015 Estraden was to change on line traffic between Rotterdam (Netherlands) and Teesport (UK). That route is entirely in the North Sea sulphur emission control area (SECA).

1.3 Background to the Flettner -rotors

Flettner rotor performance is based on the Magnus effect. Magnus effect was first studied in Germany 1854 by physicist G. Magnus (1). The effect is caused by the air flow around a rotating object, *e.g.* a cylinder or a ball. It has been known for a long time in everyday life. For example it is intuitively used in many ball games even at present time. In the past, before the guns and cannons were rifled, projectile trajectories were quite unpredictable and curved due to the Magnus effect. However, the exact theory behind the phenomenon is very complicated.

From the beginning of 1920's Prandtl *et al.* conducted series of successful experiments with rotating cylinders in order to define the theory behind the effect. Only after they added an end plate on top of the cylinder, they saw that the forces caused by the Magnus effect were significant and in good correlation with the developed theory. They began to consider the suitability for several different applications: aviation, propellers etc. However, they came to a conclusion that the energy required for the rotation was too large in comparison to the obtained forces and therefore neglected further considerations for applications. (1)

At 1920's the maritime industry was at a turning point. The era of sails was coming to an end and the machine powered ships began to dominate. The Flettner brothers were of seagoing nature and Anton was working on a conversion project on schooner Buckau by making changes on the sail structure. He already had patented some improvements he invented on the rudder and decided to apply the same idea on sails. Some time in the middle of these conversion plans his brother Andreas happened to mention the recent experiments by Prandtl *et al.* and their very promising results. The results implied that with same effective areas, the cylindrical rotors could produce ten times higher aerodynamic forces than the equal area of sails. Anton immediately

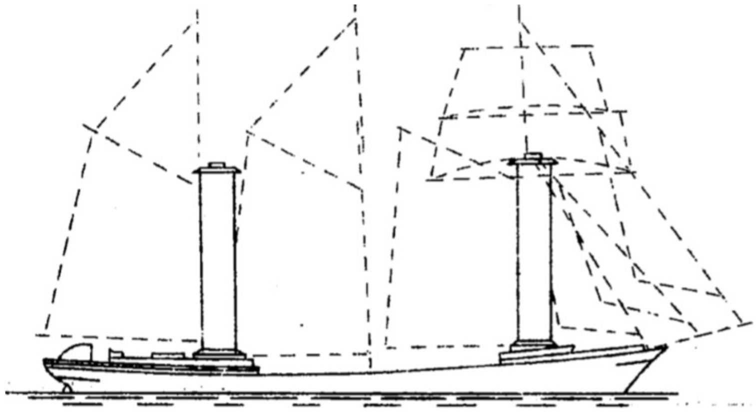

Figure 1.1: Comparison between the sail area and the rotor area on converted ship Buckau after Prandtl (1).

got excited about this new idea and decided to change Buckau into a rotor ship instead (Fig. 1.1). Two rotors were installed and they worked as an auxiliary propulsion system. The ship sailed over the Atlantic and the rotors functioned as planned. The scepticism about the rotors' sea worthiness was proven to be unjustified. (2)

At 1926 a new build Barbara was equipped with Flettner rotors. Barbara operated on the Mediterranean and survived several heavy weathers (2). However, at the time of global depression in the 1920's, the machines became more and more powerful and efficient, fuel oil was cheap, the environment was of no concern and finally the looming Second World War diverted Flettner's own focus elsewhere (3). Thus the wind power and eventually Flettner -rotors were forgotten and the engines became dominant.

And they stayed forgotten, until the oil crisis in the 70's. Environmental awakening had begun, the limited amount of oil was realized globally and the oil prices were getting higher. Even if only one of these points may had been enough, all of them together lead to the search of alternative propulsion methods. Seminars and conferences were held and wind assisted propulsion came forward as one possible option to ease the situation. Several methods were studied, sails, kites and Flettner rotor. (3, 4, 5, 6). Bergeson and Greewald (3) documented a small test cylinder performance and Fletter rotor was superior in its perfomance in comparison to any traditional sail method (Fig. 1.2).

But the time was still not ready for Flettner rotor and instead of wind power, the efficiency of ship engines was improved, ships were made larger, ship design developed

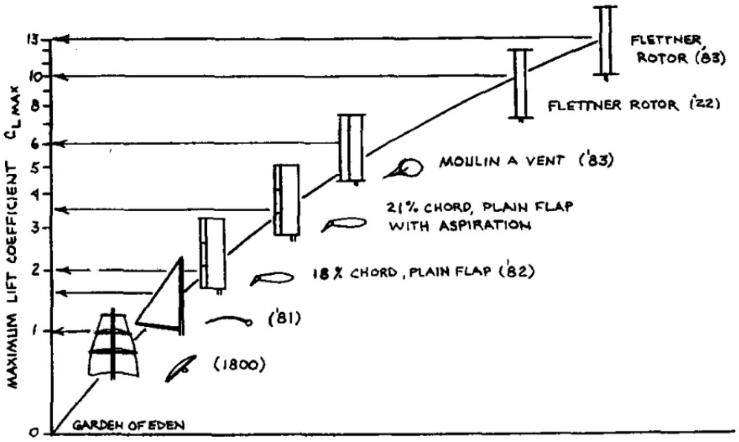

Figure 1.2: Maximum lift coefficients for various sail based methods. Flettner rotor efficiency is over 13 times higher than traditional sails (3).

to reduce the friction on the hull, special paints were invented to reduce the fouling and so on. Above all, the ship sizes have now grown so much, that the cargo capacity has risen to be four times larger than in the 70's but the CO_2 emissions are only doubled, being approx. 3 % of all the amount of CO_2 released in to the atmosphere yearly (7). However, keeping in mind that 90 % of global goods are transported by sea (8), 3% emission does not seem an unacceptable ratio between cargo and emissions.

Since 2010 a new boost has been seen in regard of Flettner -rotor tecnology as a possible propulsion method (9, 10), this time the advantages come from the bunker savings and from the environmental aspects. Old measurements have been verified (11) and new calculations and estimations (12, 13) presented. With the present day materials and technological improvements the efficiency can be expected to be even better than on the previous constructions. At 2010 German energy company Enercon[1] built E -Ship1 equipped with four Flettner -rotors, but unfortunately the exact data of rotor design or performance is not publicly available. However, the ship has been on traffic and the owners claim that substantial savings have been obtained.

[1] http://www.enercon.de/en-en/search.php?qt=E-Ship+1

1.4 The Baltic Sea

Particularly Special Sea Area (PSSA)

International Maritime Organization (IMO) is an agency working under the United Nations (UN) governing the world wide commercial shipping. The organization consists of several committees and sub-committees. One of the committees, the Marine Environment Protection Committee (MEPC), which concentrates on pollution prevention and environment protection, has defined criteria for Particularly Special Sea Areas (PSSA) (14).

Finland is surrounded by the Baltic Sea, which is an ecologically unique sea area and needs protection. On average more than 14 000 ships traffic on the area weekly, out of which 10 % are tankers up to 150 000 t (15). Together with other surrounding countries (Denmark, Estonia, Germany, Latvia, Lithuania, Poland and Sweden) Finland applied a status of particularly special sea area (PSSA (14)) to the area from MEPC. Russia was not among the applying countries.

In 2005 the Baltic sea was designated to be a PSSA by the International Maritime Organization (IMO) (15). Due to the status of PSSA a traffic separation scheme was introduced regulating the traffic into certain routes, areas to avoid were defined and growing attention was paid to pollution prevention.

Sulphur Emission Control Area (SECA)

Later it was agreed under the International Convention for the Prevention of Pollution From Ships (MARPOL), that the Baltic sea will become a part of a sulphur emission control area (SECA) from the beginning of 2015 together with the North Sea area and the English Channel (16). The Baltic sea belongs completely to the SECA, the border going from the tip of Denmark to Sweden at 55° 44' N. At the North Sea the area is defined as from 62° N to south and from 4° W to east and western limit from 5° W to east at the English Channel. Borders are shown in Fig. 1.3. As can be seen from the map, the regulation covers the whole Northern Europe. Sulphur regulation (16) states that sulphur content in the fuel oil used in ships may not exceed 0.10 % on and after 1 January 2015. On the Baltic sea area the sulphur content was previously required to be 1 % or less.

Figure 1.3: The sulphur emission control area at the North Sea and the Baltic Sea affects all northern Europe countries.

As seen in Fig. 1.3, these sea areas are confined and thus the dense maritime traffic is forced to operate relatively near to the coasts. There are many large ports in the area, which act as transit points for goods coming and going to and from Europe as well as busy ports for each country's national import and export. Emissions from ships strongly affect the air quality and the people at the heavily populated coastal and harbour areas. Ship emissions contain nitrogen oxides (NO_x), SO_x and particulates, which can cause various health problems whereas the CO_2 emissions cause climate change and their reduction is essential to lessen the global warming (17). The aim of SO_x regulation is to improve the air quality at these areas and thus minimize the health risks.

This new 0.1 % SO_x limit is so low, that the traditional heavy fuel oil (HFO) can not be used anymore. Mainly three alternative methods are suggested for existing ships in order to comply with the regulation. All of them are quite expensive and concentrate solely on the SO_x reduction, neglecting the other emission levels. It was estimated that the cost to Finnish shipowners alone was to be from 100 million euros to over 120 million euros depending of the way of calculation (18). Schinas *et al.* have developed a cost assessment calculation system for operators to use as a tool to best handle the increased expenses (19).

New builds can be made to use also environmentally friendly liquid natural gas (LNG), like Viking Grace, built in 2012. However, the LNG terminals are not yet available everywhere. For existing ships the first option is to install a scrubber on board, which cleans SO_x emissions from the exhaust gas. This technology is yet to be proven to work properly and it was speculated, that the engine efficiency may be affected by it thus causing higher bunker consumption levels and therefore increased CO_2 emission levels. The second option, use of marine diesel oil (MDO), requires alteration to the ships engines, some of which are turned to dual fuel engines. Inside SECA the ship could use MDO and outside the area cheaper HFO. However, these modifications are expensive and not affordable in old ships. Yet again, the higher refinement level of MDO may increace the total CO_2 emission level even though the emission from the ship itself is inside the limits. The third option is to use SO_x reduced HFO, which is much more expensive than the traditional HFO. (8)

The regulation has awoken criticism even among environmentalists (8, 17). There is reason to expect, that the overall emissions of CO_2 will increase as a result of the SO_x reduction (8). This is controversial from the environment protection point of view as CO_2 emission is a far more serious threat regarding the global warming and climate change, whereas SO_x (and NO_x) emissions are compensating those by cooling the atmosphere instead. Also, they are neutralized in decades while CO_2 stays in the atmosphere hundreds of years (17).

The lack of means of control and sanctions has been discussed together with the concern of unfair competition. Therefore it can not be a long term solution alone. However, after large investments and alterations concerning solely the regulated SO_x emissions, ships may not be able to comply with another demands later. The benefits of the Flettner -rotors are undeniable in regard of the bunker costs and environmental aspects as it reduces all the emission equally, not only certain part of them.

2

Basic theory and rotor design

This section consists of a brief literature review of Flettner -rotor history and experiments, familiarization of the theory and discussion of some parameters affecting the efficiency.

2.1 Flettner -rotor and Magnus -effect

Magnus effect occurs, when a rotating object is placed in a flow of water or air. Force is divided into two components, namely lift and drag. Fig. 2.1 shows these vectors. Lift is perpendicular to the direction of the flow, its direction depends of the rotation direction. Drag is smaller and parallel to the flow. The superposition of these vectors is the force, or thrust, that moves the object sideways in regard of the flow, like the swirl of a spinning ball. As the rotor is attached to the ship and not moving freely, the ship feels the thrust forward. The reason for this effect is the pressure difference that the rotation creates on the opposite sides of the object similarly to the wing of an aeroplane. The possible applications in aviation have indeed been considered, but thus far the maritime applications are the only one realized in large scale (2).

Rotors are basically fast spinning vertical cylinders. These are better in comparison to the traditional sails or even to the modern kites as they work on wider wind angles, optimum being apparent side wind in 90° angle to the bearing. Unlike with sails, rotors do not perform optimally with direct back wind, but by minimizing the lift and maximizing the drag it is possible to obtain some power to the right direction. This is not entirely practical, since lift always has larger effect than drag.

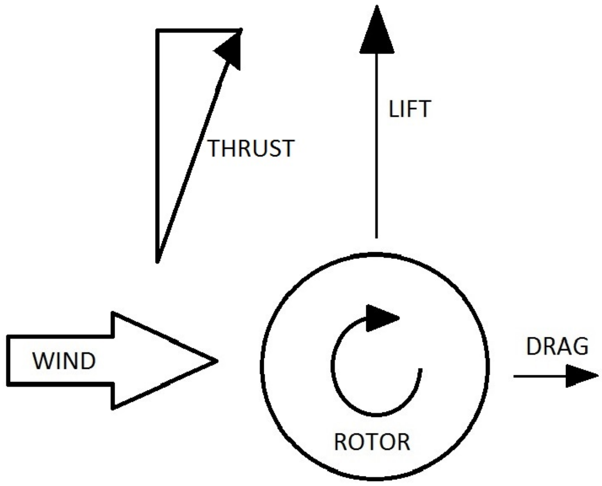

Figure 2.1: Schematic picture of the basic principle of the rotor. Two force vectors are formed from the rotor, lift is perpendicular to the wind and drag parallel. The lift force vector direction is dependent on the rotor rotation direction. The drag force is always smaller than the lift. Thrust is the superposition of these two force vectors. By adjusting the rotation speed,the amounts of drag and lift can be varied. Here the drag is presented exaggerated in theory clarifying purposes.

Also direct head wind can be problematic (5). However, already 10 to 15° deviation from the middle line is enough to make the rotor produce notable thrust. In Fig. 2.2 is shown the performance as a function of true wind. When looking at the picture one must keep in mind that the rotor experiences the apparent wind which is the superposition of true wind and the ships speed, the maximal thrust is obtained when the apparent wind is in nearly 90° angle to the rotor. Therefore the maxima in Fig. 2.2 occur on values less than 90°.

2.2 Rotor structure

The first rotor installed on Estraden is a 18 m and 3 m wide cylinder with smooth surface, and an end plate, with 5 m diameter, is placed on top as shown in Fig. 2.3. An external force is used to rotate the cylinder and together the apparent wind and rotation create thrust. In Norsepower rotor the external force comes from an electric motor which is placed inside the rotor. The motor is connected to the ship's power grid. One of the advantages in the use of electric motor is that the adjustment of the

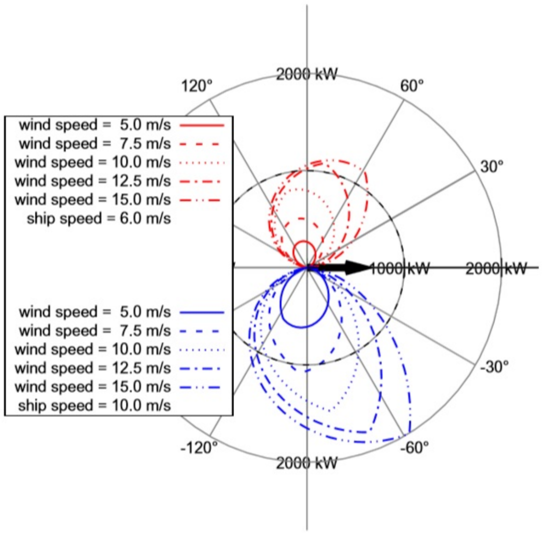

Figure 2.2: Power as a function of a true wind (12).

Figure 2.3: An image of the Norsepower rotor sail.

rotation speed or direction to correspond the wind and weather conditions is simple. In Table 2.1 is collected some structural data of past and present commercial Flettner - rotor ships.

As can be seen in Table 2.1, the rotor material has changed through the years. The aim is to get the rotor as light weighted as possible, but still robust enough to be seaworthy. Even wood and fiberglass have been considered (3). Ship movements, rolling, vibrations as well as outside conditions such as rough sea, weather, temperatures, humidity are challenges that need to be addressed.

The loads on the foundation have to be taken into account, as the long and narrow structure creates large forces on the base. Rotor balance is extremely important for the 18 m high rotor spinning up to 250 rmp. Stabilization required extreme precision and masses used were tiny in comparison to the total mass of the rotor. The effects on ship stability, deck loads and needs for supportive structures etc. have to be examined carefully. These need to be calculated ship by ship as they are strongly dependent of the ship characteristics.

Table 2.1: Structural and performance related parameters collected from the existing rotor ships, Buckau and Barbara (2), E-Ship1 and Estraden rotor by Norsepower.

Ship(year)	Buckau (1924)	Barbara(1926)	E-Ship1(2010)	Estraden(2014)
Type	Retrofit	Newbuild	Newbuild	Retrofit
Height [m]	15.6	17	27	18
Width [m]	2.8	4	4	3
Material	Zinc coated steel	Aluminum		Composite
Max. rpm	135	150		250

Lately many ships have been retrofitted with flume tanks or anti-rolling tanks. The sole purpose of these tanks is to reduce the rolling thus reducing bunker consumption, enhancing the speed and stability. It may be reasonable to study in more detail the possible steadying effects of the rotor and its rotation. As the rotor is a very large gyroscope it produces an anti-rolling stabilizer effect on the vessel. However at the moment there is no experimental or even theoretical data or approximations of the magnitude available of the subject.

The rotor is hollow and all the needed equipment and sensors are installed inside the cylinder where they are protected from the weather. Only moving part in the system is the cylinder itself, the inner parts are static. Entrance inside the rotor is on the base structure. However, the crew will not need to enter the rotor. On the hatch is an emergency stop switch which ensures that whenever someone is inside, the rotor is not turned on. There are four levels inside, connected with ladders.

Right at the entering level are the wheels. Wheels are supported to the inner circle of the cylinder via special track. The qualities of the track and of the wheels have been optimized to ensure quiet and reliable performance of the rotor. As explained above the lateral forces and the rotor stability affect most on the cylinder base.

On the next level is the electric center, where the cables are collected to and from the rotor. Electric motor is placed on the highest level. Since the Norsepower rotor is the first system made commercially available, the more detailed description of the innovative configuration or pictures from the insides will not be published in this work.

2.3 Parameters related to performance

There are several structural parameters related to the performance which will be introduced only briefly. For more detailed explanations of parameters and their effects can be found for example in the review paper by Seifert (2).

In order to obtain sufficient thrust, the rotor needs to be long and narrow. The ratio between the height, h, and width, w, is called aspect ratio, A and it is very important when considering the effectiveness of a rotor (5). Cylinders with aspect ratio 5 or 6 are structurally strong against the bending forces and loads towards the material (3). In Norsepower rotor the aspect ratio is 6.

With adjustment of the end plate size even the effects of unfavourable aspect ratio can be fixed. The end plate, called Thom disc, is crucial as observed already by Prandtl (1). More studies were made about the effect of the plates in a wind tunnel and it was observed that addition of these discs in between the cylinder increased the lift coefficient. But it was also noted that rotating such a structure required more energy so that in the end they did not enhance the efficiency (4). Theoretical approach was taken later and results were verified by Craft *et al.* by a 3D simulation study (11).

The challenge in wind tunnel experiments is the scaling problem. With a scaled ship model and wind speeds the according speed of rotation needs to be extremely high, which is difficult to realize. Moreover, the already made wind tunnel tests and theoretical simulations and calculations all support the natural next step to be an actual installation on a real scale.

The circumference of the cylinder is $c = \pi d$, where d is the diameter of the cylinder. In the case of Norsepower rotor d=3 m, thus the circumference is 9.4 m . As the max velocity used is 250 rpm = 4 rotations per second, the maximal surface velocity, or circumferential velocity, U is 37.6 m/s (= 135 km/h). The ratio between the apparent wind speed, v, and circumferential velocity U is expressed as a velocity ratio α.

$$\alpha = \frac{v}{U} \tag{2.1}$$

This is very useful ratio, as the force is usually expressed with lift coefficient, C_L, and drag coefficient, C_D as a function of α. For optimal use the C_L should be as large as possible, whereas C_D should be kept as small as possible. These can be expressed as follows:

$$C_L = \frac{L}{\frac{1}{2}\rho_{\text{air}} A U_0^2} \tag{2.2}$$

$$C_D = \frac{D}{\frac{1}{2}\rho_{\text{air}} A U_0^2}, \tag{2.3}$$

where ρ_{air} is the air density, A is the cylinder projected area $(h * d)$, U_0 is the apparent wind speed and L and D are the lift and drag forces, respectively. From fitting the existing experimental data they can be expressed as a function of α (13).

$$C_L(\alpha) = -0.8 + \frac{12}{1 + e^{-\frac{\alpha-2}{0.8}}} \tag{2.4}$$

$$C_D(\alpha) = 0.6 + \frac{3.8}{3 + e^{-(\alpha-5)}} \tag{2.5}$$

However, the actual circumstances at sea have so many variables, that all of them can not be taken into account in wind tunnel tests, simulations or numerical approaches. Therefore these are only for guidance and estimation of the large scale operation at real conditions.

3

System familiriarization

In this chapter is presented many of the steps, that need to be taken before installation of a new technology on to a ship. Some of the preliminary measurements, reliability of the performance, classification requirements. The quay trials took place in Naantali Repair Yard, from May to the late November 2014.

3.1 Design

From the ship owners point of view some consideration for adopting a wind assisted propulsion systems were presented already 1985 by G. Livanos (3). These points are valid to date:

- Significant fuel savings
- Simplicity
- Reliability at sea
- Operability from the bridge
- No additional crew required
- Classification
- No inteference to the ships normal operation, i.e. cargo handling

Figure 3.1: Rotor base build on Estraden (A) is similar to the one at the land test site in Naantali (B).

All these points are thoroughly considered in the Norsepower rotor design. VTT Technical Research Centre of Finland has been part of design, testing and implementing the Norsepower rotor sail solution. They have conducted series of measurements at the land test site as well as at sea to verify the power yield and competitiveness of the system. These measurements and results will be reported in detail by VTT Technical Research Centre. Some of the most recent calculations suggest over 50 % fuel savings on specific routes on slow steaming ships with several rotors installed (12), however this is considered to be highly optimistic estimate. Realistically 8 % fuel savings per rotor can be expected for the Norsepower rotor.

To ensure the reliability at sea, intensive land tests were conducted before installation on board. These tests included hundreds of hours of test drives, material and program optimization as well as safety tests. The rotor base is shown in Fig. 3.1(B). It is similar to the one on board (Fig.3.1(A)). From the beginning the idea was to have a "push button" solution. The rotor is operable from the bridge via simple control panel without complicated manual adjustments. It is fully automated and collects needed information through its sensors, passes the data to the program which calculates the optimal rotation speed and drives the rotor. The use does not require any crew members to attend on site.

As the rotors need deck space and they are tall, the position needs to be planned so as not to disturb any cargo operation, e.g. handling containers with cranes, restrict visibility from the bridge etc. The simulation studies made on the ship air wakes shows the complexity of the air flow around the ship structures (20). Also this needs to taken into account when the positioning of the rotor. On Estraden the rotors are possible to install on top of the ramp house not requiring deck space and in free air flow. The foundations were built during a normal docking. The ramp house roof was strengthened accordingly to withstand the loads caused by the rotors' weight and operation.

For the pilot project Estraden's engine room was equipped with a measurement system from VAF Instruments. With this system it is possible to obtain real time information of the engine power yield and bunker consumption for both engines separately. Comparing this data with the rotor data the rotor performance can be documented accurately.

3.2 Control panel

Control panel is kept simple. It has one screen, which shows the key parameters of the rotor function, emergency stop button and a lever for manual adjustment of rotation speed. There are three operation modes, on, off and invisible mode. Invisible mode means slow rotation, which reduces the drag to be smaller than it would be in the case of full stop rotor thus making the rotor "invisible". When the rotor is turned on, the program calculates the optimal rotation speed and direction from the real time wind speed and direction. These values are shown on screen. The rotor power consumption and the power yield as well as the VAF data from the engines are shown.

3.3 Safety announcements

The system is programmed to give a warning on several occasions. There are two levels of warning, yellow colour is used just to notify about a change and requires no further actions. Red colour is used for critical warnings, which will cause the rotor either to shut down or just slow the rotation speed automatically. Some of these cases may cause a need for maintenance. There are rotor component related warnings, such as the temperatures or vibrations of the bearings, wheels, data connections etc. and others are warnings from outside operating conditions such as high wind speed, humidity, icing, heavy rolling.

For example, the true wind speed limits are categorized as follows. Yellow warning notifies the user, that the true wind speed exceeds 19 m/s over 5 minutes, but it does not affect the operating of the rotor. If the wind speed is 25 m/s for 5 minutes, 30 m/s for one minute, 35 m/s for 5 s red warning is given and the rotor automatically reduces the speed to 5 rpm or shuts down.

The warnings are only shown on the control panel with these colour codes and written text without any sound signal. Green colour means no warnings.

3.4 Classification requirements for installation

Since M/S Estraden itself is classified by the Lloyd's register also the rotor was classified by Lloyd's. Lloyd's has previous experience of Flettner -rotors and was familiar with the principle. E -ship1, Enercon's new build with four rotors, was classified by Lloyd's and they were a part of the Greenwave project as well (21).

The classification society surveyed the following segments:

- Design principles
- Pedestal and hull strengthening
- Supporting structures
- Electrical power supply
- Control and automation system

Design principles included basic structures and measures of the rotor such as geometry and size etc. Also the design of installation: how many rotors are installed where on the ship. The operating conditions were stated and control principle presented. Also calculations of the loads caused by the structures and effects on ship stability were provided. Pedestal and hull strengthening included the assessment of design beforehand and auditing manufacture, including the components that were used, and installation audition both on the test site and on the ship. Similar process went through with the supporting structures.

For electrical power supply the connection interface to ship's electrical system was described and single line diagram of the whole system was provided. The principal idea is, that the rotor is an independent entity and it is not integrated into any other system. This way a rotor malfunction does not effect any other device on board. Therefore all the individual components introduced to the power grid were also to be listed. All the cable materials were chosen and inlets through ship structures were made as required by normal electrical classifications.

Section concerning control and automation systems was mainly safety related and for all the other features the design was not regulated. For instance, there are no requirements what information must be shown on the control panel screen and what is optional. This section contained the fire detector and emergency stop switch positions, limit switches, warnings and shut down limits. For example, warnings from icing, elevated component temperatures or increased vibrations can cause the rotor to shut down automatically. The emergency switches can be found at the control panel, outside the rotor on the ramp house roof and inside the rotor. The hatch on the rotor base is equipped with a switch as well, if opened the rotor will stop and can not be turned on as long as the hatch is not properly closed.

As the classification society did not encourage integration to the existing systems, the rotor is connected only to the electric grid and fire alarm system. Otherwise it is self sustaining and it collects all the data through its own sensors.

4

Sea trials

In this section the installation procedure is shown in detail and the ideas and comments after the first week sea trials are discussed.

4.1 Transport

The installation began with a transport from the land test site at Naantali Repair Yard to the Port of Turku, where M/S Estraden was to arrive on the following day.

On the top of the rotor are inbuilt hooks for lifting purposes (Fig. 4.1 (A)) The rotor was detached from the base and moved on to a transport base shown in Fig. 4.1(B). Because the crane hook was so narrow an extra piece was added to the hook to ensure safe lifting (Fig. 4.1 (C)). The weight of the whole system was approx. 30 t, 7 tonnes for the transport base and 22 t for the rotor itself.

Rotor was transported from Naantali to Turku by sea in an upright position. In Figure 4.2 (A-E) is shown the loading of the rotor on to a barge.

The voyage from Naantali to Turku took approximately 1.5 hours. All together the loading was done in less than two hours. Figure 4.3 shows the rotor on its way.

However, the unloading at Port of Turku proved to be more challenging. The original idea was to use the harbour crane as previously in Naantali, but the cranes at Turku harbour could not reach the top of the rotor, as can be seen in Figure 4.4 (A). Fortunately the hoisting car arrived just in time and it was able to reach the rotor top, Fig. 4.4 (B). This was the same car that was meant to be used for the actual installation on Estraden as well.

Figure 4.1: Rotor transport arrangements from the Naantali Repair Yard. Preparing for the lift (A), specially designed transportation base (B) and extra piece lengthening for the crane hook (C).

Figure 4.2: Loading the rotor on the barge. Lifting (A), aiming (B), lowering (C), lashing (D) and the lifting lines (E).

Figure 4.3: Rotor transport.

Figure 4.4: Some challenges.

Figure 4.5: Unloading the rotor from the barge.

Eventually the rotor was lifted on the quay side (Fig. 4.5) to wait for M/S Estraden to arrive on the following day.

4.2 Installation (in practice)

Preparations for installation on board started already during the normal docking when two rotor bases were constructed on Estraden and the mast was heighten by 6 metres for the mast light to be visible after the rotor is installed. In Figure 4.6 (D) is seen one of the bases in the front of the picture. Cables were installed while the ship was in normal traffic. For future installations all these preparations will be done during docking.

Figure 4.6: Preparations for installation. Ready to lift the rotor (A) and (B), detached from the the transportation base (C), aligning to the base on board (D).

Before Estraden arrived the rotor was made ready to be lift up, lifting lines attached and hoisting car ready. Although the suitable place was relatively easy to estimate the day before, even before ship actually had berthed, the position was checked immediately after arrival (Fig. 4.6 (A and B)). Desired position was determined by the hoisting car and its reach, distance from the ship and the required height. As the place was suitable for lifting, the rotor was detached from the transportation base (Fig. 4.6 (C)) and was lifted above its base on board (Fig. 4.6 (D)).

In Figure 4.7 (A) is shown base surface treatment before the rotor was lowered on its position. For the exact alignment one man was to enter the rotor and guide it from the inside as seen in Fig. 4.7 (B). It is notable, that the installation did not disturb the ships normal activities at all. For example, during the whole time of lifting and aligning and lowering, the ship was unloading and therefore some ship movement was present continuously.

Rotor is attached with bolts on the base, shown in Fig. 4.8. These bolts were

Figure 4.7: Base surface treatment, rotor hanging above the base (A) and lowering the rotor on its position (B).

tightened with a torque wrench, one man working inside the rotor and one holding the bolt outside. All together they were tightened and checked in three rounds.

Most time consuming was to organize the cable connections. But in six hours, which equals the normal time the harbour stop, the whole installation was completed. Including the electricity connections and testing by rotating the rotor. Taken in to account that this was the first time ever to install a Flettner -rotor as a retrofit to an existing ship, the installation went extremely well and no surprises were encountered. Next installations can be expected to go even faster and more smoothly, now that many phases can be made in a more convenient and practical way. Special care will be taken, that the cable connections will be simplified and therefore easier and faster to make inside the confined space of the rotor. Finished installation is shown in Fig. 4.9.

4.3 Operation

At the time of the installation (November 2014) Estraden was still on the line Turku (Finland) - Bremerhaven (Germany) - Harwich (UK) - Cuxhaven (Germany) - Paldiski (Estonia) - Turku (Finland). The first sea trials began immediately after installation on that route. From the beginning of 2015 Estraden's line was changed completely to the North Sea, operating between Rotterdam (Holland) and Teesport (UK). Therefore, for this work, exact effects on bunker consumption are not available as even the baseline is not yet known on that route. However, the wind conditions are expected to be optimal on the North Sea. Also most of the crew changed shortly after the installation, thus

Figure 4.8: The bolts that attach the rotor on the base.

Figure 4.9: Installations ready.

the comparison of the ships overall behaviour is not possible. However, after the first week, there were no noticeable negative changes.

4.4 First impressions

First few days the rotor was driven manually, ie. emergency stop system and automation were tested. From the beginning it was clear that neither noise nor vibrations caused by the rotor were on any disturbing levels at sea conditions. During the first week the weather was moderate sometimes even calm.

By changing the rotation direction the rotor effects were observed. It was seen in speed and power consumption. When rotated in the preferred direction the speed was higher than when the rotor was used as a brake. Similarly the power yield changed from positive to negative. These are the kind of tests that need to be done in a more systematic way in order to get reliable numerical data. But even now these observations clearly show, that the rotor is working and the ratio between used power and produced power were on average 1:15, momentarily even doubled.

It was also seen, that the power needed to rotate the rotor was mainly dependent on the rotation speed while the apparent wind conditions and weather had a smaller effect. It should be kept in mind, that during these first trials the weather was not challenging and in more demanding conditions the power consumption may vary. It was noted that the wind sensors installed on the aft mast were not functioning correctly, due to the air flow from rotor and they needed to be re-installed. New place was on top of the bridge house, where the distractions were minimal.

Also the rotor inner sensors for vibrations were too sensitive, causing the rotor stop, when bow thrusters were used. This happens mainly when leaving or arriving on port. Most likely also anchoring will cause such vibrations. It is important that the rotor vibrations do not exceed limits that would refer in some problems inside the rotor, broken wheel, bearings etc. In order to prevent further damage to the rotor in such a case, it is imperative that the safety stop limits are suitable.

However, the ship movement is individual for each ship and thus far the sensors will need adjustment accordingly. It seems, though, that rolling or other seagoing movement were not exceeding the original limits.

M/S Estraden has a large metacentric height (GM) (22), that is the distance between centre of gravity (G) and the initial metacentre (M). When the GM value is high, the ship is sensitive for lateral movements such as wind or swell and thus easily rolling. In the discussion with the crew it was pointed out, that maybe the ships movement was slightly less vigorous after the installation of the rotor. Intuitively this could be a real observation as the rotor must create a gyrostatic anti-rolling effect of some magnitude.

5

Conclusions

The whole process has been a perfect example of the potential of present Finnish maritime industry via collaboration of manufacturers, shipowners, research centres and educational institutes. This kind of collaboration is called a triple helix model and considered to be essential to the competitiveness of Finnish maritime industry in the future (23).

Advances in material technology, software development and automation technology have made this new generation Flettner -rotor more light weighted, efficient and easier to use than its predecessors. Installation time proved to be short and there is potential to even quicker installation with small changes. In the future, all preparative work can be done during normal docking, building the base structures and arranging cables. The placing of sensors may need further consideration depending of the ship. Also ships characteristics need to be measured ship by ship.

It is expected that the environmental regulations will tighten in the future and the bunker costs will remain the main operating cost. The use of Flettner -rotors is a worthy option for reducing the emissions and gain savings. Based on these preliminary results, savings up to 8% per rotor can be expected.

Further studies are needed of the anti-rolling effect produced by the rotors. At the moment flume tanks, or anti-rolling tanks, are installed on many ships. They are heavy and large constructions with the purpose of reducing ship's rolling. It would be a huge advantage, if the same effect could be achieved with the rotors, together with the other mentioned benefits.

References

[1] L. Prandtl, Technical Memorandums National Advisory Committee for Aeronautics **367**, 1 (1925). 3, 4, 14

[2] J. Seifert, Prog. Aerosp. Sci. **55**, 17 (2012). 4, 9, 12, 13

[3] L. Bergeson and C. K. Greenwald, J. Wind Eng. Ind. Aerod. **19**, 45 (1985). 4, 5, 12, 13, 16

[4] B. R. Clayton, J. Wind Eng. Ind. Aerod. **19**, 251 (1985). 4, 14

[5] J. F. Wellicome, J. Wind Eng. Ind. Aerod. **20**, 111 (1985). 4, 10, 13

[6] C. T. Nance, J. Wind Eng. Ind. Aerod. **19**, 1 (1985). 4

[7] J. Vergara, C. McKesson and M. Walczak, Energ. Policy **49**, 333 (2012). 5

[8] P. Gilbert, Mar. Policy **43**, 376 (2014). 5, 8

[9] *Future Ship Powering Options - Exploring Alternative methods for ship propulsion*, edited by J. Parker (Royal Academy of Engineering, 2013). 5

[10] P. Crist, *Greenhouse Gas Emissions Reduction Potential from International Shipping* (Joint Transport Research Centre of the OECD and the International Transport Forum, 2009), No. 2009 - 11. 5

[11] T. Craft, N. Johnson and B. Launder, Flow Turbul. Combust. **92**, 413 (2014). 5, 14

[12] M. Traut *et al.*, Appl. Energ. **113**, 362 (2014). 5, 11, 17

[13] J. Knif, in *Flettner rotors used as auxiliary propulsion for ships* (Helsinki University of Technology, Master thesis, 2009), p. 56. 5, 14

[14] Resolution A.982(24), *Revised guidelines for the identification and designation of particularly sensitive sea areas*, Intenational Maritime Organization, 2006. 6

[15] Annex 24, Resolution MEPC.136(53), *Designation of the Baltic Sea area as a particularly sensitive sea area*, International Maritime Organization, 2005. 6

[16] ANNEX 13, Resolution MEPC.176(58), *Amendments to the ANNEX of the protocol of 1997 to amend the international convention for the prevention of pollution from ships, 1973, as modified by protocol of 1978 relating thereto*, International Maritime Organization, 2008. 6

[17] V. Eyring *et al.*, Atmos. Environ. **44**, 4735 (2010). 7, 8

[18] J. Kalli, T. Karvonen and T. Makkonen, *Sulphur content in ships bunker fuel in 2015 A study on the impacts of the new IMO regulations and transportation costs* (Publications of Ministry of Transport and Communications, Finland, 2009), No. 31/2009. 7

[19] O. Schinas and C. Stefanakos, Transport Res. C **25**, 81 (2012). 8

[20] J. Forrest and I. Owen, Comput. Fluids **39**, 656 (2010). 18

[21] K. Henderson, *Wind Engine*, Maritime Propulsion, August, 2010. 19

[22] M. Rhodes, in *Ship Stability OOW* (Witherby Seamanship International, 2012), pp. 96–104. 29

[23] A. Keltaniemi *et al.*, *The challenges and best practices of structural change in the European maritime industry* (MariTime Hubs, 2013). 30