INT-NAM 2023

4th International Naval Architecture and Maritime Symposium

PROCEEDINGS

Editors:

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11-13 October 2023

Yıldız Technical University, Istanbul, Turkiye

4th International Naval Architecture and Maritime Symposium

11-13 October 2023, Istanbul, Turkiye

INT-NAM 2023

E-ISBN: 978-975-461-615-6

http://www.int-nam.yildiz.edu.tr

https://www.youtube.com/@intnam/streams

Design: A. D. *Alkan*

Cover Graphic: F. *Can*

Printing & Volume:
YTU GIDF & 1

Publising Date:
23 December 2023

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A brief history of the Flettner ship, an archetype of sustainable marine propulsion design

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Abstract
The Magnus effect, discovered by Heinrich Gustav Magnus (1802 - 1870) in 1852, is a physical phenomenon responsible for the variation of the trajectory of a rotating body in a moving fluid due to lift, the force generated on the cylinder, creating a difference in side-to-side air pressure. This physical phenomenon was investigated by Martin Kutta (1867 – 1944) and Nikolay Yegorovich Zhukovsky (1847 – 1921). The first scholar who dealt with putting the Magnus effect into practice was the German inventor and aeronautical engineer Anton Flettner (1885 - 1961), who studied a rotor inserted on a ship - which he then took on the name of "Flettner ship" - specially designed to use the Magnus effect for propulsion. The economic crisis which swept the world at the end of the First World War, and which inevitably followed the maritime boom which took place in 1914-18 was the cause of many changes which occurred in naval construction, changes dictated by the need to improve and at the same time improve the maritime transport making it more efficient and cheaper. The German engineer Anton Flettner, assisted by Albert Betz (1885 – 1968), Jakob Ackeret (1898 – 1981), Ludwig Prandtl (1875 – 1953) and Albert Einstein (1879 – 1955), began his experiments around the 1920s XX century and built an experimental rotor with the idea of reviving naval propulsion by the action of the wind. Climate change, which today has become a topic of great interest, requires greater efforts to direct scientific and technological research towards new proposals that can reduce the phenomenon of environmental and above all maritime pollution. In this brief note we want to retrace the history of an innovative idea that is still current today and which sees a renewed attention towards a marine propulsion system that is very topical today.

Keywords: Flettner, Magnus effect, Rotor ship

1. Introduction
Nowadays, the shipping industry is the main global means of transporting goods. Ships used for this purpose have evolved and specialized over time with enormous improvements in terms of efficiency.

The ever-increasing sensitivity towards the environment has led the future evolution of global cargo shipping to focus on increasingly ecological sea transport. For this reason, new solutions are being tested to reduce emissions during transport. Among the green technologies currently being developed and disseminated, there is that of rotor sails. The insertion of rotors on ships, exploiting the so-called "Magnus effect", allows to accelerate the speed of the unit without consuming further carburets. This translates into a reduction in emissions at the same speed. The interest in this technology can be denoted by the recent influx of money and energy introduced by large entities from all over the world for the development and installation of rotors on board. In the current year, Norsepower, a Finnish company founded in 2012 and one of the leaders in this sector, signed an agreement with Mitsui O.S.K. Lines (MOL) of Tokyo and Vale International SA (VALE) of Rio de Janeiro for the insertion of two rotors on a 200,000-ton class bulk carrier.[1] Later, Norsepower received a funding of 28 million Euros to increase the production of its system. Sponsors come from all over the world, and include major energy giants involved in the green transaction such as the Oil and Gas Climate Initiative (OGCI), an organization made up of 12 of the world's leading energy companies, which produce about a third of global oil and gas.[2] The English company Anemoi Marine Technologies, which has been interested in the development of rotors since 2008, obtained a commission in 2022 from COSCO Shipping Heavy Industry, one of the Chinese shipbuilding giants.[3]

Not only have there been many orders for the rotor sail plant, but since 2022, the growing interest has also led many companies to launch into this business, trying to design and produce their own rotor sails. In 2022, Hyundai Heavy Industries Co. was the first Korean shipyard to design its own propulsion system that uses rotor technology called Hi-Rotor,[4] and in the same year, Chinese high-tech composite products company Zhongfu Lianzhong produced its first rotor sail.[5]

All this demonstrates the global interest in this innovative technology. However, while rotor sails present themselves as an interesting solution to modern problems, they are by no means an invention of our century. On the contrary, the history of this auxiliary propulsion system originates at the beginning of the past century, when the engineer Anton Flettner devoted himself to the study of the Magnus effect.

2. The Magnus effect and the Flettner rotor

The so-called Magnus effect was discovered by Heinrich Gustav Magnus (1802 – 1870) in 1852. It is a physical phenomenon responsible for the variation of the trajectory of a rotating body in a moving fluid

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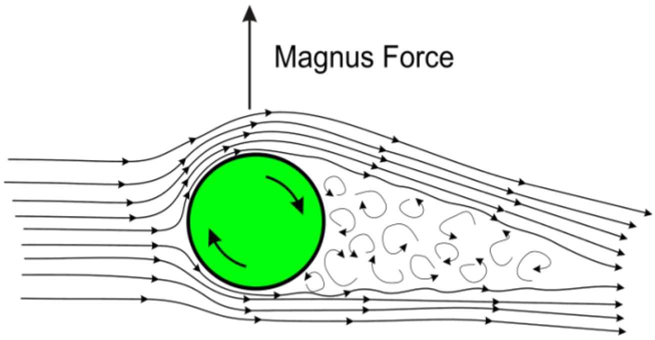
[1] "MOL and VALE agree to install Two Norsepower Rotor SailsTM to an in-service Capesize Bulk Carrier" in *Mitsui O.S.K. Lines*, March 08, 2023.
[2] "Norsepower raises € 28m to scale up rotor sails production" in *ShipTechnology*, March 29, 2023.
[3] Sam Chambers, "British rotor sail manufacturer ties with COSCO's shipyard division" in *Splash247*, October 5, 2022.
[4] "HHI Designs In-House Rotor Sail Wind Propulsion System" in *Ship&Bunker*, August 30, 2022.
[5] "China's Zhongfu Lianzhong has manufactured the first domestic marine rotor sail" in *JEC*, June 17, 2022.

as a result of a difference in air pressure from one side of the object. This difference in air pressure was previously discovered and investigated by Martin Kutta (1867 – 1944) and Nikolay Yegorovich Zhukovsky (1847 – 1921). A rotating body (a cylinder in the case of naval applications) immersed in a fluid drags the layer of fluid immediately in contact with it. The latter, in turn, drags the adjacent layer with it; layers of fluid rotating on concentric circles are thus formed around the rotating body. If the body has a rectilinear translation motion it is as if it were hit by a current of fluid that moves in the opposite direction to that of the body. If the motion is purely linear in translation, the current lines will be equally spaced around the body.



The Magnus effect uses wind energy to produce lateral thrust, thanks to a rotating cylinder that generates lift, similar to an airplane wing.

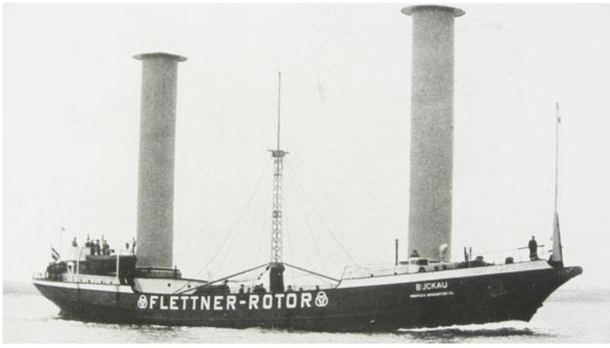
If the body has both rotational and translational motion, the speed of the fluid increases above or below the body according to the direction of rotation of the body, precisely due to the dragging of the fluid around the body itself. Indeed, the speed of the layers of fluid in rotation amplify the motion of the current, due to the translation in a concordant direction, and decrease the speed in the area where the verses are discordant. For this phenomenon, the rotating cylinder pushes the air flow upwards, and the air pushes the cylinder downwards, according to Newton's third law. This push is known as the Magnus force after its discoverer. In summary, as an example, it can be observed that:

- if a vertical cylinder rotates clockwise,
- if the action of the fluid acts from the west,

then, the Magnus force pushes the cylinder north.

In the case of a ship, this lateral force is resisted by the hull and a component of this force can be used to propel the vessel forward, provided the vessel's heading is generally within the low-pressure zone.
The first scholar who took care of implementing the Magnus effect was the German inventor and aeronautical engineer Anton Flettner (1885 – 1961). He studied a rotating cylinder called rotor fitted

to a ship specially designed to use the Magnus effect for propulsion; this ship took the name of "Flettner ship".[6]



On the left: Heinrich Gustav Magnus [picture by Rudolf Hoffmann (1820 –1882), Eigenes Foto einer Originallithographie der ÖNB (Wien); in the center The *Buckau* (also known as *Flettner Rotor Ship*) during the crossing of the Atlantic in November 1924. The ship was equipped with two cylinders capable of using the wind to propel the vessel, each of which was 18.5 meters high and 2.8 meters in diameter [Deutsches Bundesarchiv]; on the right: Anton Flettner [George Grantham Bain Collection, Library of Congress, Washington, DC].

A Magnus rotor used to propel a ship is called "rotor sail" and is mounted with its axis vertical on the ship's deck. Rotating around its vertical axis, it creates a pressure difference between the windward part of the rotor and the rear of the rotor, generating lift that pushes the ship. When the wind blows sideways, the Magnus Effect creates forward thrust. A peculiarity that can occur in smaller ships, for example racing boats, lies in the fact that if the vessel turns and changes direction so that the wind comes from the other side, the direction of rotation of the rotor must be reversed or the vessel would be pushed backwards.

Propulsion	$V_m(V)$	$V_m(S)$	$R_m(C)$
	Knots	Knots	%
M+R	16,1	7,0	44
M+R	12,9	6,0	27
R	17,7	5,3	100

$V_m(V)$ = average speed, $V_m(S)$ = average ship speed, $R_m(C)$ = average fuel economy, M+R = engine propulsion assisted by the Flettner rotor, R = propulsion guaranteed only by the Flettner rotor.[7]

[6] Chanson, Hubert. *Applied Hydrodynamics: An Introduction*. London: CRC Press, 2013, pp. 100-102; Seifert, Jost. A review of the Magnus effect in aeronautics. Progress in Aerospace Sciences, Volume 55, November 2012, pp. 17-45.
[7] Gilmore, *op. cit.,* p. 73.

The most common form of rotor sail is the so-called Flettner Rotor, clearly named after its inventor.[8] This system saves fuel for motor-propelled ships, and in some cases can even be the sole propulsion of the vessel. In this case, likewise any sailing vessel, a rotor vessel powered by Flettner rotors alone can only move forward when the wind is blowing.

The wind does not power the rotor itself, which must have its own power source anyway. Like many mixed-propulsion vessels, rotor vessels are often fitted with a conventional small propeller. This is to ensure a minimum of manoeuvrability and propulsion at low speeds, when the wind is not blowing or the rotor is stopped. Thus, in a hybrid rotor vessel, the propeller is the primary source of propulsion and the rotor, by contributing to propulsion, increases overall fuel economy. Rotor sails have been found to generate fuel savings that can range from 5% to 20%.

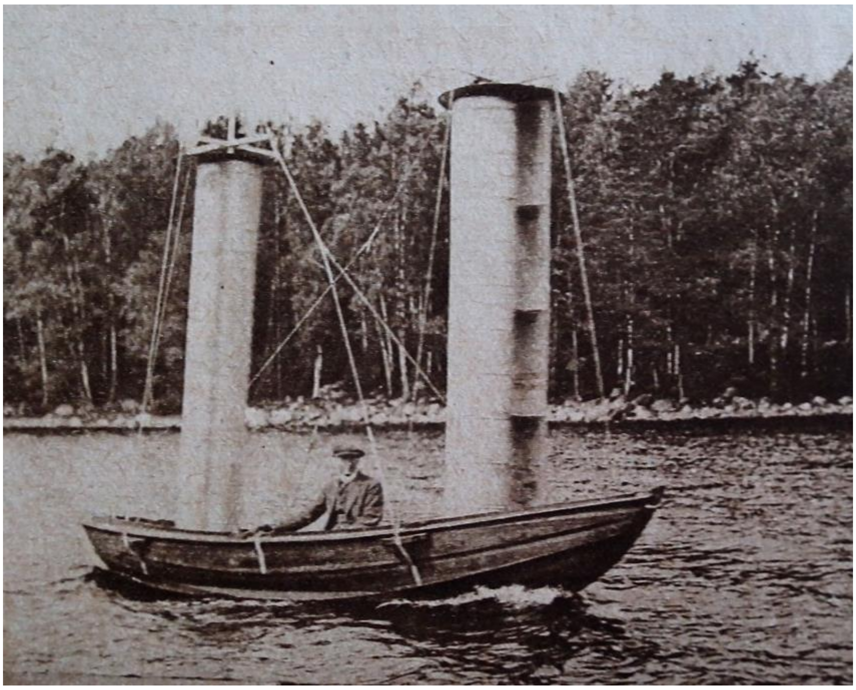
The same phenomenon is also used in a special type of naval stabilizer consisting of a rotating cylinder mounted below the waterline and emerging laterally. By controlling the direction and speed of rotation, strong lift or down force can be generated. The largest system to date is that of the motor yacht *Eclipse*. The yacht, built by Blohm+Voss of Hamburg, adopts a lateral stabilization system to counteract movement at anchor and at low speeds, based on the Magnus effect thanks to a rotor.

The worldwide economic crisis at the end of the First World War which inevitably followed the maritime boom in 1914-18, was the cause of many changes which took place in shipbuilding. These changes were dictated by the need to improve maritime transport making it more efficient and cheaper. Many ingenious inventions were developed; but many of these were not tested while others, after a promising start, were forgotten and went into oblivion once the fervour of novelty disappeared. The principle that the ship should be the main economic means prompted ship owners and designers to look for innovative solutions. Germany, particularly affected by the collapse of its merchant shipping, had the greatest need for cheap ships. And since it possessed well-known scientists and inventors, it was among the nations that most developed new technologies.

Often in the history of navigation, the disastrous effects of a crisis have been overcome only by introducing drastic technical improvements, such as the propulsive propeller replacing the paddle wheel, the composite engine, the triple expansion engine and other systems to economize fuel consumption. Many of these inventions were the result of experience gained in warfare, and men knew how to adapt both material and knowledge to purposes very different from those for which they were originally intended. This is the case of the origins of Flettner's rotors. Indeed, the principle he used for his rotors

[8] Gilmore, C.P. Spin Sail: harnesses mysterious Magnus Effect for Ship Propulsion, *Popular Science*, Vol. 224, n. 1 (January 1984), pp. 70-73.

was originally developed to study the motion of an artillery shell in the air, and was later developed to evaluate the force of the wind on the wings of airplanes which tends to rise at right angles to its direction. Flettner, assisted by Albert Betz (1885 – 1968), Jakob Ackeret (1898 – 1981), Ludwig Prandtl (1875 – 1953), and Albert Einstein (1879 – 1955), began his experiments around the 1920s of the twentieth century and built an experimental rotor with the idea of reviving naval propulsion by the action of the wind. Actually, Flettner had imagined using metal sails, much smaller and more manageable than ordinary canvas ones, and carefully balanced and shaped, to take advantage of the action of the wind. The ship with this curious propulsion system was presented to the public in 1924.[9] It immediately captured the attention of the popular imagination, perhaps because the tall rotor towers were something clearly visible, as were the paddle wheels that have always found their enthusiastic admirers.
His studies can be traced back to the experiences made on rotating cylinders at the adynamic research institute Aerodynamische Versuchsanstalt in Göttingen. Thanks to these studies, Flettner designed his rotor that exploited the Magnus effect, and developed the first rotor ship, built in 1925, the so-called *Dreiflächenruder*.
His first studies in the naval field were conducted in 1923 together with the Finnish Sigurd Johannes Savonius (1884 - 1931) introducing the so-called Savonius wind turbine.[10]

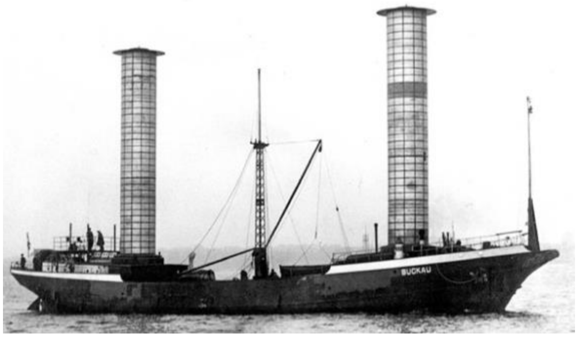


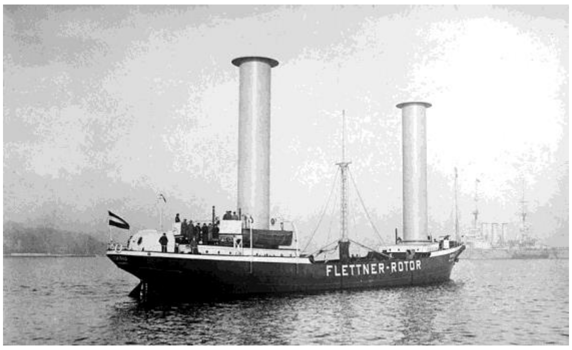
The Finnish engineer S.J. Savonius aboard his rotor sailboat (1925). Savonius' boat does not use a Flettner rotor, as these were not simple cylinders, but a sort of Savonius rotor.

[9] The German patent is from 1923, the US one from 1928: Flettner A., *Verfahren zur Erzeugung des Quertriebes an Quertriebskorpern, Patentschrift: z. B. An Segeln von Schiffen*, DE420840 (1923); Flettner A., *Arrangement for exchanging energy between a current and a body therein*, U.S. Patent N. 1,674,169 (1928).
[10] Savonius, Sugurd J. *The Wing-rotor in Theory and Practice*. Helsingfors: Savonius & Co., [s.d.].

3. The first Flettner rotor ship: the *Buckau*

The first example of rotors was built in 1924-1926 and placed in a 455t schooner built in 1920. This ship was called *Buckau*[11] and was 164 feet (c. 50 m) long, 39 feet (11.89 m) wide and with a draft of 13 feet (3.96 m).[12]

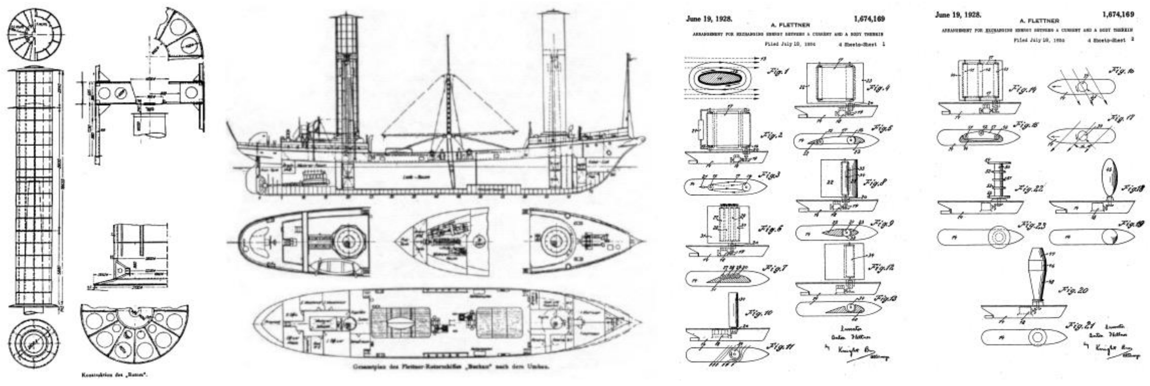




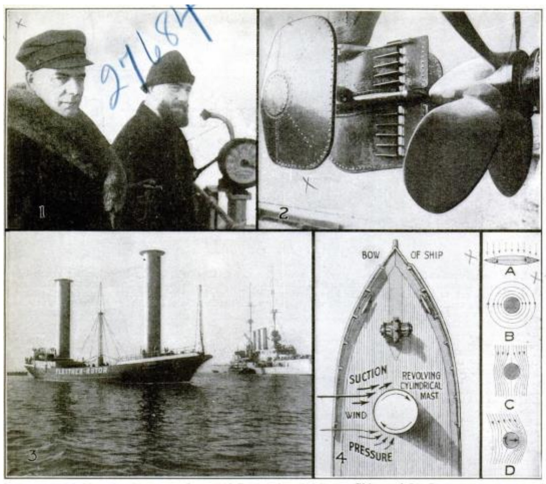
On the left: the *Buckau* with the rotors just installed [Deutsches Schiffahrtsmuseum]; on the right: The *Buckau* in 1924.

She was refitted in October 1924 at Germaniawerft (the Friedrich Krupp Germaniawerft), a German shipbuilding firm, based in the port of Kiel, and one of the largest and most important U-boat builders for the Kaiserliche Marine in the World War I and for the Kriegsmarine in World War II. The two cylinders (or rotors) placed on the ship were about 51 feet 2 inches (15.60 m) high and 9 feet 2 inches (2.79 meters) in diameter; they were made of 3.65 inches (9 cm) thick sheet steel, with a usable area of 88 m^2 and were powered by an electric propulsion system of 40 hp (37 kW) of power.[13] The outer surface of the rotors was made of 1.0 to 1.5 mm thick galvanized sheet steel and reinforced with angles in the transverse direction and profiles in the longitudinal direction. The rotors were turned at a speed of 140 rpm by a small motor with an output of c. 45 hp, while the propulsive propeller was driven by a normal motor engine of c. 217 hp. Rotor towers were a replacement for the sail. Their purpose was to take advantage of the wind as an auxiliary to the engines and to allow for greater speed with the same power and economy. Flettner's consideration was that the rotor towers were more efficient than the normal canvas sail and that they would get more out of the wind and be able to take full advantage of it regardless of its direction.

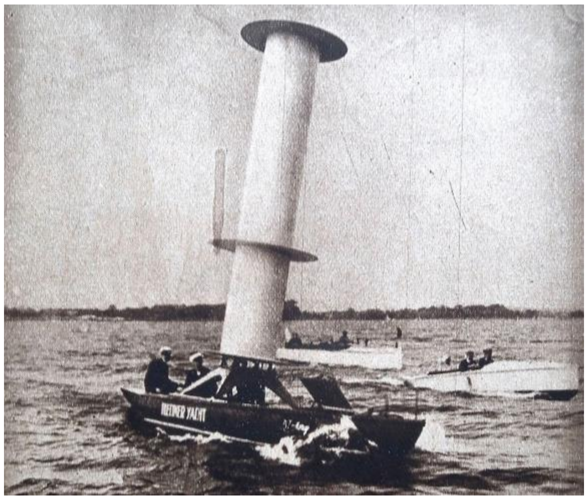
[11] Seufert, Wolf & Seufert, Ulrich. Critics in a spin over Flettner's Ships, in *New Scientist*, 10 March 1983, pp. 656-659.
[12] Dati raccolti da: Borg, John. *Magnus effect. An overview of its past and future practical applications*. Volume I. Washington, DC: Naval Sea System Command Department of the Navy, [S.d.], p. 7.
[13] Other unverified sources mention that the rotors were driven by two 7.5 kW or 11 kW DC motors, driven by a 33 kW diesel engine with a maximum rotational speed of 125 rpm.



On the left: rotors of the *Buckau*; in the center: the *Buckau*, plans for the design. The design of the *Buckau* required a new classification of the vessel by Germanischer Lloyd, as it was not yet entirely clear whether she should continue to be classified as a sailing vessel or as a motor vessel with additional wind propulsion; on the right: Flettner patent filed in the United States: patent no. 1.674.169 of June 19, 1928 in which different and distinct solutions are seen for exploiting the action of the wind combined with the rotation of the rotors to increase the propulsive thrust of the vessel.



A New Application of an Old Principle—the Rotor Ship and Its Inventor



On the left: the ship designed by Flettner aroused great interest in the specialist press, see: Seybold, G.B. A Sailing Ship without Sails; New Wonder of the Seas, in *Popular Science Monthly*, February 1925, p. 36; on the right: Flettner rotor boat 6 meters long and 1 meter diameter, on the Wannsee in Potsdam in 1925.

The thin steel towers were quite light despite their bulky appearance and posed no problems for the ship's stability. Taking advantage of the Magnus effect, these rotors were rotated clockwise or counter clockwise, depending on the direction of the wind. Flettner pointed out a ship could not sail on rotors alone but would still need an engine and a propulsive propeller; the rotors alone could only be used on small boats, yachts and pleasure boats. The trials carried out in the Baltic Sea in October 1924 "exceeded all expectations", according to the chronicles of the time.[14] The advantage of the rotors was undisputed: simpler to handle than the sails and fewer people involved in their operation. Furthermore, sea trials

[14] Wharton, James B. Rotor-Ship's stormy voyage from Danzig to Kiel Canal, *The Manchester Guardian*, February 9, 1925, p. 9.

showed that with wind speeds up to 7 m/s the results obtained were equivalent to those of sail propulsion, while with wind speeds greater than 7 m/s the sailboat proved to be inferior to the rotor. Indeed, when the wind speed exceeded 7 m/s, a sailing boat had to remove or reef the sails, while the rotor boat was not affected by the effects of gusts which were not dangerous for navigation. Moreover, tests carried out with a tailwind showed that the wind pressure could be exploited to the fullest by achieving high speeds. The *Buckau* sailed from Danzig to the Firth of Forth in Scotland via the North Sea in February 1925.[15] The ship could sail against the wind with an inclination varying from 20 to 30 degrees,[16] factor that gave no cause for concern in the event of a storm. The ship gave extraordinarily good results. She was absolutely reliable and seaworthy.

She was later renamed *Baden-Baden* (Flettner called her the “Kamin Sailing Boat”) and set sail on 31 March 1926 with a crew of 15 under the command of Captain Peter Callsen, a veteran of 14 sailing voyages. Rounded Cape Horn to New York via South America, arriving in New York Harbor on May 9 of the same year cruising the Hudson at a speed of 8½ knots.[17] She used only 12 tons of fuel oil, nothing compared to 45 tons for a motor vessel of the same size without rotors.[18] Upon her arrival in the United States she was judged curiously: she looked like a maritime carousel, a schooner with chimneys, one of the strangest ships that ever sailed the seas. Her rotors were judged to be “a pair of silos rotating fore and aft”.

Despite the success of the crossing, the prototype was not without criticism. Some sources claim that the vessel had proved inefficient on these voyages, and that the power consumed by the rotation of the 15m high rotors was disproportionate to the propulsive effect of conventional propellers.[19]

After the great depression, the rotors were taken away and the *Baden-Baden* converted to a schooner under the Panamanian flag. Then she entered in the Costa Rican registry as *Rio Mozara*. The name *Baden-Baden* was returned to her in 1931, and in November of the same year she was abandoned at sea while on her way from Colombia to Panama. Taking on water, the old ship sank bearing the name that had made her famous in her short career as one of the strangest ships that ever sailed the seas.

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[15] Tokaty, G.A. *A History and Philosophy of Fluid Mechanics*. New York: Dover Publications Inc., 1971, pp. 152-154.

[16] Seufert, Wolf & Seufert, Ulrich. Critics in a spin over Flettner’s Ships, *New Scientist*, 10 March 1983, Volume 97, n. 1348, pp. 656-659.

[17] Bunker, John. The Ship That Sailed Without Sails. *Proceedings*. United States Naval Institute, Vol. 96, N. 4, April 1970.

[18] Nuttall, Peter & John Kaitu’u. The Magnus Effect and the Flettner Rotor: Potential Application for Future Oceanic Shipping. *The Journal of Pacific Studies*, Volume 3, Issue 2, 2016, pp. 161-182.

[19] Ray, Keith. *The Strangest Aircraft of All Time*. Stroud, Gloucestershire: The History Press, 2013, p. 48.

The *Baden-Baden* arriving in New York from Hamburg in 1926.

Nevertheless, the *Buckau* found other admirers who found the vessel's performance impressive in bulk cargo service across the North Atlantic and Baltic Seas.[20] The German Admiralty itself had taken an interest in this propulsion system, not with the idea of attaching huge rotor towers to the decks of warships, which would obviously have been absurd, but by looking for alternative ways. The successes of this voyage led to the development of a new rotor vessel, the *Barbara*, operated by Sloman Line of Hamburg.

4. The second Flettner rotor ship: the *Barbara*

The *Barbara* was built by the AG Weser shipyard in Bremen, a German shipbuilding industry based in Bremen and the shipyard was located on the River Weser. She was completed on the 26 of July 1926.[21] The *Barbara* had three rotors made of "Lauta" metal, an aluminum alloy; they were 56 feet 1 inch (17.09 m) high and 13 feet 2 inches (4.01 m) in diameter. They produced an additional power of about 440-450 kW with a wind speed of c. 11-14m/s. The total area of these rotors was 2,196 square feet. They

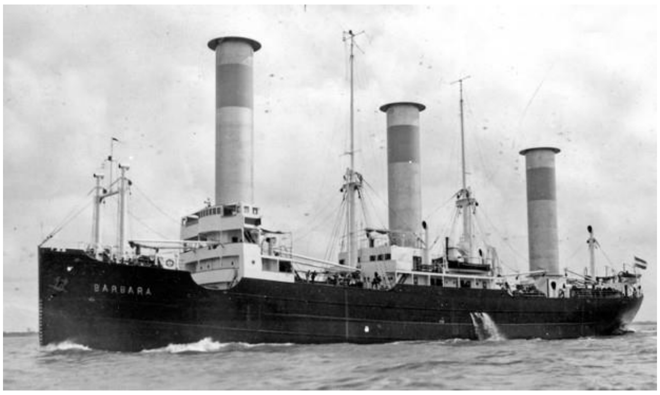
[20] Seufert, Wolf & Seufert, Ulrich, *op. cit.*, p. 658.
[21] Walker, Fred M. *Ships and Shipbuilders: Pioneers of Design and Construction*. Seaforth Publishing, 2010, pp. 220-221.

were powered by electric gear motors and the speed was easily controlled from the deck; the maximum speed was 160 rpm. The ship had a tonnage of 2,077 tons and was powered by two four-stroke six-cylinder diesel engines coupled to a single shaft; to this was connected the propulsive propeller which had a power of 1,060 hp for a speed of ten knots. In the first sea trials *Barbara* reached a speed of 6 knots with only the rotors and with a favourable wind, 9 knots with only the engines, and 10 and a half knots with engines and rotors together. After some experience with the setting, they were able to easily get her to a speed of 13 knots with both propulsion systems engaged. It was calculated that this speed was achieved thanks to an extra three knots added by the rotors, having an engine of 60 hp which it would have done the job of a 530 horsepower had it been inserted into the driveshaft. The *Barbara* was immediately placed in the transport of fruit from the Mediterranean. She sailed there from 1926 to 1929 and proved as reliable as an ordinary cargo ship. The rotors were used to full advantage about twenty-five per cent of the time at sea, and when the wind was right they increased speed by about 2.5 to 3 knots. This increase was achieved with about ten percent of the power that would have been required to do the same with traditional propulsion. The disadvantages of this propulsion system were linked to the onset of gyroscopic forces, which in turn generated annoying centrifugal forces and produced vibrations. These forces created problems for the ship's robustness. Moreover, it was not possible to start quickly and quickly change the direction of rotation of the rotor.

By 1928, Flettner had secured orders for six new *Barbara*-class ships. Nevertheless, the decrease in the price of diesel fuel for naval applications associated with an increasingly performing engine technology in terms of reduced consumption meant that any savings obtained from the rotor were too modest for the shipping companies to consider the investment necessary for the construction of this type of vessel in consideration of the long period of depreciation of expenses.[22]

In 1933 the *Barbara* was sold to the Bugsier-Reederei-und Bergungs AG Line in Hamburg, was stripped of her rotors and renamed *Birkenau*, then used as a normal motor vessel. Subsequently, she was ceded to Denmark and operated until 1963 as *Else Skou*, and later served in the Mediterranean as a Greek vessel called *Fotis P*. Finally, under the flag of Saudi Arabia, sailed for the Greek Libyan Lines as *Star of Riyadh* and sank in 1978 off the coast of Jeddah.

[22] Nuttall, Peter & John Kaitu'u. The Magnus Effect and the Flettner Rotor: Potential Application for Future Oceanic Shipping. *The Journal of Pacific Studies*, Volume 3, Issue 2, 2016, pp. 161-182.



On the left: *Barbara* [Deutsches Technik Museum, Berlin]. The vessel was 300 feet (91.49 m) long, 43 feet (13.16 m) wide, and c. 27 feet (8.28 m) and had a tonnage of c. 3,000 tons. Propulsion was entrusted to two 1,060 hp diesel engines;[23] on the right: The *Barbara* in the port of Barcelona in 1926. The photograph was taken with the vessel anchored at the Indústria shipyard, in Moll Nou. The perspective shows us the starboard side of the ship. During the maiden voyage directed to the Mediterranean, the *Barbara* touched the ports of Santander, Bilbao, Malaga, and Barcelona arousing great interest and showing that a merchant ship could navigate normally with this means of propulsion and be profitable [Deutsches Schifffahrtsmuseum].

5. New Flettner's rotor ship solution

Flettner's solution found, at the time, two admirers in the United States. They were Marine Lieutenants Joseph M.K. Kiernan and W.W. Hastings, naval architecture students at the Massachusetts Institute of Technology. They decided to set up a boat with this propulsion system and bought an abandoned US Navy boat, which was about 30 feet (9.14 m) long and eight feet (2.44 m) wide. Using the materials recovered from other abandoned boats they repaired the engine.

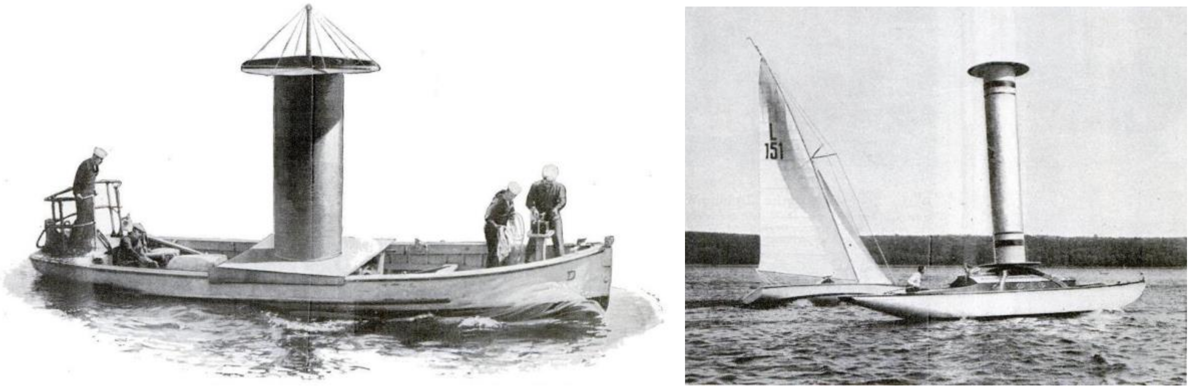
In designing the rotor, they used the data collected through experiments carried out on the airfield of Langley Field, in Virginia, where the United States Army had been studying the application of the Magnus effect for some time in order to evaluate the air pressure on aircraft. Using Flettner's ideas, but with some technical modifications, the American boat was equipped with only one rotor because they were convinced that two rotors interfered with each other.

Flettner himself, having reached this conclusion, experimented with a single rotor system on a modest motor yacht in competition with sailing yachts. On the Flettner's rotor, at the top of each of the cylinders, there was a 14-inch (36 cm) projecting edge for the purpose of keeping the suction and pressure zones which extend along opposite sides of the cylinder separate and thus preventing the air to enter these areas from above and disturb the rotor.

The rotor designed by Hastings and Kiernan was 3.5 feet (1.07 m) in diameter and 9.5 feet (2.90 m) tall. The rotor was mounted amidships on a ball bearing base and was supported by an internal structure. The movement was powered by a five-horsepower motor located at its base. In the first trial on the Charles River, her estimated speed was about three knots, with the rotor spinning at 360 revolutions per minute

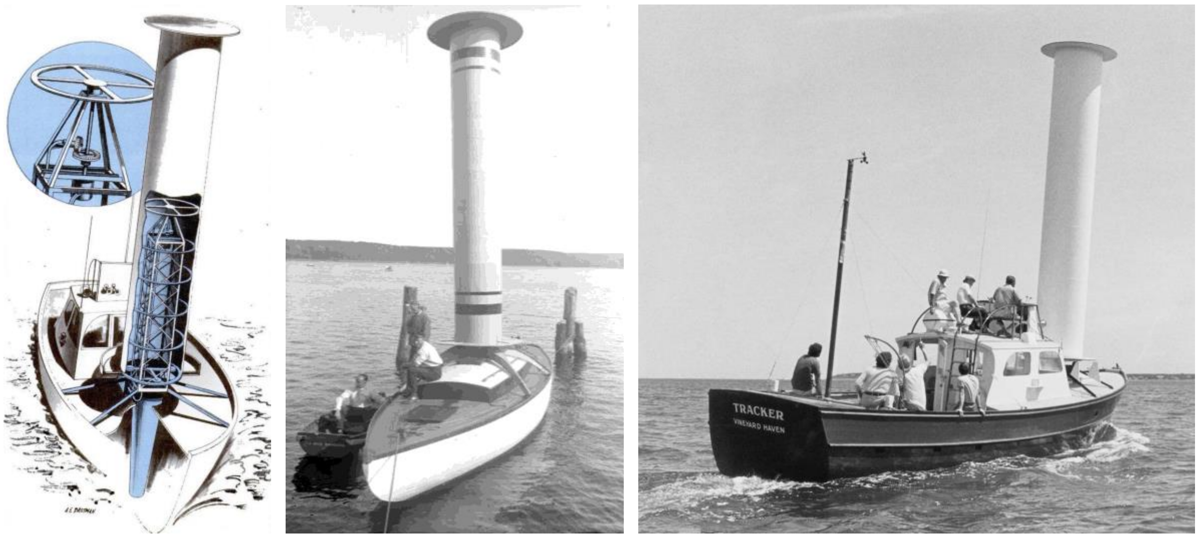
[23] Data collected by Borg, John. *Magnus effect. An overview of its past and future practical applications*. Volume I. Washington, DC: Naval Sea System Command Department of the Navy, [n.d.], p. 10.

and a 15-mile wind. The experiences in the water made the designers believe that their boat would reach a speed of seven knots, with the help of a 10 hp motor apparatus to push the propulsive propeller.[24] Thus, Flettner's invention lost interest because the wind energy gain was not sufficient to compensate for the energy required to operate the rotating cylinder, so the propulsion system became uneconomical.



On the left: the boat designed by Kiernan and Hastings[25]; on the right: image of the competition between Flettner's rotor boat and a sailing boat, staged in Potsdam, near Berlin, in 1925 which saw the sailing boat prevail.[26]

In the early 1970s Thomas F. Hanson, a West Coast engineer who had worked on helicopter design, turned his attention to wind turbines with the Flettner system and built a small boat, the rotor-propelled *Tracker*.



On the left: *Tacker* from Gilmore, *op. cit.,* p. 72; in the center: Wannsee Lake, motor yacht with Flettner rotor [picture by Giorgio Pahl (1900 – 1963), Bundesarchiv], on the right: The *Tracker* during sea trials, from *National Fisherman*, October 1983, p. 25. Length 42 feet, displacement 8 tons, rotor 23 feet 9 inches high with a diameter of 3 feet 9 inches, cylinder rotation occurred at 600 rpm.[27]

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[24] Anon. America's First Rotor Boat, *Popular Science Monthly*, Vol. 107, No. 3, September 1925, p. 27; Tokaty, G.A. *A History and Philosophy of Fluid Mechanics*. New York: Dover Publications Inc., 2013, pp. 150-154.
[25] Anon. America's First Rotor Boat, *Popular Science Monthly*, Vol. 107, No. 3, September 1925, p. 27.
[26] *Idem*.
[27] Borg, John. *Magnus effect. An overview of its past and future practical applications*. Volume I. Washington, DC: Naval Sea System Command Department of the Navy, [n.d.], p. 15.

The *Tracker* had a rotor with a diameter of 42 inches (1.07 m) and 24 feet (7.32 m) high. The engine could reach approximately 600 rpm and was controlled by a hydraulic pump system driven by a small petrol engine. The speed achieved with the rotor alone was c. 6.1 knots with a wind of 18.4 knots at an angle of 122 degrees. In trials, en route from New Orleans to Jamaica, where the winds are generally unfavourable, he managed to achieve a staggering 36% fuel economy while increasing speed by 18%.

Lloyd Bergeson (1917 – 2007), naval architect who participated in Hanson's experiences at sea, was attracted by this idea and built a 43-foot yacht, the *Cockatoo II*. Thanks to this yacht, he became convinced of the potential of this propulsion system to economize on traditional fuels, as ships could use the wind to provide part of their propulsion. Bergeson developed these studies[28] in 1981, he put his studies into practice by building a 3,000-square-foot sail for a 3,100-ton displacement vessel, the *Mini Lace*, a cargo vessel that operated in the Caribbean from New Orleans. He showed that the system used on the Mini Lace held great promise for energy savings in navigation, as did the wing sail, shaped like an airplane wing.
So, we read in a newspaper of the time: « At 11:15 A.M. Monday, the 220-foot general cargo tramp steamer "Mini-Lace" left a wharf in New Bedford, Mass., took a harbour pilot aboard, and headed out into the afternoon south-westerly on Buzzard's Bay. The tough fishermen left behind on the quayside, busy welding their rigs and preparing to take on fuel oil, hardly followed her with their eyes. Ships have come and gone from New Bedford for 300 years. And they go for profit, or they come to scrap. The unglamorous "Mini-Lace" was going for profit too -- but when she got beyond the breakwater, she she did something a merchantman hasn't done there in many generations. She spread a sail to the wind. »[29]

The 6,700-ton tanker *Nura*, built in South Korea in 1982, was fitted with 2 Flettner rotors as an additional propulsion unit at the Blohm+Voss AG shipyard in Hamburg in 1984, thanks to a project funded by the Federal Ministry for Research and the Technology (Bundesministerium für Bildung und Forschung or BMFT). Tests conducted by the research group in the wind tunnel showed that a rotor with the following characteristics was required for a 4,500 t ship: length/rotor diameter respectively 19.5 m/3.8 m. At a ship's speed of 12 knots and a wind angle of 100° (or 260°), the rotors would have absorbed 35% of the engine power; while at a ship's speed of 12 knots, with the same wind angles, the Flettner rotors would propel the ship with their full propulsion power. All this would have allowed annual fuel savings on a route from Europe to Central America equal to about 25% of average consumption.

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[28] Bergeson, Lloyd and C. Kent Greenwald. Sail assist developments 1979-1985, in *Journal of Wind Engineering and Industrial Aerodynamics*, Volume 19, Issues 1–3, July 1985, pp. 45-114.
[29] *The Washington Post*, August 30, 1981.

On the left: the *Transition II* of Reiner Höhndorf [Wismars Amateurfunk]; on the right: rotor catamaran (with Flettner rotor) *Uni-Kat Flensburg* of the University of Flensburg, Germany, at Kiel Week 2007 in the Kiel "Hörn", the southern end of the Kiel Fjord.

Reiner Höhndorf (1927 – 2015), mechanical engineer and visionary, tried to promote the construction of boats with the Flettner rotor to save energy. He equipped a cutter bought in Denmark and made a crossing of the Baltic Sea up to Schwerin thanks to the propulsion of two Flettner rotors. On July 3, 2003, she was called *Transition II* and, according to her designer, she was a boat with which you could "navigate" even in the absence of wind.

In mid-August 2006, physicist Lutz Fiesser (1945 – Unk) of the University of Flensburg tested the Flettner rotor on a boat 6.10 meters long and 4.50 meters wide in the Flensburg Fjord; yesterday was the *Uni-Kat*.

On the left: cargo vessel *Mini Lace*, by: Bergeson, Lloyd and C. Kent Greenwald. Sail assist developments 1979-1985, in *Journal of Wind Engineering and Industrial Aerodynamics*, Volume 19, Issues 1–3, July 1985, p. 50; on the right: Yacht *Alcyone* at La Seyne-sur-Mer on the 25 April 2010, used by Cousteau [picture by Stéphane Saissi (born 1974)]. The yacht is equipped with cylindrical masts and showed excellent results when the angle between the wind direction and the vessel's axis was between 50° and 140°. The characteristics of the Alcyone are length 31.1 metres, max beam 8.92 metres, draft 2.34 metres, displacement at half load calculated with the boat equipped for sailing with crew and half of the consumables (wins, water, fuel, supplies) on board equal to 76.8 t.

The Cousteau Society ship *Alcyone*, built in 1985. The *Alcyone* uses Turbosail technology. A fan draws air into each of its two 10-metre-high cylindrical shafts. This creates forward lift that exceeds that achieved by a normal sail and reduces the vessel's fuel consumption by a third.

Flettner's principle was then taken up decades later by the *Alcyone* used by Jacques-Yves Cousteau (1910 - 1997); in 2006 the catamaran *Uni-Kat Flensburg* was built. Subsequently, Flettner's rotors were fitted to the cargo vessel *E-Ship 1*, launched on the second of August 2008 at the Lindenau shipyard in Kiel.[30] *E-Ship 1* was made for the German wind turbine manufacturer Enercon. She was a 10,500-ton Ro-Ro vessel with a length of 130 meters and used conventional diesel power assisted by four Flettner rotors 25 met high and 4 m in diameter to harness wind energy and reduce fuel costs and emissions. She had a top speed of 17.5 knots. In addition to the rotor sail, E-Ship 1 used two diesel engines that deliver a total power of 3.5 MW. The boilers are connected to a steam turbine which in turn drives the Flettner rotors. The vessel made her maiden voyage in August 2010, carrying nine turbines for Castledockrell Wind Farm from Emden to Dublin, Ireland. After that, *E-Ship 1* travelled 170,000 nautical miles by 2013 and achieved an overall average fuel economy of 25%, 15% of which was directly attributable to the use of the rotors. Today, she regularly ships wind turbines all over the world.[31]

[30] Gerke, Thomas. E-Ship 1 - 21st-Century Sailing, *Cleantechnica*, April 10, 2012.
[31] Bălţăţeanu, Dragoş. The Return of Rotor Sail Ships: E-Ship 1 – Harnessing the Power of Wind, *DriveMag Boats*, March 17, 2017.

On the left: The *E-Ship 1* with Flettner rotors at Emden; on the right: wind turbine transport vessel Enercon departing the Port of Dieppe on 24 September 2016.

M/S *Viking Grace* is the first large-scale passenger ferry to be powered by liquefied natural gas (LNG) as well as being fitted with a rotor sail. The cruise ferry is owned by the Finnish "Viking Line" and went into service on January 13, 2013. The cylindrical rotor sail installed on M/S *Viking Grace* is 24m high and 4m in diameter and is a modernized version of the Flettner Rotor. This rotor uses technology developed by Finnish clean technology and engineering company Norsepower Oy Ltd. The technology is fully automated and senses whenever the wind is strong enough to save fuel, at which point the rotors spin automatically.[32] *Viking Grace* sails on the sea route between Turku (Finland) and Stockholm (Sweden). LNG gives the ferry greater engine efficiency and lower fuel consumption. The new technology, which is a hybrid use of LNG and wind energy, is called the Rotor Sail Solution. It has proven its economic efficiency by allowing fuel savings of up to 20% in favourable wind conditions.

On the left: The M/V *Sea Zhoushan* of Brazilian mining company Vale, in Zhoushan, China on April 29, 2021, with five rotor sails installed along the vessel to allow for better efficiency; on the right: M/S Viking Grace, 57,565 gross tonnage ferry. The rotor is 24m high and 4m in diameter and is a modernized version of the rotor invented by Flettner. The rotor is controlled by a computerized system which detects the wind speed and puts it into operation automatically.

In 2008, the University of Edinburgh rebuilt the *Cloudia*, a Searunner 34 trimaran, to test Flettner/Thom propulsion. The ship is equipped with a 6-meter-high rotor with Thom discs, invented by the Scottish engineer and amateur archaeologist Alexander Thom (1894 – 1985). John Marples (1970 – Unk)'s

[32] Bǎltǎţeanu, Dragoş. The Viking Grace becomes the first cruise ship to use a rotor sail, *DriveMag Boats*, April 12, 2018.

Cloudia tested at Fort Pierce, Florida, with rotor drive power of 600 W, could sail faster than the crosswind, stop, reverse, and yaw 180° in either direction about its axis.

Cloudia of John Marples [Discovery Channel].

6. Conclusion: new trends in rotor ship solution

Subsequent developments of the Flettner rotor system can be seen in recent years.

Tests carried out in 2010 at Auckland University in New Zealand showed that the Flettner rotor system, with the same surface area, gave an 8-10 times power increase compared to traditional wings. And that a ship with a propulsion system of this type in support of the traditional fossil fuel one would have produced significant reductions in consumption.[33] In 2014 and 2015, Norsepower installed a double rotor on the RoRo vessel M/V *Estraden* of the Finnish shipping company Bore. In May 2018, the cargo ship *Fehn Pollux* of Fehn Ship Management GmbH & Co. from Leer in Saxony (Germany), built in 1996, was equipped with an 18-metre long Flettner rotor, of the type EcoFlettner, in the fore part.[34] In 2018, Norsepower modified the Maersk Pelican, a 109,647 tonne, LR2 class tanker,[35] by installing two Norsepower Rotor Sails 30 meters high and 5 meters in diameter with the aim of achieving a 10% savings consume.

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[33] Brown, Nicholas. Powered by the wind. *Insight. The Lloyd's Register Group Magazine*, Issue 1, June 2010, p. 10.

[34] With Flettner's wind power. In: *Hansa International Maritime Journal*, 1. September 2018, Hamburg 2018, pp. 58/59.

[35] Le navi cisterna di tipo LR2 (Long-range 2) hanno una stazza (dwt) di 115.000 tonnellate, e possono offrire grandi vantaggi in termini di quantità di combustibile trasportato e redditività.

The bulk carrier M/V Afros of 36,452 tons, 199 m long and 32 m wide, has installed four mobile rotors and has achieved positive results in one year.

On the left: another vessel fitted with rotors is the 18,205-gross tonne, 162.7m long Ro-Ro *Estraden* which is currently sailing for Bore Ltd. with rotors from Norsepower; on the right: *Maersk Pelican*, from Rotorsegel senken Treibstoffverbrauch auf Maersk Tanker *DVZ*, 25. Oktober 2019.

In 2021, Norsepower installed five tilting rotor sails on an iron ore carrier vessel – VLOC (Very Large Ore Carrier). The newly built vessel was chartered by Vale, a Brazilian mining company. Finally, Scandlines, a Danish ferry company, operates two hybrid ferries with Flettner rotors; these are M/F *Copenhagen* and M/F *Berlin*.

On the left: in the foreground, the M/S *Copenhagen*, which has now been sailing with a rotor for more than a year, while in the background, the M/S *Berlin*, who is having her rotor installed [picture by: Scandline]; on the right: Scandlines hybrid ferry *M/V Copenhagen* [picture by Peter Therkildsen].

Today, research in this particular sector shows a new interest from shipyards, with the aim of contributing to a more sustainable development of naval propulsion. New propulsion systems, new ideas and new instances have, in fact, drawn the attention of scholars and researchers, builders and shipowners towards decidedly innovative and sustainable shipbuilding.

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(e-proceedings: www.int-nam.yildiz.edu.tr)

(E) ISBN 978-605-4123-32-2

ISBN 978-605-4123-31-5