Development of the Waveco passively adaptive twisting rotor blade

Anton B. Schaap, Simon J. Stark, Inge Bakke

Abstract—**The Waveco twisting rotor blade can passively adapt to the current direction and flow speed. The Waveco blade twists progressively from the tip to the root and includes the entire blade from the leading to the trailing edge. Under load the twist will be restricted at the tip and will increase towards the root. It will also be self-pitching to the direction of the current and will secure unidirectional rotation in an oscillating current. This twisting blade will present new opportunities for wave as well as tidal power applications. In the Subwave configuration a double counter-rotating rotor is suspended about 100 m below a surface buoy. This can be used for utility scale wave power, but also for powering a self-positioning ocean observation platform. In another application an Orbital-type floating tidal device can be converted to a wave energy device. The efficiency of a Nova Innovation type tidal turbine can be improved by replacing the symmetrical Wells rotor blades with the self-twisting blades. First calculations show that the Waveco twisting blade can be constructed with standard blade construction materials (epoxy or polyester resin with a reinforcement of glass or carbon fibres).**

Keywords— **Self-pitching blades, tidal power, twisting blades, wave power.**

I. INTRODUCTION

For horizontal axis bidirectional tidal turbines typically two different blade solutions are applied: actively pitched blades or symmetrical Wells blades [1]. The advantage of the pitched blades is the superior efficiency of the hydrofoil. The advantage of the Wells type straight blades is the much simpler construction, leaving out the active pitching mechanism. The Wells concept is also applied in wave power devices like the oscillating water column turbine. Wells turbines have been studied for direct conversion of wave energy in a unidirectional rotating movement (see IV-A).

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Waveco develops a straight blade for a Wells turbine that twists passively from the tip to the root and includes the entire blade from the leading to the trailing edge (see Fig. 1). Under load the twist angle will be restricted at the tip and will increase towards the root. Therefore, the twisted blade can have an optimal angle of attack over the whole length of the blade. It will also be self-pitching to the direction of the current and will secure unidirectional rotation in an oscillating or circulating motion, like a wave induced motion.

A relatively stiff shaft runs through the blade along the leading edge. The blade is fixed to the shaft only at the tip, allowing the rest of the blade to rotate around it. A (sleeve) bearing accommodates this movement.

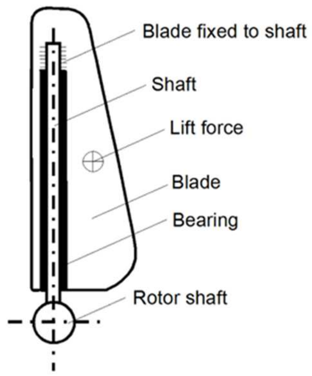

Fig. 1. Schematic cross section of the Waveco tidal blade.

Fig. 2 shows a conceptual Waveco blade that is twisted to the right due to a lift pressure at the left side of the blade. We see that near the root the twist angle of the blade is bigger than at the tip. Without an external lift pressure, the blade will be straight. The blade will in the same way twist to the left when there is a lift pressure on the right side of the blade.

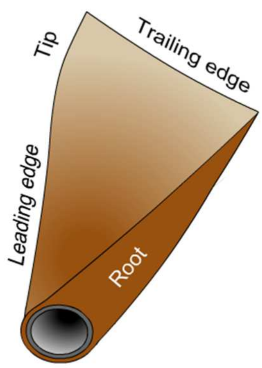

Fig. 2. Simplified 3D drawing of a flexible blade design. We see the blade twist to the right. The blade can also twist to the left.

Twisting blades have been studied at several research groups. Murray [1] has designed a blade that uses the so called bend-twist coupling. In this design the spar of the blade is constructed from anisotropic materials that twist under bending and this spar is an integrate part of the blade construction. Such a blade will twist progressively from the root to the tip and is therefore very suited to reduce the loading on the blade above rated power. At tidal sites there can be a big gradient in the tidal velocity from the sea floor to the surface, which could impose high fatigue loads on the rotor. There can also be high turbulence due to e.g. sea floor bathymetry. Therefore, pitching of each individual blade during a single rotation can be attractive. For an active pitching mechanism this will be hard to achieve since the loads will have to be measured and the blade pitch mechanism will have to react very fast. The bend-twist coupling however can achieve this.

Where Murray concentrates on the laminated material of the spar, Nicholls-Lee [2] develops a double box beam as the bend-twist coupled blade spar. Hernández-Somoza [3] expands the analysis to the application of the bend-twist self adaptive blade to a variable pitch controlled tidal blade, especially to reduce hydrodynamic loads. For the same reason Dai [4] designs a morphing blade in which the trailing edge can bend under load and thus reduce the hydrodynamic loads on the blade.

The bend-twist coupling and the morphing blade can deliver reduction of the hydrodynamic loads on the blade above rated power, however these concepts cannot passively twist a bidirectional straight blade to the optimal angle of attack along the whole blade span at rated power, as the Waveco solution can. Above rated power the Waveco concept can also reduce the hydrodynamic loads by increasing the twist angles under the increased load.

The Waveco blade presents new opportunities for tidal as well as wave energy devices. The passively adaptive twisting rotor blades can self-pitch to an optimal angle of attack in tidal currents as well as in wave motions. With this self twisting blade also double counter-rotating rotors can be designed (the Subwave concept).

This paper describes the application of the Waveco blade for tidal turbines (see II) and low TRL (technology readiness level) finite element stress and strain calculations on a Waveco tidal blade (see III). In IV the application of the Waveco blade in wave energy is given.

To get an idea of the possibilities of Wells rotors in wave motion, WaveRotor measurements are described (see IV-B) and also measurements on the Subwave turbine (see IV-C and IV-D). In the other subsections (IV-E to IV-H) possible applications of the Waveco turbine (single or double) for wave power are described. See V for the conclusions.

II. APPLICATION IN TIDAL TURBINES

Nova Innovation uses straight Wells blades for their bidirectional tidal turbines. This makes the Nova turbine a robust design without mechanical yawing of the rotor or pitching of the blades (see Fig. 3). Table 1 gives the main characteristics of the Nova turbine [5].

With these figures we can calculate a rated TSR (tip speed ratio) of 6, which is rather high. This is because the Nova Wells blades are symmetrical. Only at high speeds the rotor can reach the necessary low angles of attack of about 7 to 10 degrees and only near the tip. The parts of the blades near the root are not receiving optimal angles of attack and high drag or stall could appear there.

The Waveco flexible blades can present an improvement for the Nova turbines since the angles of attack along the blade will be more optimal compared to non-flexible Wells blades, without adding much mechanical complexity.

The Nova turbine is bottom mounted just like the turbines of SIMEC Atlantis. The Waveco blade can also be applied on float mounted turbines like the Orbital turbines where it can replace the pitching system of the blades.

Fig. 3. Nova Innovation tidal turbine [5].

TABLE 1. SPECIFICATIONS OF THE NOVA INNOVATION 100 KW TURBINE

Nova Innovations turbine specifications		
Rotor diameter	8.5	m
Number of blades	2	
Cut-in current speed	0.5	m/s
Rated water speed	2.0	m/s
Rated power	100	kW
Cut-in rotational speed	10	RPM
Rated rotational speed	27	RPM

III. ANALYSIS OF BLADE DESIGN FOR TIDAL TURBINES

DMEC (Dutch Marine Energy Centre) made a conceptual Waveco blade design for a tidal turbine. The dimensions of the Nova Innovation turbine were used. A symmetrical NACA 0018 hydrofoil is chosen. This hydrofoil has a maximum thickness of 18% of its chord length. The hydrofoil should have sufficient space inside for the Waveco twisting mechanism as well as to resist all the loads on the blade. Lift and drag data were acquired from an airfoil database [6]. Of course, other symmetrical hydrofoils can be used as well and there can be different hydrofoils from the root to the tip.

Table 2 gives an overview of the pressure on the blade model, using the Nova Innovation specifications and the NACA 0018 hydrofoil lift and drag data. The pressure is assumed to be perpendicular to the blade surface, which is a simplification of a much more complex reality.

TABLE 2 HYDRODYNAMIC PRESSURE ON THE ELEVEN SEGMENTS

Segment	Chord	Radius (from hub)	Pressure
(from tip)	(m)	(m)	(MPa)
1	0.525	4.1	4.9E-02
2	0.575	3.8	4.2E-02
3	0.625	3.5	4.1E-02
4	0.675	3.2	3.4E-02
5	0.725	2.9	3.3E-02
6	0.775	2.6	3.0E-02
7	0.825	2.3	2.3E-02
8	0.875	2	1.8E-02
9	0.925	1.7	1.3E-02
10	0.975	1.4	8.9E-03
11	1.025	1.1	5.7E-03

DMEC made a simplified 3D model of the blade and performed finite element calculations to determine if such a Waveco twisting rotor blade can be made with the standard industry composite materials for blade design (epoxy or polyester resin with a reinforcement of glass or carbon fibres). Most important is the maximum strain that occurs in the surface layer of the blade. This should stay under an allowable level for these standard construction materials.

The 3D blade model consists of eleven segments with different stiffness (see Fig. 4). The model is a segmented solid body with a hole that runs from the root to the tip. The blade length is 3.9 m and the chord length at the tip is 0.5 m. The maximum chord length is 1 m. At the maximum chord length, the blade should flex 16 degrees to both sides at rated power using the Waveco flexing mechanism.

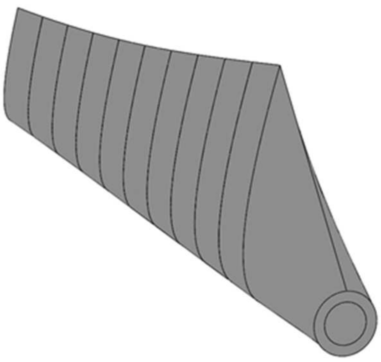

Fig. 4. Simplified 3D blade model for a Waveco turbine blade seen from the root.

Fig. 5 shows a cross section through the blade showing the tapered hole that runs from the root to the tip. In this hole the tapered shaft can rotate.

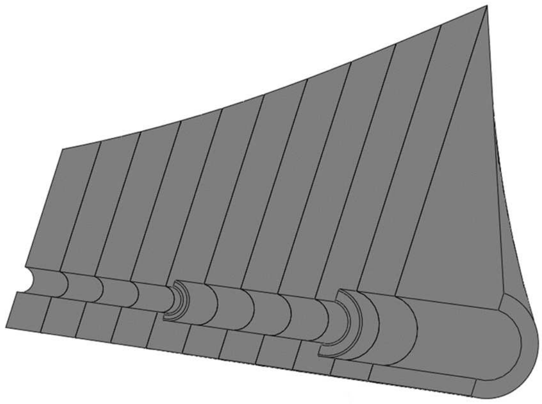

Fig. 5. Cross section of the 3D blade model showing the tapered hole that runs through the blade from the root to the tip.

The shaft that runs all the way from the turbine hub to the tip of the blade is not part of this model. Finite element calculations with this model were performed to calculate the stress, deformation, and strain of the blade. Fig. 6 shows the mesh for the finite element calculations. A fixed boundary condition was applied at the tip and a hinged boundary condition at the surface of the hole.

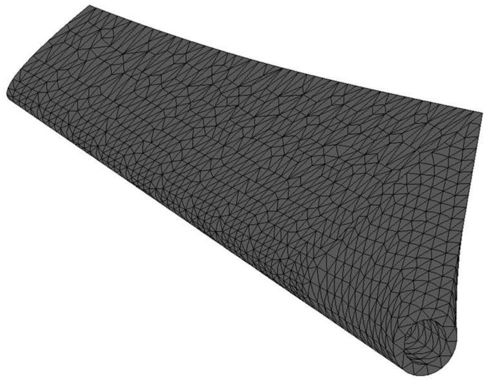

Fig. 6. Mesh for the finite element calculations.

The stiffness (elasticity modulus) of each segment was tuned to the desired twist angle of the segment. We assume an isotropic material with a Poisson ratio of 0.3. Table 3 presents the desired twist angles and the tuned stiffness of the segments. The stiffness is the highest at the tip and the lowest at the root of the blade, since the lift pressure on the blade is the highest at the tip where the twisting should be the lowest.

TABLE 3 BLADE TWIST AND MATERIAL STIFFNESS FOR THE ELEVEN SEGMENTS

Segment (from tip)	Radius (from hub)	Blade twist	Elasticity modulus
	(m)	(degrees)	(MPa)
1	4.1	0.0	5000
2	3.8	0.1	4000
3	3.5	0.7	2000
4	3.2	1.4	1200
5	2.9	2.2	700
6	2.6	3.3	300
7	2.3	4.6	200
8	2	6.3	70
9	1.7	8.5	30
10	1.4	11.6	13
11	1.1	16.2	7

For the segments near the root of the blade the stiffness value becomes very low because the solid model has most material in that region. Of course, these sections will be hollowed out in a real blade design.

The blade shaft can also have a certain twisting angle, depending on the stiffness of its construction and the loads on the blade. This is not taken into account in this model.

Fig. 7 shows that the deformation of the blade is the highest (red colour) near the root of the blade and the lowest near the tip (blue colour), as demanded. The deformation is the distance from the neutral position for each surface area grid element of the model. Note that we performed the finite element method (FEM) analysis with a ten times lower load than calculated, because of the large deformations which would induce nonlinearities otherwise. However, we suppose that stress, strain, and deformation are predominantly linear and so we have multiplied the results with a factor of ten. This of course introduces some uncertainty.

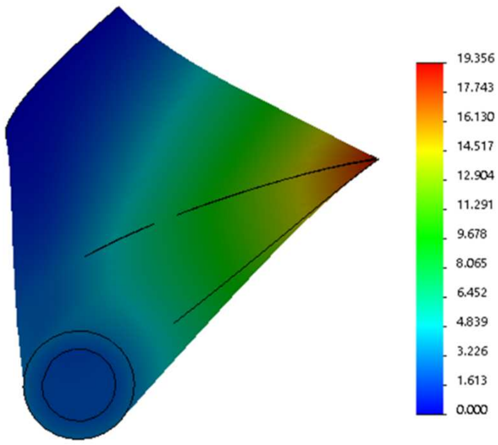

Fig. 7. Deformation (displacement) of the surface of the Waveco blade under loading seen from the root (deformation in mm). The deformation values should be multiplied with a factor of ten.

The stress levels in the material are not relevant since the model is a solid body. Interesting are the strain levels in the surface of the blade that are necessary to twist the blade to the desired shape (see Fig. 8). The highest strains occur near the location of the highest chord length. The influence of the different stiffness levels of the segments are visible in this graph, as the step changes in strain. The highest (red) values stay below 2%. This is within the possibilities of the standard composite blade construction materials [7].

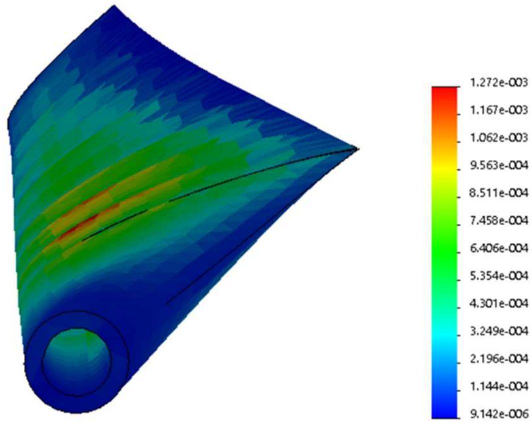

Fig. 8. Strain levels at the surface of the blade. Red are the highest strain levels and blue are the lowest strain levels. The strain values should be multiplied by a factor ten. With 1.27% the highest strain level stays below 2%.

This analysis gives a first indication that such a blade can be fabricated with standard composite materials for blade design. If a higher twist angle than 16 degrees is desired, more elastic materials might have to be used (like polyurethane rubbers etc.), since the blade surface must be able to endure these strain levels.

With an optimised Waveco blade design DMEC expects that the yield of the Nova Innovation turbine can be increased by 10 to 20% over a year. However more study will be necessary to elaborate this optimised flexible blade. Important aspects for future study are:

- Part load efficiency design and calculation of annual energy production (AEP)
- 2 or 3 bladed rotors (at lower TSR operation, a third blade can be beneficial)
- Effects of lower TSR on the drive train design
- Optimal hydrofoil along the blade
- Designing the hollow composite structure inside the blade
- Choosing the composite blade material for the flexing structure
- Designing the bearing between the blade material and the internal shaft in the blade
- Designing the stiff tapering blade shaft from root to tip

IV. APPLICATION IN WAVE POWER TURBINES

A. *Introduction*

The development of wave energy converters (WECs) is proceeding slowly. A technological hurdle is the development of a reliable, robust and efficient power take off. Mostly there is a prime mover that moves relative to a float or to some connection to the seabed or shore. With these WECs the power is transferred in the form of a reciprocating movement with very low speed and extreme high force or torque [8]. This does present several technological challenges for the bearings (e.g. low hydrodynamic lubrication in combination with very high loads), for the power conversion (e.g. low conversion efficiency at hydraulic, mechanical, and electrical systems) and for the sealings (e.g. reciprocating movements creating clearances). If we use a Waveco turbine for the conversion of wave power, there is no reciprocating motion, and we get lower torques and higher speeds (the optimal TSR of a Waveco turbine will be around 4 to 6). There is better bearing lubrication, higher efficiency, and easier sealing. Moreover, these kinds of turbines have already been developed by the tidal power industry, which is at higher TRL than the wave power industry. We will first discuss earlier work on lift based (Wells) rotors in waves and then discuss the possible Waveco blade applications.

B. The Wave Rotor

In the past, research has been performed to study the performance of Wells and Darrieus type rotors directly in waves.

In the years around 2000, considerable effort was made by the company Ecofys to develop the WaveRotor [9]. This device was able to convert wave motion directly into a unidirectional rotational movement of a combined Wells and Darrieus rotor (see Fig. 9).

Fig. 9. WaveRotor scale model deployed in the Westerschelde, The Netherlands.

The vertical blades are the Darrieus blades, and the horizontal blades are the Wells blades. The picture was taken at the test site in the Westerschelde near Vlissingen, The Netherlands. Both types of rotors can convert the rotational movement of a wave into a unidirectional rotational movement of the turbine. In this location, however, the WaveRotor functioned more as a tidal rotor, because of the reasonably good tidal regime and the very low wave regime.

TSR and Cp (power coefficient) were used for performance analysis. Where the TSR is defined as the speed of the tip of the rotor divided by the undisturbed current speed (or carriage speed) and the Cp is defined as the power produced by the rotor (rotor rotational speed times rotor torque) divided by the power in the undisturbed current P. This power P (W) is defined as (1).

$$P = \frac{1}{2}\rho U^3 A \qquad (1)$$

Where ρ is the density of the water (kg/m^3), U is the current speed (m/s) and A is the rotor area (m^2).

From scale testing and simulations, it became clear that the Wells rotor and Darrieus rotor have different optimal tip speed ratios. The Wells blade reaches its maximum Cp at 2 to 3 times higher TSR than the Darrieus blade. Since they are connected at the Wells-tip, the TSR should be the same. In the design this was compensated for by increasing the thickness and the solidity of the Wells blades relative to the Darrieus blades. This solved the problem but at the cost of a decrease of efficiency of the Wells rotor [10].

See Fig. 10 for test results from scale model testing at Ifremer, France, in regular waves [11]. The rotor diameter was 2.4 m. In the graph BW are the measurement points of the Wells turbine only (with increased solidity), BD are the measuring points of the Darrieus turbine only (with reduced solidity) and BWDf are the measuring points of a combined Wells and Darrieus rotor. There are polynomials drawn through the measuring points (dashed lines) and the grey polynomial is the summation of the efficiency of the BW polynomial and the BD polynomial. The efficiency of the combined Wells-Darrieus turbine (BWDf) is somewhat lower than the summation of the two separate efficiencies.

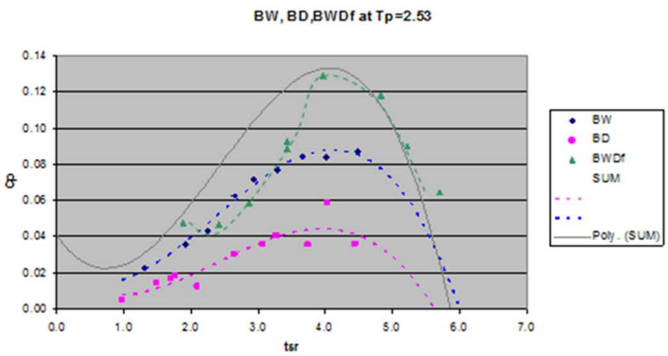

Fig. 10. Cp versus TSR; scale test results at Ifremer France, for different turbine configurations in regular waves (wave height = 0.4 m, wave period = 2.53 s). BW is only a Wells-rotor, BD is only a Darrieus rotor and BWDf is a combined Wells and Darrieus rotor. Poly (SUM) is the addition of the BW and BD polynomials.

The Wells type of rotor performs better in waves than the Darrieus type of rotor. The Wells type can reach efficiencies (Cp) of around 10% in scale testing. The Darrieus type can reach efficiencies of about 4%. The combined Wells and Darrieus can reach efficiencies just above 12%.

It should be noted that these are efficiencies in scale testing in regular waves with a rotor diameter of 2.4 m and a wave height of 0.4 m, meaning very low Reynolds numbers compared to full scale machines. From simulation work it is known that the efficiency increases at higher Reynolds numbers [10].

From all this work it became clear that it is advantageous to use only the Wells turbine and that Cp values between 10 and 20% should be possible for large scale machines.

However, with the addition of the Waveco flexible blade there is the opportunity to raise the Cp further, because a smaller proportion of the blade span will be in stall and so the drag can be diminished considerably. Each individual Waveco blade twists almost instantly according to the loads exerted on the blade. The lift forces will also be raised because the Waveco blade twists to an improved angle of attack under load. Thus, the self-pitching Waveco blade could also improve the efficiency in irregular waves.

C. *The Subwave Concept*

Waveco concentrates on a configuration of double counter-rotating rotors, primarily for wave energy application (the Subwave turbine). In this concept the double rotors are suspended on a cable about 100 m below a float. The turbines shall be located at a depth of at least half the prevailing wavelength in the sea area where it is deployed. Here, the turbines will be shielded from the direct impact of the surface waves. The counter-rotating rotors present the possibility to have zero torque on the cable (see Fig. 11 and Fig. 14). The vertical movement of the turbine will be predominant over the horizontal movement, which is beneficial for the efficiency of the turbine.

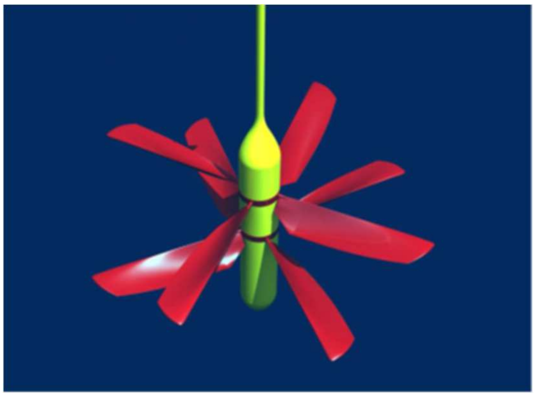

Fig. 11. Turbine with double counter-rotating rotors (red) connected to a cable (not shown) and suspended about 100 m below a float.

D. *Subwave testing*

Scale testing of the Waveco Subwave counter-rotating turbine has been performed by bachelor students of The University College of Western Norway at Stadt Towing Tank in 2018 (see Fig. 12). The towing tank has a length of 185 m, a width of 8 m and a depth of 4 m. A turbine with two counter-rotating rotors was connected to a carriage and was controlled at a variable speed and torque [12]. The diameter of the rotors is 1.05 m and the turbine nacelle is 0,85 m long with a diameter is 0.25 m. The students developed the braking mechanism that produced the braking torque. Stadt Towing Tank delivered the torque sensor and the monitoring system.

The turbine was driven back and forth for five times (five tests), each time with a different braking torque on each rotor. During a test the carriage speed was raised from 0.5 to 1.1 m/s in steps of 0.1 m/s. There were no waves applied to the rotor, only a constant current comparable to a tidal current.

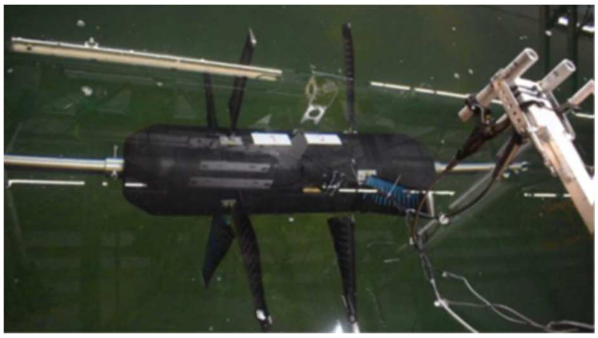

Fig. 12. Scale model test of the Subwave turbine in Stadt Towing Tank, University College of Western Norway.

Since the second rotor is in the wake of the first rotor, the performance of the rotors are coupled and thus we can only analyse both rotors together. To define the Cp of the whole system the summation of the power production of both rotors was used. Fig. 13 gives the power coefficient as a function of the TSR of both rotors together.

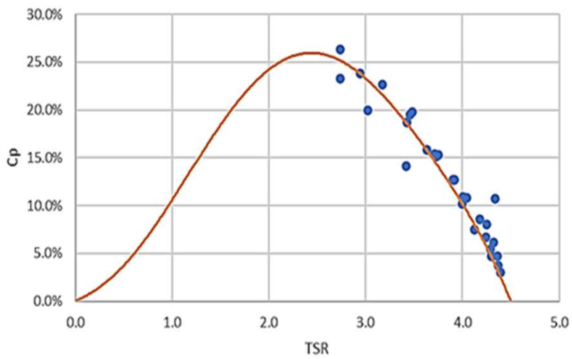

Fig. 13. Cp versus TSR for the measurements (blue dots) in Stadt Towing Tank, as well as a typical Cp versus TSR curve (orange) drawn through the measurements for illustration.

The TSR shown in the graph is the average of the TSR of rotor one and rotor two. The blue dots are the measurements. The measurements were taken at the higher values of the TSR. This was however not noted during testing. The orange line is a typical power curve drawn through the measurements for illustration. The curve shows that the maximum Cp could well be at an average TSR just below the measured values. The Cp of both rotors together will be around 26% at a TSR of around

2.5. This Cp is lower than might be expected for a rotor in a constant current. The optimal TSR of a single current turbine is around 4 to 6 [13]. At this TSR a single rotor should reach a maximum Cp of about 40%. So, the Subwave turbines operate at much lower TSRs at which the efficiencies are also much lower. The cause of this is the too big flexing angles of the blades of the rotors in this test. Stiffer blades will decrease the flexing angles, to reach higher TSRs.

E. *Utility scale wave power*

For utility scale Waveco is developing a concept for wave energy conversion using a number of this counter-rotating Subwave double turbines about one hundred meters below floating buoys (see Fig. 14). A single buoy with a 15 meter diameter turbine can have a rated power of about 200 kW (in a 50 kW/m wave energy area). The turbines can be combined in a wave park in which several floats are coupled in a network structure (see Fig. 15). Since the network is coupled at junction boxes about 20 m below sea level, service vessels can navigate between the buoys.

This configuration has the following advantages:

- The surface buoy will be a simple and robust structure that is easy to design for extreme conditions.
- The turbines are away from the surface environment, avoiding high stresses, and biological growth.
- Single turbines are relatively easy to pick up and maintain by disconnecting them at the junction box and taking them ashore.
- The systems has no end stops.

Fig. 14. Several Waveco's unidirectional counter-rotating double rotor turbines suspended under floating buoys.

Anchored groups of Subwave units will be deployed in waters with suitable depths. A cable will transmit power to the consumer, offshore or onshore, from a central tension moored converter buoy.

Ocean currents will cause horizontal loads on the turbines. In some cases, measures will be necessary to counteract this. A master thesis study at the Norwegian University of Science and Technology (NTNU) is currently being performed on analysing proposed methods and École Centrale de Nantes will study the Technology Performance Level (TPL) of this system.

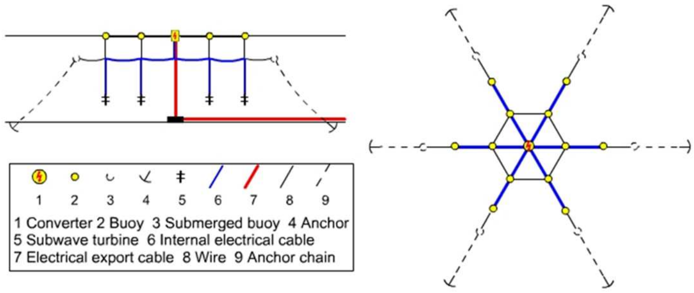

Fig. 15. A park of Subwave turbines suspended from buoys. Six anchors and one tension mooring hold twelve units and a central unit for electrical conversion and export. Profile at left, top view at right.

F. *Ocean Observation Platform*

Waveco is developing an unanchored, dynamically positioned observation platform (see Fig. 16) using the Subwave turbine as the power supply. This is a platform for long-term observations from a fixed position in sea areas that are too deep for the practical use of a mooring system. The freeboard will be low, and the hull formed to catch as little wind- and water-current resistance as possible.

To maintain its fixed position against wind, current, and waves, it has two independent fixed propellers protected in cages to avoid being caught in floating debris. There is no rudder. The mast contains a radar reflector, navigation lights, antennas and meteorological instruments.

Energy for electric motors, instruments and payload comes from a large battery that is constantly charged by Waveco's Subwave turbine.

The cable, with built-in conductors and slip ring, allows free rotation between the platform and the turbine without the cable being twisted.

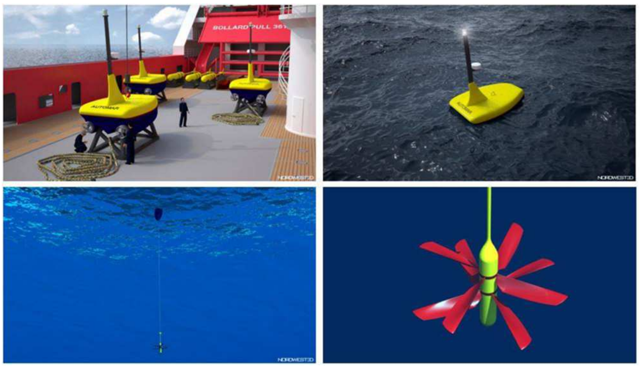

Fig. 16. Self-positioning ocean observation platform (top figures) with the Subwave turbine suspended underneath (lower figures).

In March 2021, NORCE Norwegian Research Centre AS completed an analysis of the system [14]. It shows that the concept is physically feasible and harvesting of the wave energy should be enough to maintain the position and provide additional energy for powering a significant payload. Exceedence Ltd. studies the market potential of this concept.

G. *Waveco turbines connected directly to a Float*

The Waveco turbine can also be connected directly to a float anchored perpendicular to the wave crests. In this application the two (single) rotors have opposite rotational directions. The construction is comparable to the Orbital tidal turbine, however with the turbines placed in a vertical axis position (see Fig. 17). The preliminary length of the float is 36-meters, and the diameter is 4 meters. The diameter of the turbines is 16 meters. The estimated rated power of such a system can be around 500 kW.

The rotor acts as a damping unit of a resonant floating body. The control of the rotor also gives control over the damping force. So, the highest efficiencies can be reached when the damping is optimal for the present sea state. The damping force delivered by the rotor is composed of the lift forces and the drag forces (stall) on the rotor, where the passively twisting Waveco rotor can increase the lift forces over the drag forces compared to a standard fixed bladed Wells rotor.

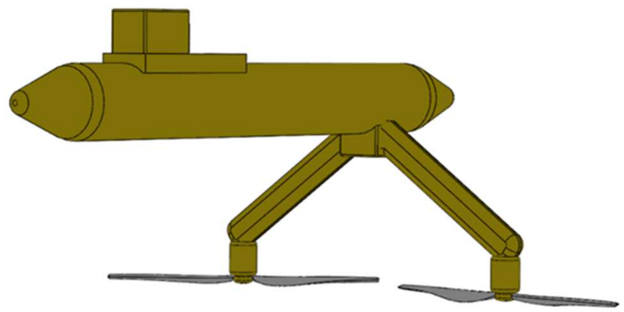

Fig. 17. Waveco turbines directly coupled to a float.

For this application there needs to be a relative movement between the float and the wave motions. Therefore, the float must either be in resonance (longer waves) or lie still in the water (short waves). In resonance the rotors can capture the relative movement of the float in the pitch, roll and/or heave directions. In extreme conditions the turbines can be stopped to lower the loading.

If we compare such a construction with for example the Mocean device [15], we see that the construction has the following advantages:

- One float instead of two.
- No highly loaded hinge between floats.
- No low speed reciprocating power take off.

And moreover, comparable floats and turbines have already been developed and tested by the company Orbital for tidal application. Main changes that must be made are:

- Dimensioning of the float to optimise resonance.
- Design of a mooring system that accommodates the resonant movement.
- Development of the Waveco blades instead of stiff Wells blades.

We could add water tanks to the interior of the device with which the inertia can be tuned to the (forecasted) sea state to optimise the resonant frequency. The water tanks can also be used to bring the system into survival mode during storm conditions.

If we can increase the relative speed between the turbine swept area and the surrounding water by about a factor of two, the speeds that the turbine encounters will be of the same magnitude as for tidal turbines. Such an increase could be accomplished by bringing the float in resonance. Some preliminary dynamic simulations have been performed. The simulations were performed without the turbines and only the resonance of the float in the heave direction was calculated. It became clear that heave resonance can be accomplished but will not be sufficient to achieve a significant increase in relative speed. The biggest increase could be provided by resonance in the pitch direction. Resonance in the roll direction is also a possibility. This will be studied in a later stage.

H. *Oscillating Water Column Turbine*

The oscillating water column (OWC) wave energy converters use the movement of the air in an enclosed space above the water surface to drive a Wells type air turbine. In this application the efficiency can be improved by replacing the straight Wells blades with Waveco blades. Since these are pressure turbines rather than free stream turbines, the analysis will be different from the hydrodynamic analysis of a free stream turbine.

V. CONCLUSION

- The Waveco passively adaptive twisting rotor blade can self-pitch to the direction of the current and will secure unidirectional rotation in an oscillating current.
- This twisting blade presents new opportunities for wave as well as tidal power applications.
- In the Subwave configuration a double counter-rotating rotor is suspended about 100 m below a surface buoy. This can be used for utility scale wave power, but also for powering a self-positioning ocean observation platform.
- In another application an Orbital-type floating tidal device could be converted to a wave energy device.
- The efficiency of a Nova Innovation type tidal turbine could be improved by replacing the symmetrical Wells rotor blades with the Waveco self-twisting blades.
- First scale measurements of the efficiency of the Subwave double rotor show that there is room for improvement by reducing the twisting angles.
- First calculations show that the Waveco twisting blade could be constructed with standard blade construction materials (epoxy or polyester resin with a reinforcement of glass or carbon fibres).

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