Common pre-study and demonstration of wave energy challenges, PSO project # 12057

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Denmark

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Content

Project organisation and participants

Project leaders	**AAU (Aalborg University, Wave Energy Dept.) and DanWec, Hanstholm**			
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Work Packages´s	**3 kW Inverter**	**Flexible joints**	**Anchor technology**	**Partnership meetings**
Coordinator + report	Resen Energy	Resen Energy	Rambøll	AAU- DanWec
Participant	AAU	BPI Chambers	CrestWing	All wave energy
Participant	BPI Chambers	Gravlund	Resen Energy	developers
Participant		Aqua Leak	BPI Chambers	
Participant			Aqua Leak	
Sub contractors		Sea trials	Sea trials	
Sub contractors	Components	Components	Components	

Report Authors: Kim Nielsen, Per Resen Steenstrup and Henning Pilgaard

Project description

Pre-study to design and demonstrate, in small scale, cost effective solutions for 3 commonly identified challenges in the wave power industry, which typically involves floating devices.

1. High efficient inverter control of Permanent Magnetic Generators PMG´s
2. Flexible waterproof cables, joint connections and
3. Low cost innovative anchoring methods.

Pre-study to design and demonstrate, in small scale, cost effective solutions for 3 commonly identified challenges in the wave power industry, which typically involves floating devices. The challenges are of a common nature and are not tied in to a specific wave power device:

1. High efficient Inverter control of multi-phase brushless Permanent Magnetic Generators (PMG´s) could provide a very efficient power conversion solution for wave energy. Wave power developers are not widely familiar with these possibilities and need to see systems in operation and be inspired for future optimization.

2. Flexible waterproof cables, joints and connections which allow constant movement with the wave action and yet provides a reliable transmission of power, sensor - and control signals to shore.

3. Low cost anchoring methods that are easy to install, maintain and decommission and provide the required safety. Even though anchors have been around for centuries it is necessary to find the best total economical solutions, which drives down the costs of wave energy.

Danish:
Forstudie på konstruktion og demonstration i lille skala af cost effektive løsninger til 3 generelle problem stillinger i bølgekraft industrien: Høj effektiv inverter styring af PM Generatorer, fleksible vand tættet kabler, led samlinger og pris gunstige innovative anker løsninger.

Forstudie på konstruktion og demonstration i lille skala af omkostnings effektive løsninger til 3 generelle problem stillinger i bølgekraft industrien: Høj effektiv inverter styring af PM Generatorer, fleksible vandtættet kabler og led samlinger og pris gunstige innovative anker løsninger. Udfordringerne er fælles for alle flydende bølgekraft anlæg.

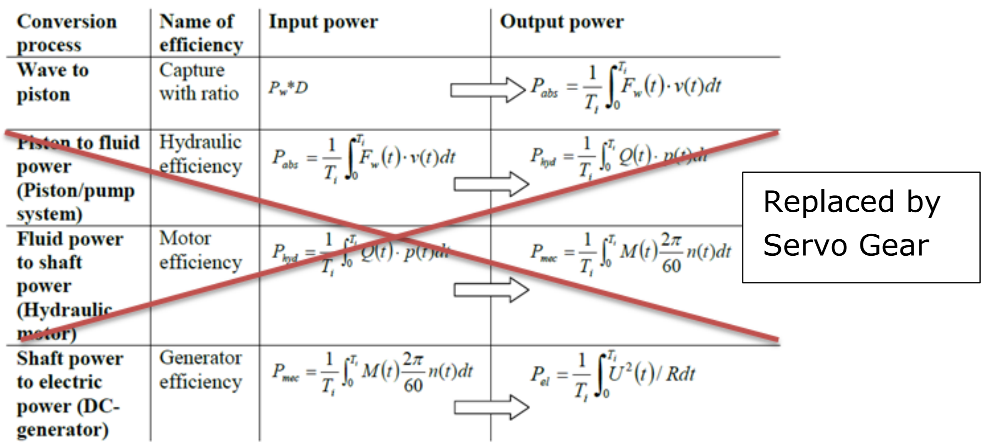
1) *Høj effektiv inverter styring af multi fase Permanent Magnet Generatorer PMGér kunne være den høj effektive effekt konvertering som der er brug for i bølgekraft systemer. Mange udviklere er ikke praktisk bekendt med mulighederne, så formålet er at demonstrere det i praksis på små 3 kW systemer.*

2) *Fleksible og bevægelige kabler og led der kan klare konstant bevægelse mellem flydende anlæg og havbunden. Det vil vi designe og demonstrere så effekt, sensor - og styre signaler kan transmitteres på en pålidelig måde.*

3) *Prisgunstige og innovative anker løsninger som er enkle og billige at installere, vedligeholde og demontere. Der er brug for nye løsninger i en konservativ industri.*

High efficient Inverter control of multi-phase brushless Permanent Magnetic (PMG´s) generators

The idea behind this project is to set up simple experimental trials with high efficiency PMG´s and a standard inverter to investigate how efficient a pure mechanical to electrical PTO (Power Take Off) could be for wave energy applications, without using any hydraulic components. The hydraulic power conversion train has i.e. been studied with an overall efficiency of about 40 – 60% (Christensen, 2001). In the Mechanical PTO process the hydraulic pump (90%) and motor conversion (85%) is excluded and replaced with a servo gear (95%) as illustrated on the figure below.



Conversion process	Name of efficiency	Input power	Output power
Wave to piston	Capture with ratio	P_w*D	$P_{abs}=\frac{1}{T_i}\int_0^{T_i} F_w(t)\cdot v(t)dt$
Piston to fluid power (Piston/pump system)	Hydraulic efficiency	$P_{abs}=\frac{1}{T_i}\int_0^{T_i} F_w(t)\cdot v(t)dt$	$P_{hyd}=\frac{1}{T_i}\int_0^{T_i} Q(t)\cdot p(t)dt$
Fluid power to shaft power (Hydraulic motor)	Motor efficiency	$P_{hyd}=\frac{1}{T_i}\int_0^{T_i} Q(t)\cdot p(t)dt$	$P_{mec}=\frac{1}{T_i}\int_0^{T_i} M(t)\frac{2\pi}{60}n(t)dt$
Shaft power to electric power (DC-generator)	Generator efficiency	$P_{mec}=\frac{1}{T_i}\int_0^{T_i} M(t)\frac{2\pi}{60}n(t)dt$	$P_{el}=\frac{1}{T_i}\int_0^{T_i} U^2(t)/R dt$

Figure 1 The Direct Mechanical PTO skips the hydraulic Pump and Motor conversion steps.

Simplicity, cost effectiveness and high conversion efficiency are critical and important areas for all PTO´s in general to achieve as well as reliable and stable operation.

By looking at the different components of the drive train from mechanical input, speed up gear, PMG and through the inverter and measure the losses in each step we will learn how efficient the overall PTO drive train is as well as the efficiency in each part of the PTO drive train.

Setup

A "dry" test bench was designed for making practical tests that could cover and transfer most of the typical movement's encountered in a wave energy PTO at power levels up to 3 kW.

The characteristic rocking wave movement was reproduced by a computer controlled servo motor and a low revolution gear head which provided an arbitrarily high torque rotation, forth and back, in the range of +/- 10 RPM. The drive and holding torque was up to +/- 6.000 Nm, representing a power of T x ω = T x 2 x ∏ x RPM / 60 , in the range up to 6 kW of mechanical power.

With the servo gear head it is possible to drive the complete PTO power train from mechanical input to inverter output as shown on the illustration below.

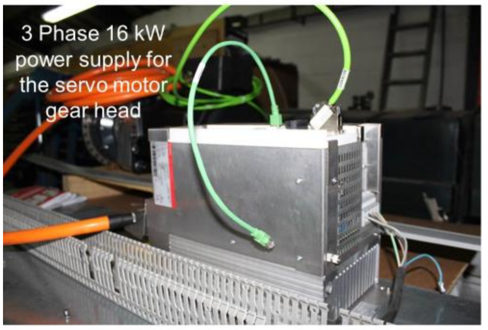


Figure 2 Components used to generate the simulated input power from the waves.

The test set-up consists of the following main components:

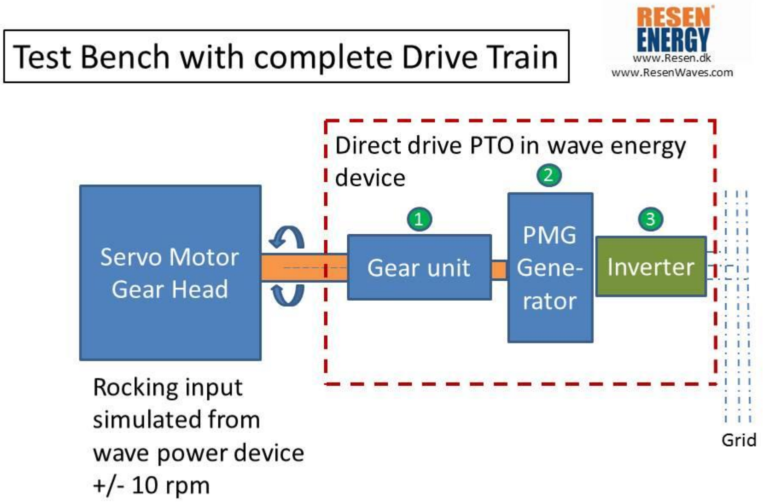


Figure 3 Illustration of the Test Bench setup.

The servo motor gear head is controlled from a PLC and it is possible to induce almost any kind of movement into the PTO drive train. It is only limited by the angular speed of 10 rpm and the torque of 6.000 Nm. The angular speed and the torque can be changed by using a gear head with a different gear ratio. If the maximum angular speed is increased the torque is decreased accordingly and vice versa.

To get a common time base in the system the same PLC is also used for data acquisition of the mechanical and electric power in the wave train.

Mechanical power is measured as Torque x Angular speed = T x ω and electric power is measured as Voltage x Current = U x I.

The 2–stage gear unit showed an efficiency of 95%. Gear manufactures claim a loss of typical 2% per gear stage.

For the test only non-cocking, (no stick torque on startup), rare earth brushless PMG´s were used. They all showed a very high efficiency of minimum 90%. No PGM´s stood out from the rest as better or worse. Only the quality and prices could vary a great deal.

For the inverter we have looked at a selection of standard inverters used for PV or for small wind turbine. This covered SMA, Eltek, DVE and Ginlong. They all proved to be good options; however there are differences in how the power curve can be set up and what power algorithm could be applied for optimized power production in real time operation. In order to handle spiky power from the wave energy device the inverters were over dimensioned by a factor of 2 as a good first choice. In general the inverter efficiencies are very high with a minimum of 90 % and typically around 95%.

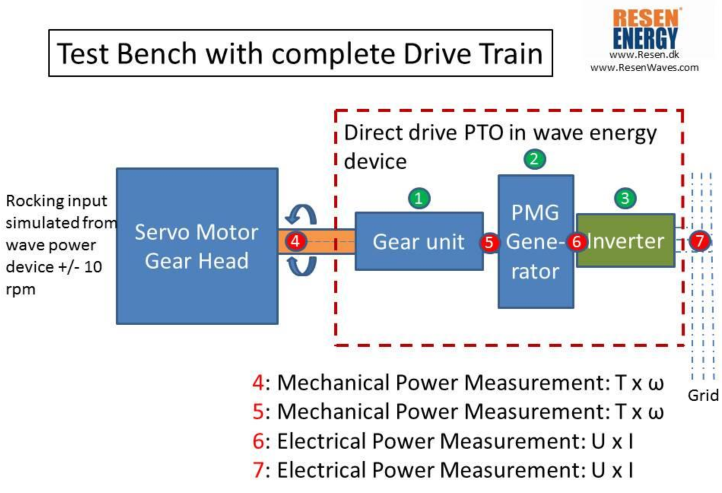


Figure 4 Measured power levels in the Mechanical PTO conversion process.

As a typical result the overall efficiency of the PTO showed an efficiency of 80% from mechanical input to the grid, which is quite acceptable, bearing in mind it is standard off the shelf standard technology.

Conclusions and areas that have potential for further future investigation

The direct mechanical to electric power conversion is a simple and very efficient solution with few components and an efficiency of 80%. Brushless rare earth PMG´s are a very good solution with practically no wear and tear. The all solid state inverters also have very high conversion efficiencies and are fairly inexpensive. It looks like a very good choice for PTO´s.

The control of the inverters and how reliable they are in operation is an open question that has to be studied more in detail. It is also necessary to build up experience of the operational stability and identify service issues, because they are power components, which are traditionally the weak parts that fail first.

Similar to hydraulic power which can be smoothened using hydraulic accumulators the direct mechanical PTO will produce much more fluctuating and “spiky” power. It is therefore also necessary to test how spiky wave power can be smoothed in a power efficient way or what is required for the inverter to handle spiky data. What is the better choice to achieve constant high efficiency and reliability has to be proved in practical test.

Flywheel stabilization, super capacitors and control algorithms could all be part of the solution for power optimization in wave cycles of 3 to 15 seconds.

Flexible waterproof cables joints and connections

The flexible electric and signal connections are vital connections for all floating wave energy devices, from the device itself to the touch down point on the sea bed. The big challenge is that floating devices are in constant movement with the waves and have to deal with fatigue issues as bending, as well as variable longitudinal mechanical stress loading during operation.

This project deals with a small scale integrated tension moored 10 ton anchor line including 3 low power lines of maximum 1.000 V and signal transmission for Ethernet and video. The purpose is to demonstrate operational issues in small scale before scaling to bigger flexible transmission lines.

Design considerations

The flexible joint is designed to handle a longitudinal stress of up to 10 tons.

- The electric leads are transferred on a GRP (Glass fiber Reinforced Plastics) band, which the leads are attached to. This allows a controlled bending of the leads when the rotary joint is rotated +/- 170 deg´s and avoids the use of a slip ring.
- The electric leads are also attached to a GRP band, which allows the cardan joint to bend forth and back +/- 90 deg and does not require a slip ring assembly.
- The rotary joint where the sea cable is attached requires a slip ring and allows unlimited twisting of the cable. Slip rings are available in many configurations and can accommodate a combination of high ampere leads as well as fiber optic connection. Slip rings are a specialty provided by many different suppliers depending on the specific requirements. They normally consist of a number of parallel brushes and slip rings and with optical lenses in the center that allows non-contact transfer of fiber optic data transmission.

Defining the flexible joint with 3 axes rotation

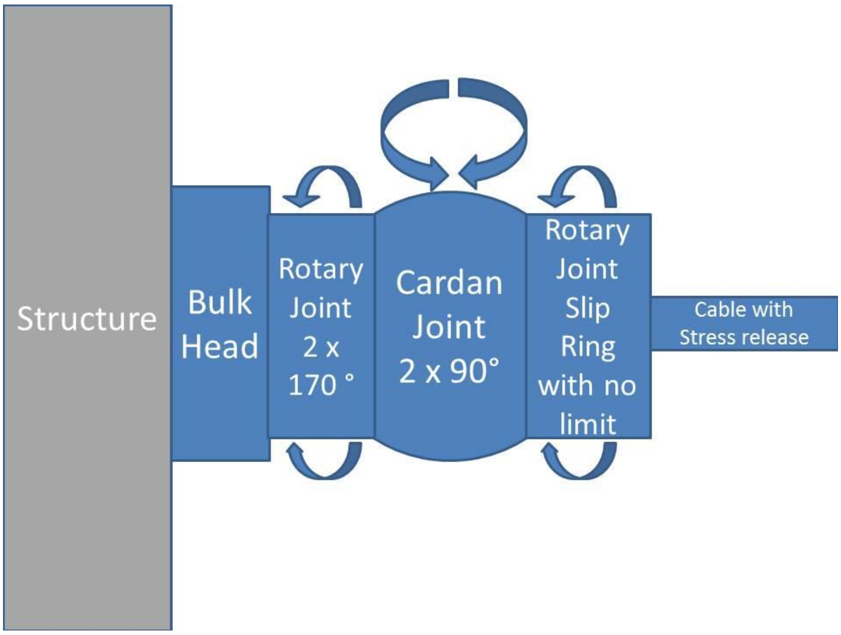


Figure 5 The cardan joint in straight line to the seabed.

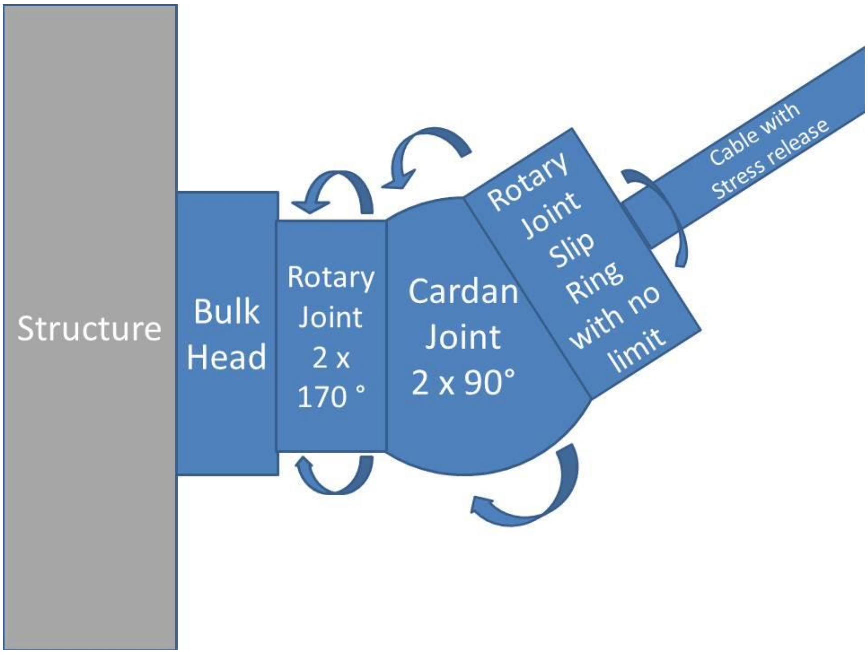


Figure 6The cardan joint bent 45 deg side ways.

When the cable is stress loaded in the longitudinal direction or twisted, the flexible joint will turn and align itself in the direction of the cable. A bend stiffener will limit the cable from bending when attached to the Rotary Slip Ring Joint.

The underwater armored cable that will transfer the power, signals and video could look like the illustration figure 7.

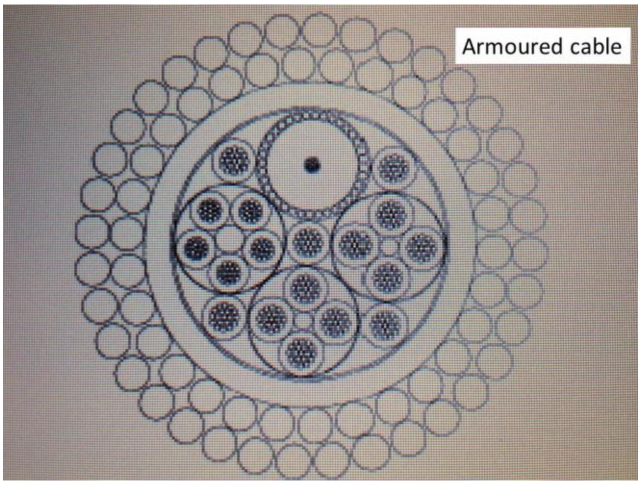


Figure 7 The underwater armored cable that will transfer the power, signals and video.

The cable has an outer diameter of Ø 23 mm and the minimum bending radius is 460 mm for indefinite fatigue handling. This type of cable is a standard for umbilical's used in ROV (Remote Operated Vehice) industry and is well documented.

The galvanized steel armoring consists of Ø 2 mm strands and the diameter inside the steel armoring is Ø 14 mm.

Besides from the video cable the electric Cu leads are 2,5 mm^2. The power handling can be up to as much as 50 to 100 kW at distances up to 300 m, if the power is transmitted at 1000 V DC.

A pre stressed gland around the diameter inside the armoring makes the electric cable water proof. The galvanized steel armoring is attached to the rotary joint with a treaded cone and lock, which transfers the full longitudinal pull force of 10 ton´s to the joint.

And finally the bending of the cable when it is joined to the rotary joint is restricted by a conical PU molded bend stiffener, which protects the cable from fatigue failure and wear and is a well-documented way of doing it.

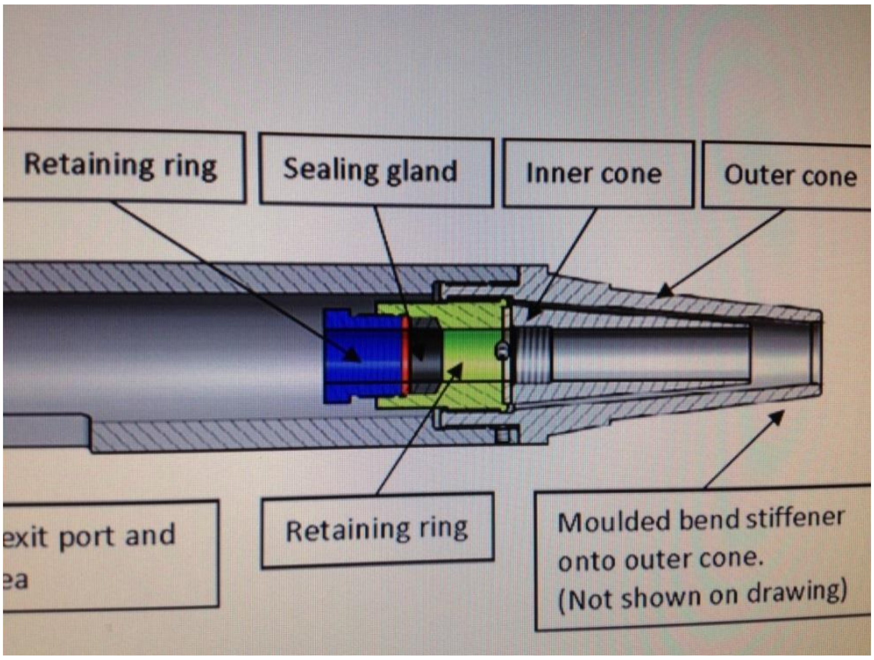


Figure 8 Termination of cable section (MacArtney A/S)

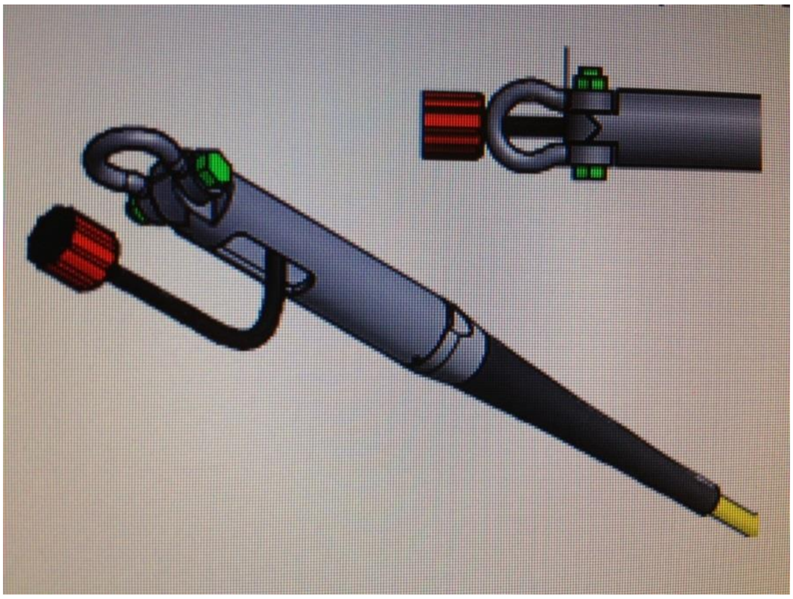


Figure 9 Seperation of cable and wire termination in a standard solution (MacArtney)

This could be used at the touch down point on the seabed as well as the surface. The connector is under water pluggable and easy to connect in the sea.

Checklist for standardized flexible cable joints

The 3 axis rotational joint can be made so they fit almost any size or capacity. They can be built more or less from standard components.

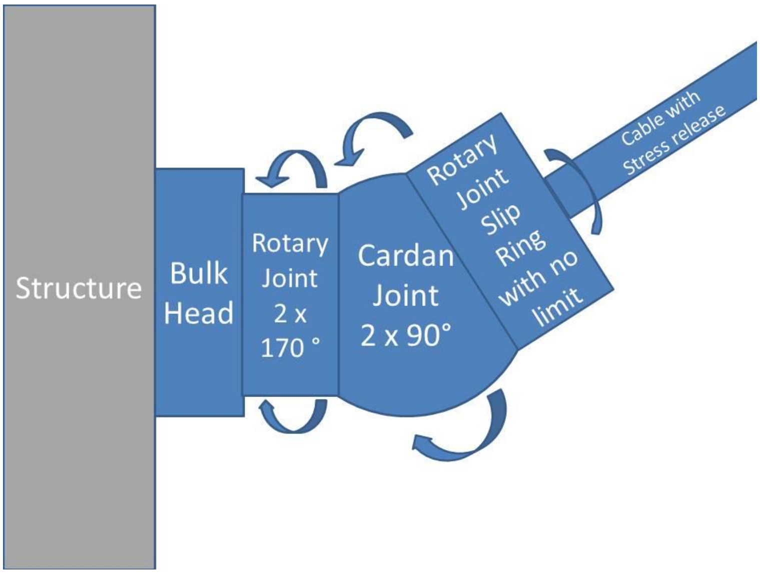


Figure 10 Main components of the Joint

They will contain the following main components:

- Bulk Head which is a flange that connect the whole assembly to the floating wave energy device.
- Rotary Joint with 2 x 170° rotation contains a trust bearing and 2 roller bearings for centering the rotation and with soft end stops.
- Cardan joins with one axis rotation, which allows 2 x 90° rotation.
- Rotary Joint with slip rings with no rotational limits contains a trust bearing and 2 roller bearings for centering the rotation and centering the slip ring. In addition it also contains the cable stress release and bend stiffener.
- Water tight proofing with bellows and filled with grease.

Power cable with fiber optic connection

A way to simplify the cable connections with high speed data transfer and with slip ring assemblies is to use an armored cable with only Cu power leads and optic fibers. In that case the fiber optic transmission is on the center line of the slip ring and the outer slip rings are used for the power transmission.

It simplifies the whole design as well as provides a galvanic separation of the data transfer from medium to high tension power, which means standard Ethernet connections can be used at very high data speeds, that can also accommodate video links, without any interference from the high tension power leads.

Low cost mooring and anchoring methods

In this pre-study two different types of mooring technologies were selected and are studied further because they have a general interest among the Danish wave energy developers:

- Tight mooring (reactive)
- Flexible mooring (passive mooring)

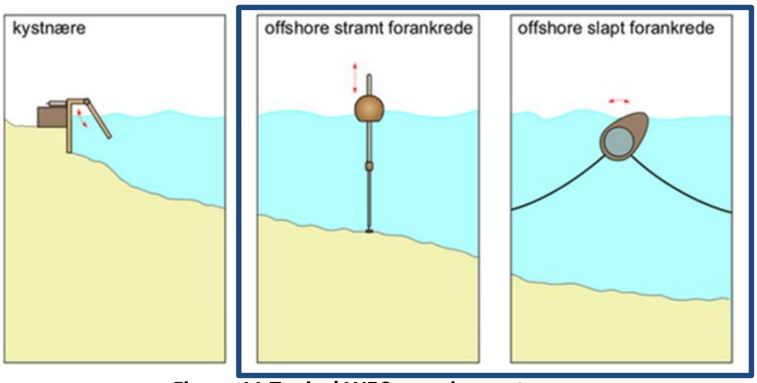


Figure 11 Typical WEC mooring systems

For both type of mooring systems the anchor technology to which the mooring is attached is also of common interest. Conventional drag plate anchors are well known for slack mooring systems, but these require time consuming installation procedures and extensive sea space.

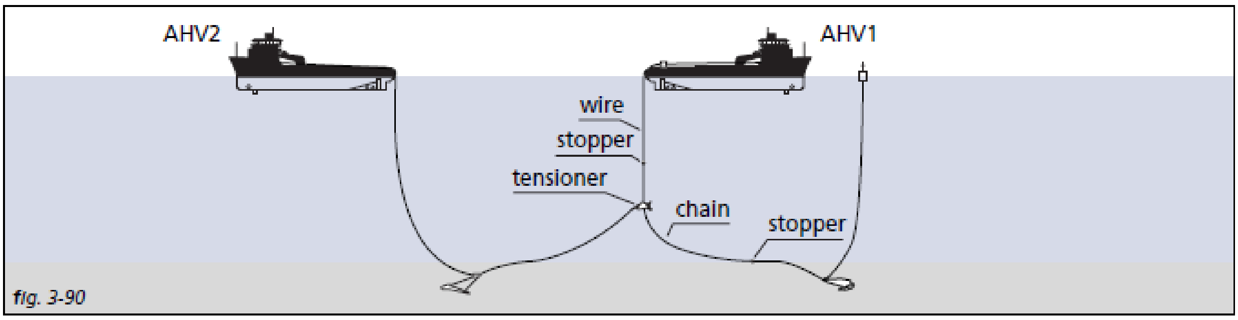


Figure 12 Example of the installation of drag embedment anchors (vryhof, 2010)

The tight moored WEC systems are typically attached to a gravity structure, a suction cup foundation, a pile foundation or as investigated in this project - screw anchors. A screw anchor is well suited for vertical pull loads and not well known in the WEC community. Therefore the pre-study has initiated some small scale hand-on experiments to gain practical experience with this type of anchors and their installation procedures as a basis for further development.

Screw anchors

Screw anchors are interesting in comparison to gravity anchors because they are low weight by a factor of 20 compared to gravity anchors and a factor of 10 times cheaper than an equivalent gravity anchor. The challenge is to install the screw anchors in a controlled way because it requires some kind of tooling to secure it in the seabed with the required torque and it requires a seabed with good friction angle between the sand particles to hold the sand screw anchors firmly in the seabed.

Background knowledge from literature and internet

Screw anchors on land have been used for many years, so there is already a fair amount of literature available on the subject (Adel Hanna, Tahar Ayadat, Mohab Sabry, 2007).

They are characterized by a one turn screw blade surface which is attached to a long slender massive rod. There can also be multiple screw blades attached, but then they are typically spaced by 1 to 2 m or more.

The parameters that control the holding force in the soil, as the dominant parameters are shown in the table below illustrated with typical parameters for this experiment.

Table 1 Screw anchor parameters with example units

Component (rest position)	Unit	Symbol	example
The shearing resistant angle of the soil	degrees	ϕ	37
Unit weight of sand γ (submerged)	kN/m^3	γ	11
The screw blade diameter	m	D	0,3
The pitch of the screw blade	m	p	0,06
The screw blade thickness	m	t	0,012
The depth of the screw blade	m	H	2,30
Diameter of the anchor shaft	m	D_1	0,03
Required driving torque (from web)	kNm	T	3,3
Ultimate pull out load (from web)	kN	QU_{33}	112

The shearing resistance angle is a measure for friction between sand particles and gives an indication of the torque applied to the screw anchor and holding force.

The screw blade diameter provides the total area that carries the pull force. The depth, soil density and the diameter of the screw blade provide the weight of the cylindrical soil sample above the blade which is also related to the pull force limitation.

As a useful reference for preliminary calculation of the basic holding capacity characteristics of a screw anchor the Anchor Design Homepage can be used as illustrated below:

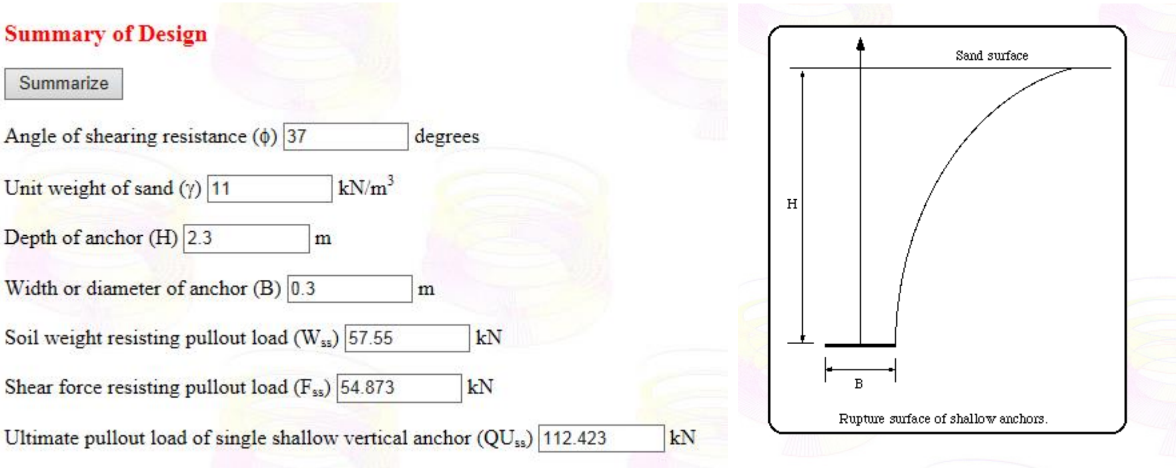


Figure 13 Forces acting on a screw anchor during installation Copyright 2007-2014 A. Ghaly. All rights reserved. Contact A. Ghaly at ghalya@union.edu

On the same page a tool for calculating the required driving torque can be found http://ghaly.union.edu/ANCHOR/torque-single-pitch-SI.htm

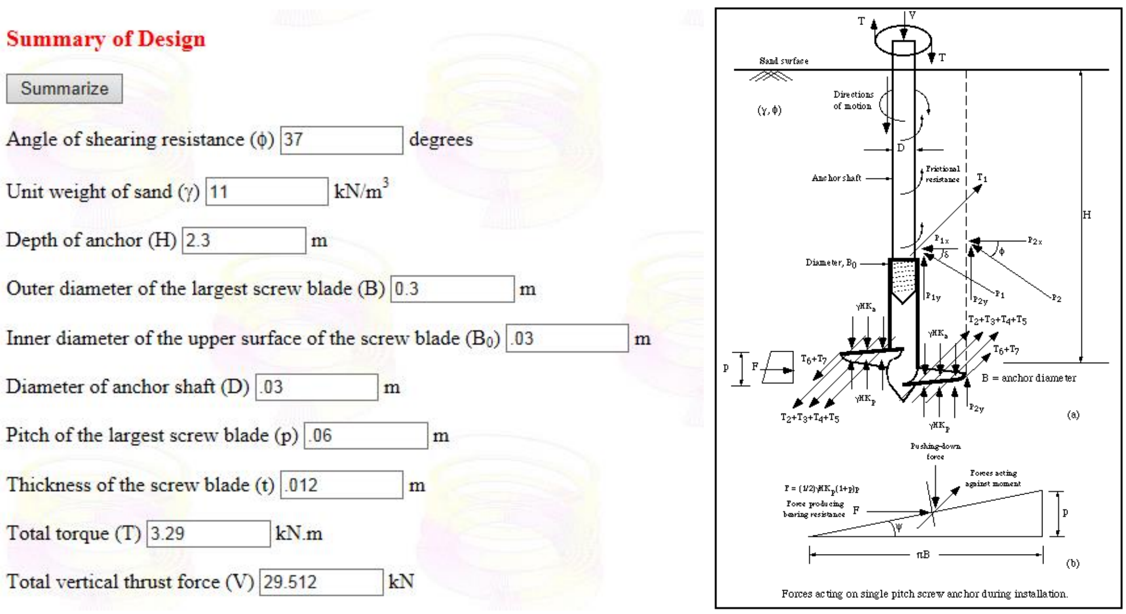


Figure 14 Forces acting on a screw anchor during installation Copyright 2007-2014 A. Ghaly. All rights reserved. Contact A. Ghaly at ghalya@union.edu

"Lærebog i Geoteknik" , p. 339, Chapter : "Ankre i Jord" is another very useful reference for understanding the critical parameters for screw anchors in soil. And the following links can also be helpful:| A. Ghaly Homepage | Union College Homepage

Set up

To start somewhere it was decided to make a screw anchor installation that could hold approximately 10 tons (100 kN) in vertical pull force (the weakest angle of the anchor). It was also decide to purchase standard certified screw anchors and make the practical trials on land first and later follow up with longer term testing in the sea. The longer term testing is important to identify any gradual movement of the screw anchors due to the pulsing forces of the wave energy devices or other practical issues which could be identified from operation in the sea.

The plan was to:

- Measure the torque when installing the screw anchor and observe operational issues, if any.
- Make a standard geotechnical sampling down to 4 meters and extract the relevant parameters that are relevant for the holding force of the screw anchor.
- Make a pull test of the anchor to investigate how well theory and real life tests match.

Geotechnical experts recommend a mix of measurements and pull tests to verify the pull forces that can be used for the design basis of an anchor system. In the beginning we do not expect good consistency between geotechnical data and actual pull tests. But after some iteration we expect better consistency.

Practical tests

A low field close to the sea between Helligsø and Lyngs was selected for the initial land based trials. The soil is expected to be raised seabed.

Typical selection of mooring wire and shackle’s for 10 ton operation

	
Double screw anchor 1 m part	Screw blade O.D. 30cm. Pitch : 6 cm /rev
	
Pointed end	Torque app. : 50 kg x 1 m = 500 Nm

Torque applied to drive the anchor 2 m into the ground: 40 kg x 3 m = 1200 Nm

Driving the screw anchor into the ground is pretty smooth and without vertical force. The screw anchor only has to be kept in the vertical position during the insertion.

	
The screw anchor installed to 2m depth	Initial pull test to 3 tons showed no movement. It only gives way sideways

The next step now is to build a galleon structure around the screw anchor and pull the anchor out with a nut and a treaded bolt. The pull operation will be done with an in line load cell and a displacement sensor to monitor the operation.

Next to the anchor a soil core sample will be extracted to make a geotechnical analysis of the soil.

And finally the pull test will be compared to the calculated pull force on the anchor.

After that the anchor will be installed in the sea and the tests will be repeated once and an additional anchor will be put into operation in the sea to monitor more long term behavior of the anchor.

Conclusions and areas that has more potential for the future

The screw anchor approach is very promising as a low cost and low weight solution and has the potential for driving down costs on wave energy devices.

Future areas for improvements:

The anchors have to be positioned during the screw insertion to work well. This will in 10 m to 20 m of water depth require an underwater robot that can drive the screws into the seabed under control from the surface. With video cameras on the robot it can be done without the use of divers (http://www.youtube.com/watch?v=saRe4UyIERM)

In addition it would also be a big advantage if the screws could be installed with the robot in a pattern and at different angles, so a central plate on the sea bed can be attached to the seabed and act as a center plate that distributes anchor forces from the mooring line.

CPT measurements are normally recommended for geotechnical tests in sand as the most stable method to measure the soil parameters, but it is difficult to apply if the content of stones or pebbles is too high as it is in Nissum Bredning. Other geotechnical methods do not provide the same accuracy. Therefor it is necessary to experiment with alternative ways of measuring the soil parameters.

There is room for making future practical mechanical trials and combining geotechnical experience on a variety of seabed like sand, clay and limestone to understand how screw anchors should be dimensioned to meet Eurocode partial coefficients at the appropriate safety level, when designing specific wave energy projects.

3-point turret mooring

Every mooring system is to some extent site and device specific – but with some general features in common. The practical experience concerning mooring of WECs is limited and not well published, mainly due to the fact that developers are not keen on publishing failures – even though the failures of mooring systems are part of the learning process towards reliable and cost effective mooring systems.

Mooring systems as a common focus area for the Danish Wave Energy Developers is described in the strategy report (K. Nielsen, J. Krogh, N. E. H. Jensen, J. P. Kofoed, 2012) and the present mooring system investigation is a joint project initiated by Resen Energy as a first attempt to gain practical experience in the development of a common mooring system.

The project will document the experimental development of the mooring system using the iterative design procedure described in (Zanuttigh, 2013) illustrated below.

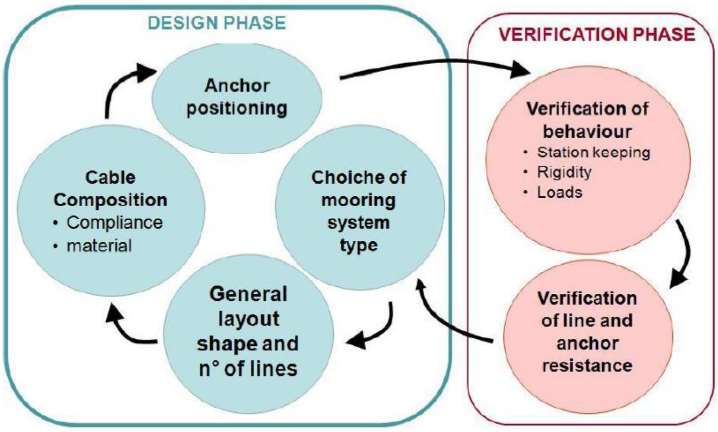


Figure 15 The design procedure concerning the mooring development

The mooring system under consideration will focus on reducing the cost, the foot-print of the mooring system – and increase the compliance of the system using the Sea-flex the mooring lines.

The mooring compliance (stiffness) has an influence on the maximum mooring load and in general the more flexible the mooring system is the lower mooring loads can be expected. However a very flexible mooring system also place additional requirements on the electrical connection that has to extend further in order not to be pulled over.

Set up

Choice of mooring system

The choice of mooring system has fallen upon a system with small environmental impact (no chains dragging on the seabed) and it is moored using synthetic ropes to three fixed anchor points. The mooring system is called "the triple / flex principle", developed for the Crestwing WEC concept in cooperation between Waveenergyfyn's and Seaflex with the following requirements:

- survive the specified design conditions
- adaptable to a specified WEC
- ability to allow the device to move
- minimum seabed contact and environmental footprint
- insure that the mooring and power line are compatible
- allow for weathervaning in relation to incoming wind and wave direction (360 horizontal rotation)

General Layout

The mooring design consists of three mooring legs as illustrated on the figure below, including the following components:

- Mooring blocks
- Synthetic ropes (vertical parts)
- Buoyancy floats
- Seaflex lines (horizontal parts)
- Anchor line connection tower

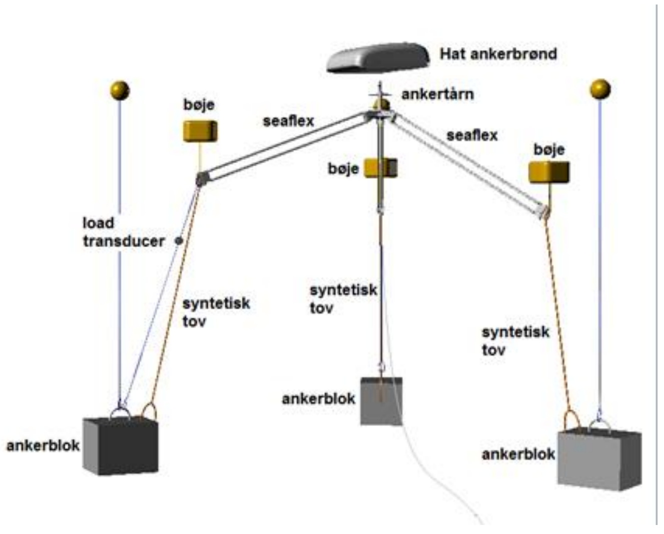


Figure 16 The triple / flex anchoring principle

The three mooring legs are connected to a central “anchor tower” that enables the WEC to sway 360 degrees, while the electrical connection is connected through a pipe in the center. The development, construction and installation of the anchor tower for quick on site on and off coupling has been a major achievement of this preliminary experiment. Photos of the tower can be found in Appendix 1.

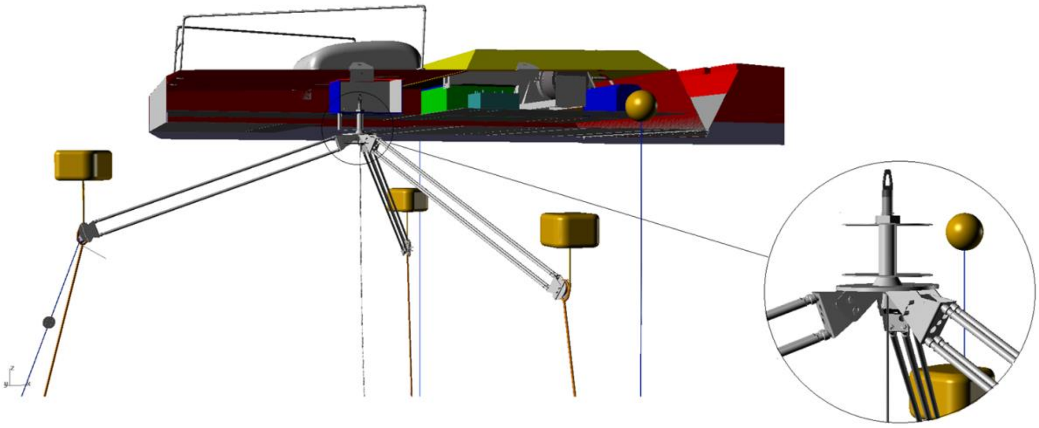


Figure 17 The central anchor tower

Defining the general lay-out

The geometry of the mooring system is characterized by the following parameters:

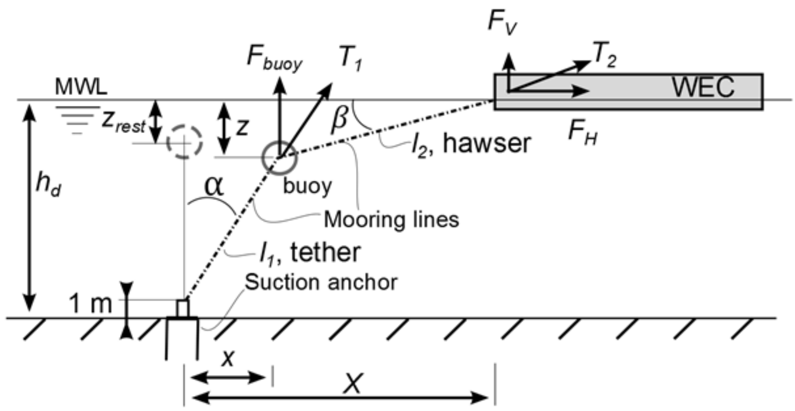


Figure 18 Geometric definition of one mooring leg

Table 2 Geometry of mooring line system rest position (approximated in no tension condition)

Component (rest position)	Unit	Symbol	Value scale (1:5)
Water depth	[m]	h_d	4,5
Synthetic rope length	[m]	L_1	5,5
Vertical force from buoyancy buoy	[kN]	F_{buoy}	0,120
Installed length of seaflex	[m]	L_2	2
Horizontal distance Anchor to Tower	[m]	X	5

Cable composition compliance and material

Composition of one anchor leg:

1. Anchor block, dry weight and volume (xx ton, volume m^3)
2. Floater (weight, volume and net bouancy)
3. Synthetic rope (length, breaking strength (load extension curve)
4. Sea-flex element (unloaded length, breaking strength (load extension curve)

Table 3 Cable compositions and material

	Unit	symbol	Value (1:5)
Anchor block dry weight	[ton]	M_a	0,640
Anchor block volume	[m^3]	V_a	0,275
Anchor submerged weight	[ton]	M'_a	0,365
Floater weight effective bouyancy	[ton]	M_f	0,0120
Rope length	[m]	l_1	6
Rope breaking strength	[kN]	F_1	200
Sea Flex Rope length	[m]	l_2	2
Sea Flex Rope breaking strength	[kN]	F_2	40

The load extension curve can be determined experimentally on land by measuring corresponding data of load and extension.

Scale and Design loads

The mooring system is developed in scale 1:5. Based on the experiments carried out at DHI, and AAU, [ref] the maximum design loads to be obtained by the mooring system is shown in table 1 presented in full scale values corresponding to a design suited for Hanstholm (1:1) and values for the present open sea tests in scale 1:5

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Table 4 Overview of the design load case

	Unit	symbol	DanWEC (1:1)	Scale (1:5)
WEC Length	[m]	L	60	10
WEC beam	[m]	B	20	2,5
WEC weight	[ton]	M	260	2
Water depth	[m]	h_d	25	4,5
H_s max (design wave case)	[m]	H_s	7	1,4
Max WEC mooring force	[kN]	F_{Hm}	125	2,5
Max Mooring compliance (at F_{Hm})	[m]	X_m	6	1,0

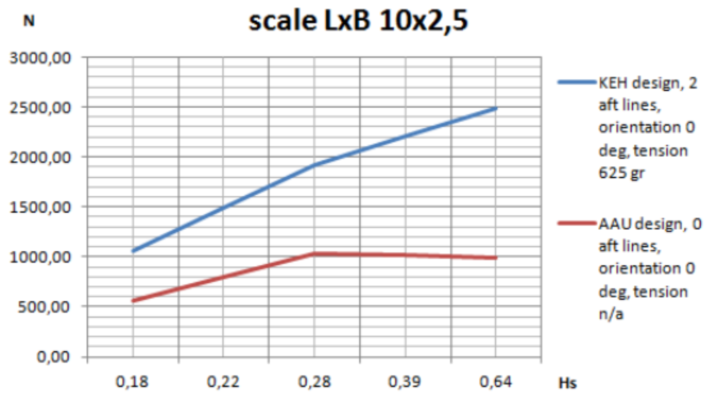


Figure 19 Measure mooring loads at AAU comparing a stiff and a soft mooring system.

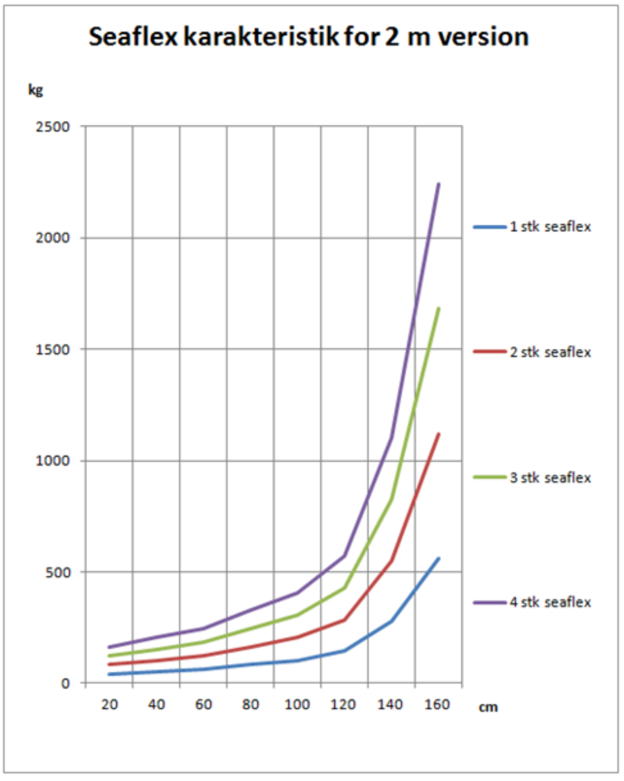


Figure 20 Load extension tests with 1 – 4 seaflex mooring lines in parallel. The experiment starts with 2 lines is used as a in parallel giving a load of about 8000 N at 1,5 meter extension.

Elongation at 10% of break load				1.00 %
Ø [mm]	kg/100 m	Bl. real [kN]*	Bl. linear [kN]**	Break length [km]***
4	1	7	8	68.6
5	2.1	12	13	56
6	2.6	16.5	18	62.2
8	4	30	33	73.5
10	6.8	49	54	70.6
12	9.9	75	83	74.2
14	13.3	95	105	70
16	17.5	120	132	67.2
18	22.3	150	165	65.9
20	28	190	209	66.5
22	33	230	253	68.3
24	39	255	281	64.1
26	44	275	303	61.3
28	46	317	349	67.5
30	58	360	396	60.8
32	60	410	451	67
34	68	460	506	66.3
36	76	510	561	65.8
38	85	563.2	620	64.9
40	94	624	686	65.1
42	104	688	757	64.8
44	114	750	825	64.5
48	135	885	974	64.2
52	159	1032	1135	63.6
56	184	1185	1304	63.1
60	212	1350	1485	62.4
64	241	1525	1678	62
72	305	1916	2108	61.6
80	376	2350	2585	61.3
88	455	2820	3102	60.7
96	541	3325	3658	60.2

Selected rope sixe

* Spliced break load
** Break load in accordance with DIN EN ISO 2307
*** Break length in spliced condition

Figure 21 Data concerning the rope type selected for the experiment-

Practical tests

Verification of mooring scale 1:5 component stiffness's in terms of experimentally defined load extension tests of actual mooring system, on land.

The complete mooring system has been assembled on land prior to bringing it to sea as shown on the figure below.

Figure 22 Complete mooring system assembled on land

Sea tests

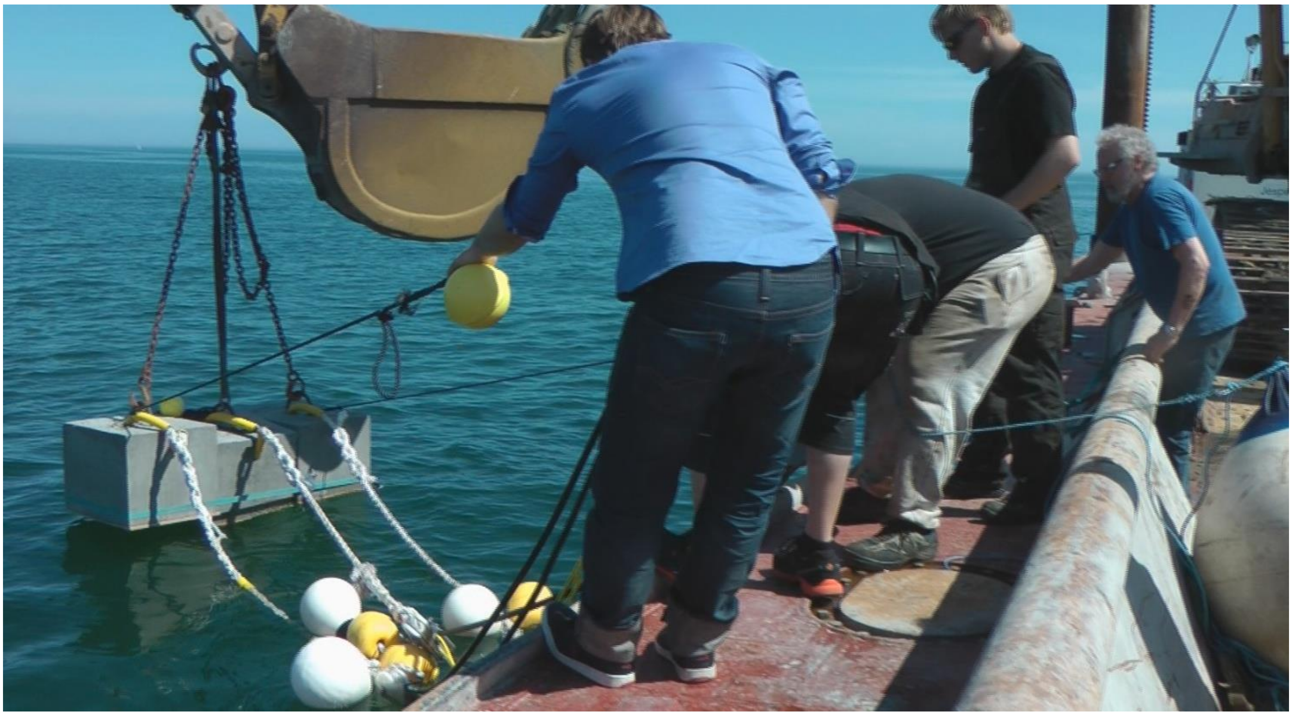
Anchor positioning

The first task is to position the anchor blocks, so that sufficient pretension in each line is achieved. This will requires weather conditions with calm sea – and a boat with sufficient power to pull the anchors in place. Laying and adjustment of the mooring and WEC system includes tracking of orientation, water level, force transducer monitoring of mooring and finally a visual surveillance including diver's inspection.

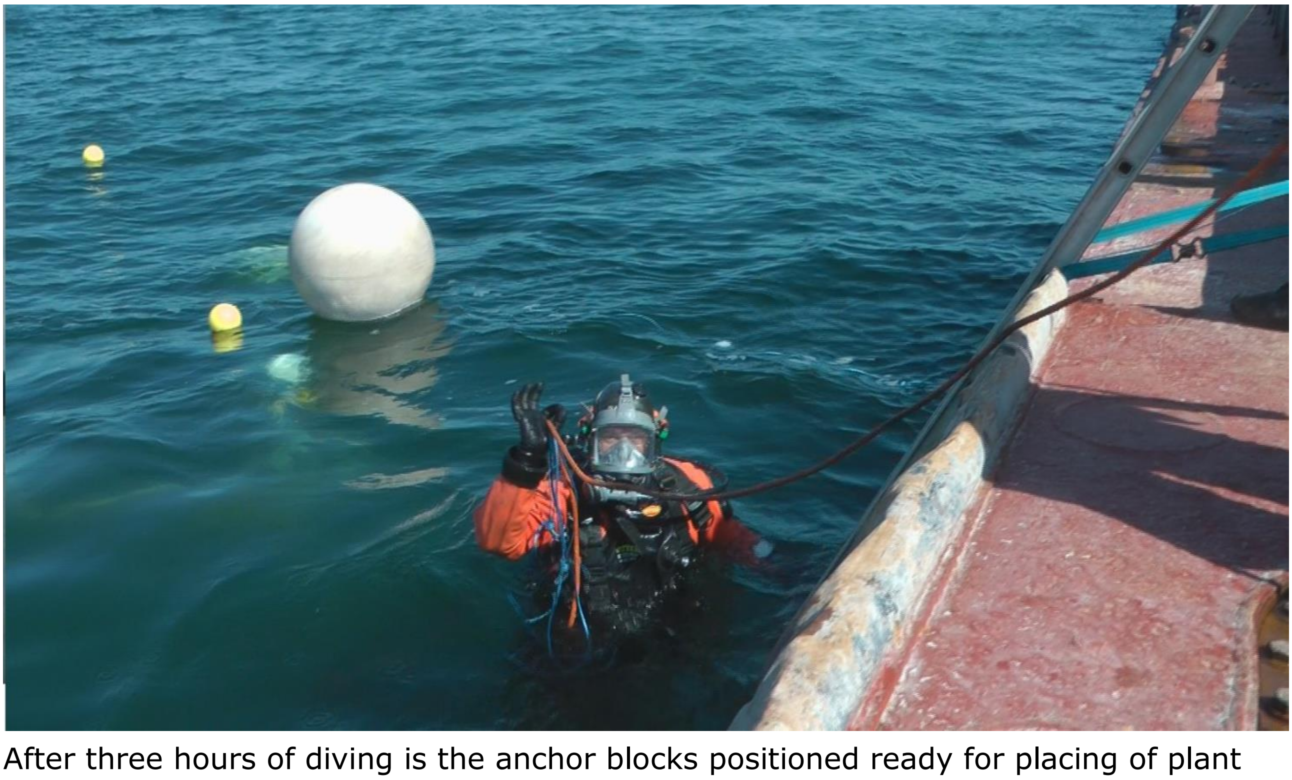
This includes a check that all shackles and connections are secured against unwinding, a typical course of mooring failure.

Deployment and anchor positioning of Crestwing 30 May 2014

Anchor blocks lifted up onto boat



Anchor blocks on the way to the bottom



After three hours of diving is the anchor blocks positioned ready for placing of plant

Quick on-site connections completed

Initial test of three-point mooring system is starting

Monitoring and verification of mooring behavior,

The mooring system will be monitored during operation - both onsite and online. The testing of the WEC includes using different PTO settings for the given operating parameters. The test program includes the measurement of following parameters:

- Waves (Hs, Tp, direction)
- Wind
- Power
- Water
- WEC motion and position
- Mooring forces

The monitoring system will be operated by Waveenergyfyn and AAU. The results of the testing will be collected and reported as a basis for further development. This will include analyses of the Power production in relation to the wave conditions as well as the resulting mooring load curves plotted against the significant wave height for a few main directions of incoming waves.

Conclusions and areas that has potential and requires more investigation in the future

A simplified numerical model of the mooring system can help support the development and based on the measure WEC motions and resulting mooring forces.

The use of gravity anchor blocks as used in this project allows adjustment of anchoring setup during the tests. Further the anchor blocks in case of overload will slide along the seabed and the risk of overloading and breaking the ropes is limited. Screw Anchors as investigated as part of this project has the potential to become the preferable economic and environmental best solution.

Further development therefore should include COE calculations i.e. based on the system developed by Energinet.dk, estimates of O&M (Operations and Maintenance in general underestimated), expected lifetime, important issues that will need the involvement of other industry.

Planning a full scale test at DanWEC should include an investigation of how to insure and certify the WEC and moorings. This could include procedures and technologies for damage control.

Further development of anchor tower with yaw bearing, yaw control, wired up with 360 degree swivel joint, automatic on / off switching of the WEC.

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