Performance improvements of mooring systems for wave energy converters

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ABSTRACT: In the development of wave energy converters, the mooring system is a key component for a safe station-keeping and an important factor in the cost of the wave energy production. Generally, when designing a mooring system for a wave energy converter, two important conditions must be considered: (i) that the mooring system must be strong enough to limit the drifting motions, even in extreme waves, tidal and wind conditions and (ii) it must be compliant enough so that the impact on wave energy production can be minimised. It is frequently found that these two conditions are contradictory. The existing solutions mainly include the use of heavy chains, which create a catenary shaped mooring configuration, allowing limited flexibility within the mooring system, and hence very large forces may still be present on mooring lines and thus on anchors. This solution is normally quite expensive if the costs of the materials and installation are included.

This paper presents a new solution to the mooring system for wave energy converters within the FP7 project, 'GeoWAVE', which is a project aiming to develop a new generation of the moorings system for minimising the loads on mooring lines and anchors, the impact on the device motions for power conversion, and the footprint if it is applicable, and meanwhile the new types of anchors are also addressed within the project. However this paper will focus on the new mooring system by presenting the wave tank test results of the Pelamis wave energy converter model and the new developed mooring system. It can be seen that the new generation of mooring system can significantly reduce the loads on mooring lines and anchors, and reduce the device excursions as a result of the new mooring system when compare to the conventional catenary mooring.

1 INTRODUCTION

Mooring systems have been the subject of extensive research for the offshore oil and gas industry to stabilise structures. These existing mooring technologies have been adopted since then in renewable energy with wave energy converters (WEC) (Iraide 2013, Fadaeenejad 2014, Ringwood 2008). Concepts have been considered and implemented depending on their principle and the location. Offshore WEC would give the opportunity in the deep waters (~100 m), to make use of the energy potential of large waves in both amplitude and period (Ringwood 2008). Catenary moorings are generally employed to attach structures to the seabed, and it was first suggested that the catenaries were ideal for WEC (Harris 2004).

Several catenary mooring configurations were proposed which could be accomplished with single- or multi-connections (Fitzgerald 2008). These can have an influence on the motion, orientation of structure and the performance of the system. Multi-point connections are more likely to reduce the excursion and the system will not be able to easily align to the incoming waves. However, the use of catenaries may suffer from wear and fatigue damage (Thanos March 2001) and affect the structure safety due to vortex-induced vibration (Thies 2011, Wang 2014).

The use of other materials (e.g. synthetic braided nylon, steel rope), alone or in conjunction with catenary lines were analysed (Fitzgerald 2007, Fitzgerald 2008). When the catenary line was used alone, large forces on the anchor were obtained. The use of an intermediate floating buoy with a rope was found to help reduce the force on the structure attachment.

Fitzgerald et al. (Fitzgerald 2008) presented the progress of the AWS Waveswing™ prototype using the principle of Archimedes, comparing fixed structure and single point attachment devices. Less force on the anchor was measured when the articulated concept was considered due to the damping effect of the air.

Analysis of the possibility of using a tether in floating platform showed that it could help in saving cost compared to a multi-point catenary arrangement (Wang 2013). The restoring force from the tether arrangement was found to be much higher. However, it must be noted that the conventional mooring systems for oil and gas platforms are used for much deeper waters (so far larger than 2000 m, (Clauss 2009)), for which the mooring flexibility may be easily achieved. Instead, in the wave energy converters, the water depths are more likely in the contours of about 100 m, hence the mooring systems are essentially different. In addition, in the shallow water regions, the water depths may be affected very much by the tidal ranges. However, the mooring system design for wave energy converters must consider all these factors. Due to the survivability in the extreme waves, wind and current conditions, the moorings for wave energy converters have to be designed to be strong enough, for example, using heavy chains in the catenary mooring system. This brings some practical difficulties in the mooring systems for wave energy converters in providing very limited flexibility which in turn may create larger loads on anchors (as a result of this, larger anchors must be used), and the costs of the materials and installation may be high. In the GeoWAVE project, a new generation mooring and anchoring system has been developed and the relevant problems have been addressed as a systematic research. For example, the new mooring system may indeed significantly reduce loads on mooring lines and on anchors and the anchoring problems are also addressed by designing efficient anchors as well as the reduction of the relevant installation cost.

In this paper, the focus is on the mooring systems for the wave energy converters, and the wave tank test results will be presented to show the benefits of the new generation mooring system when compared to the production catenary mooring system.

2 PHYSICAL MODEL AND RELEVANT ISSUES

Figure 1 shows the general arrangements of two different types of mooring systems considered in this research. The first mooring is the catenary mooring system, which is also the existing mooring used in the Pelamis wave energy converters, while the second mooring is a new developed mooring system, the taut-leg mooring by incorporating the Seaflex elastic components.

With the catenary mooring line type, the first part of the catenary lies started from the anchor on the seabed and the rest in a catenary shape reaches the WEC. Therefore, the mooring load on the anchor is only horizontal unless all the chain has been lifted up. The existing catenary mooring design for the Pelamis device is considered as a reference (Twidell 2006).

In the second mooring system, the taut-leg mooring is considered. To provide flexibility of the mooring system, part or all of the mooring line has been replaced by the Seaflex elastic components (Seaflex).

Seaflex products have been used for a long time in many countries around the world to secure boats and docks as conservation moorings (Urban Harbors Institute 2013). Figure 2 presents the cross section of a Seaflex strand.

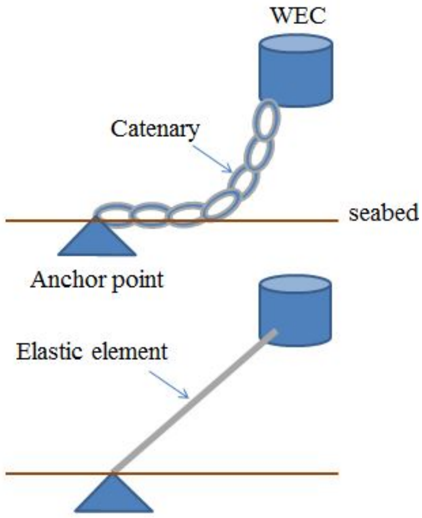

Figure 1. General principle of the catenary and elastic mooring line

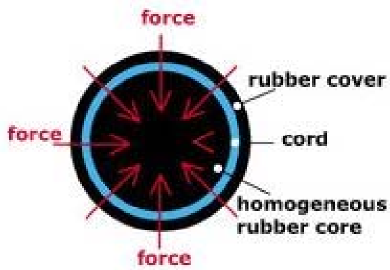

Figure 2. Cross-section of a Seaflex strand

Seaflex elastic component is a type of the elastomer materials family and has been used in many applications due to its unique characteristics for providing larger resistance to the mooring system and being able to smoothen the motions of the moored structures. Figure 3 shows the typical force – strain curve for a Seaflex elastic component. The curve can be split in two distinctive parts: in the low extension (0-0.65), the material is very flexible, after that the component becomes much stiffer in a manner to provide a large resistance to the mooring system.

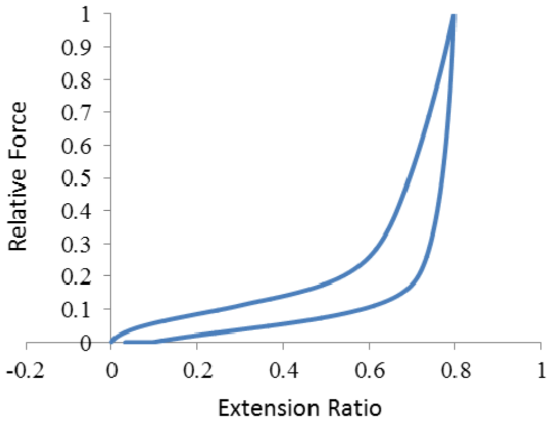

Figure 3. Seaflex elastic component Force – extension curve

Another feature of the Seaflex elastic component is the hysteresis in the strain-force curve (see Figure 3). By this feature, the Seaflex elastic component itself can perform as a damper to the mooring system, meaning the mooring line itself can dissipate energy acting on the mooring. This damper can actually smoothen the motions of moored structures (Sheng 2014).

3 CONSIDERATIONS

3.1 *Wave basin*

The pre-commercial Pelamis wave energy converters is being tested at the European marine Energy Centre (EMEC), and the wave conditions are the target we considered for the tank test. In the tank test, the extreme wave was chosen from the wave scatter diagram as a significant wave height of 10.76 m, and an energy period of 13.0 s which is usually considered a wave for testing the device survivability. However, different waves for both survivability and operability were also used, even regular waves.

3.2 *Basin waves*

Experimental tests were carried out using the existing Pelamis model (1:28.87) at the Plymouth COAST wave basin to investigate the behaviour of mooring lines in different sea states, especially the extreme waves at the site where the Pelamis wave energy devices are supposed to be deployed. The basin has a length of 35.0 m, a width of 15.65 m and water depth of 3.0 m, and the tank has a movable floor, which can be used to adjust the water depth. For instance, the water depth has been set as 2.77 m which corresponds to the targeted water depth of 80 m in full scale.

3.3 *Model design*

The Pelamis wave energy converter model is the existing scaled model, composed of a set of movable elements, linked together to allow relative motions. The orientation of the device in this research is heading to the wave makers in the tank.

The head of the Pelamis device is designed to facilitate the connections to the moorings lines.

The control and power take-off within the Pelamis were also installed, hence the model can be easily set as the state of survival (without power conversion) or of power conversion.

3.4 *Measurements*

The Qualisys tracking system (Qualisys 2011) is used to measure the motions of the device in waves in a non-intrusive manner. The Qualisys cameras capture the reflective markers fixed on the model and record the coordinates of the markers in 3 dimensions. Based on the coordinates, the 6 degree of freedom (DOF) motions (surge, sway, heave, roll, pitch, and yaw) can be obtained using the relevant software.

Forces on the mooring lines and on anchors were measured using load cells that were installed in the relevant positions.

A set of wave gauges were placed in the basin at specific locations in order to correlate the movements and the propagation of the waves.

3.5 *Scaling issues*

In the model test, the Froude similarity is used, hence the relevant scaling factors are listed in Table 1.

Table 1. Scaling coefficients for units

Parameter	Unit	Scaling factor
Length	m	λ
Area	m^2	λ^2
Volume	m^3	λ^3
Mass	kg	λ^3
Force	N	λ^3
Torque	Nm	λ^4
Power	W	$\lambda^{3.5}$
Time	s	$\lambda^{0.5}$
Velocity	m/s	$\lambda^{0.5}$
Angular speed	rad/s	$\lambda^{-0.5}$
Unit mass of mooring line	Kg/m	λ^2
Stiffness	N/m	λ^2

It must be noted that in the model test, the Pelamis model and mooring model are exactly scaled down using the relations given in Table 1. However, for a scale model, fully scaling of the mooring lines is neither necessary, nor practical

(Pfister 2012). In this model test, the most important aspects of the mooring modelling were considered, that is, the length and the stiffness of the mooring system. As a result of the consideration, the mooring length and the unit weight of the catenary mooring lines or the stiffness of the elastic component were only modelled, but not the sizes of the mooring lines.

3.6 *Modelling of the Seaflex elastic components*

A Seaflex mooring component is an elastic unit, which could provide the required flexibility to the mooring system. The unique feature of the Seaflex elastic component is the hysteresis when the component is stretched and de-stretched. To appropriately model the component, it is found that the O-ring cord can experience the hysteresis when it is stretched and de-stretched (see Figure 4). That is why in the model test, O-ring cords have been used to model the target mooring with the Seaflex elastic component.

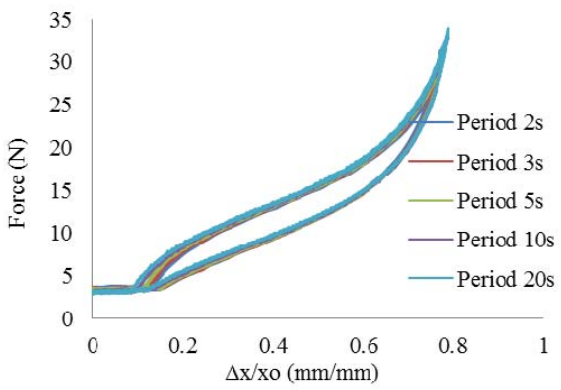

Figure 4. O-ring cord 3.5 mm test

But it must be noted that though the O-ring cords are similar in the hysteretic force-strain curve, the full modelling of the Seaflex elastic components are not straightforward. In addition, it is also found that the O-ring cords experience creeps if a consistent force is applied on the component. In the experiment, all this phenomena must be considered and addressed so that an appropriate modelling can be possible.

4 MOORING ARRANGEMENTS

The two mooring configurations are presented in Figure 5. Figure 5-a) is the schematic plot of the current mooring system for the Pelamis wave energy converter. The WEC is connected to three anchor points via the catenary mooring lines. Load cells have been placed in-line of the catenary chain at the level of the anchor point. Lines with L2 and L3 are sideways, where L1 is at the front. In this mooring setup, the front mooring experiences largest force on mooring line and anchor. Relatively, the loads on the side mooring lines are smaller than that on the front mooring.

Figure 5-b) is the new mooring system proposed in the GeoWAVE project, a taut configuration using tether mooring lines by incorporating the Seaflex elastic components in the taut leg mooring lines so that the mooring system can be compliant enough. Two taut legs are placed at the front and one is at the back. Unlike the catenary mooring, there are two mooring lines symmetrically at the front of the wave energy converter, which experience largest force on two mooring lines. Hence, the main loads on the taut-leg mooring lines may be evenly shared.

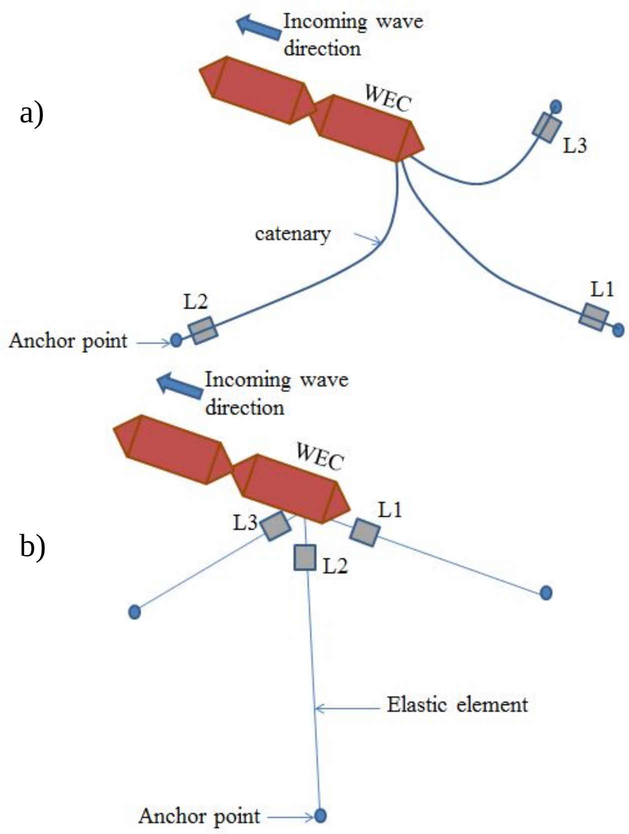

Figure 5. Schematically drawings of the mooring system for the test model, a) Catenary and b) taut arrangement; L1, L2 and L3: load cells

5 RESULTS AND DISCUSSION

5.1 *Comparison in extreme waves*

The extreme waves are the most important aspects for testing the survivability of the device and the mooring system.

Figure 6 shows the comparison of the dynamic load (‘dynamic load on mooring line/anchor’ mean the pretension has not been included for analysis) for the catenary mooring and the taut-mooring. The load has been normalised using the maximal dynamic load on the anchors. It can be seen that the taut-leg mooring has reduced the load on anchor very much. If we examine the loads carefully, it can be seen that the second loads (the slowly varying components) are very similar for both mooring systems. However, the first order loads are very different for the two mooring setups, probably due to the flexibilities of the mooring lines. In the catenary mooring, the high stiffness of the mooring line cannot response well with the first-order motions, for example, heave and pitch motions, hence a large load on the mooring line is induced. For the taut-leg mooring, the elastic component can provide much higher flexibility on the mooring line, and hence cope with the first-order motion very well.

It must be noted that in the catenary mooring, the anchor loads are only horizontal, while for the taut-leg mooring, the anchors must provide both vertical and horizontal holding capacities, hence different anchoring technologies may be needed. Luckily, the anchoring problem is also addressed within the GeoWAVE project.

Figure 7 shows the corresponding surge motions in the two mooring setups. It can be seen that in the taut-leg mooring, the surge motion is smaller than that of the catenary mooring. This is very beneficial because the reduction of the device excursion is achieved under the condition of smaller loads on mooring line and anchors. Another feature of the surge motion is that the surge motions of the device have been dominated by the second-order motion, i.e., the slowly varying motions in surge. If we correlate the surge motion with the loads on anchors, one can easily see that the second-order loads are mainly induced by the surge motions.

Figure 8 andFigure 9 are the comparisons of the heave and pitch motions. It can be seen that both of the motions are mainly first-order motions, and they are similar for the very different mooring setups. Hence it can be deduced that the taut-leg mooring will not affect the device motions for power conversion, though in the extreme waves, the power conversion is normally switched off.

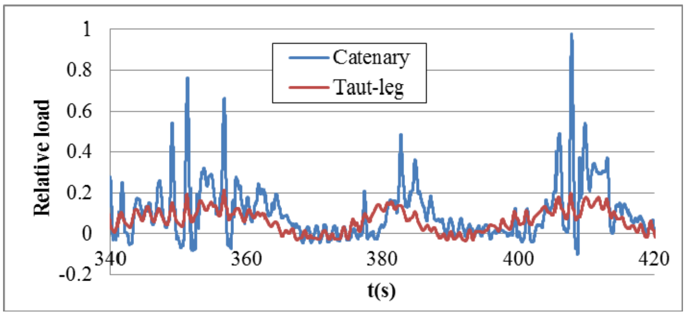

Figure 6. Loads on front anchor (normalised by the largest load on anchors)

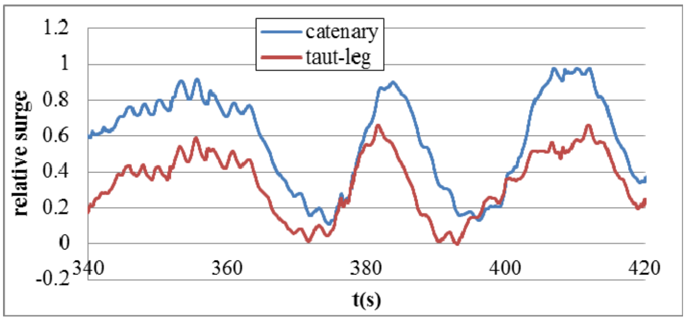

Figure 7. Surge motion (normalised by using the largest excursion)

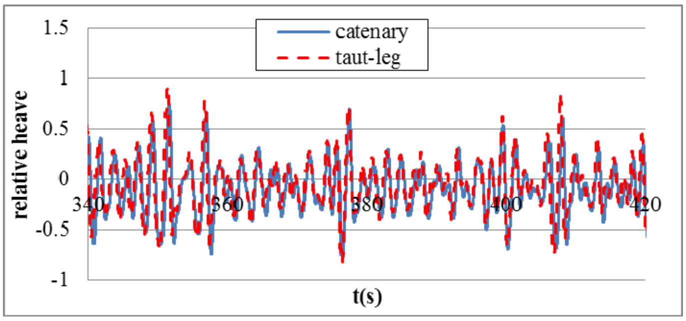

Figure 8. Heave motion (normalised by the maximal significant height of heave motion)

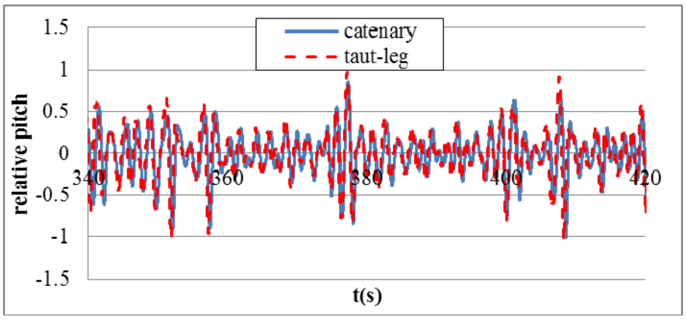

Figure 9. Pitch motion (normalised by the maximal significant height of pitch motion)

5.2 *Comparison in operation waves*

In this section, the comparisons are made for waves in operation condition with a wave significant height of 4.95 m and an energy period of 8.97 s. It can be seen from Figure 10 that under these operational waves, the loads on mooring lines/anchors are much smaller than those in the extreme waves (compare to Figure 6). As a result of lesser wave excitation, the surge motions are smaller (Figure 11). Again, the heave and pitch motions for two different moorings are very similar.

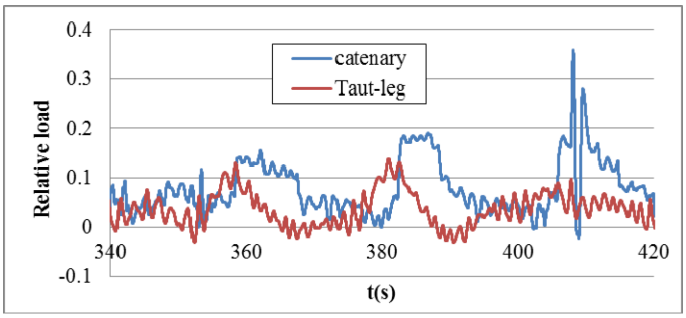

Figure 10. Loads on front anchor (normalised by the largest load on anchors)

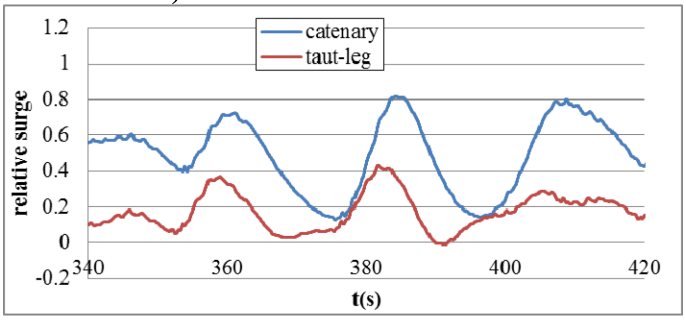

Figure 11. Surge motion (normalised by using the largest excursion)

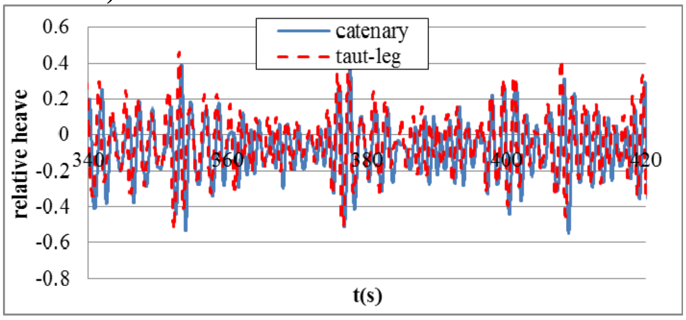

Figure 12. Heave motion (normalised by the maximal significant height of heave motion)

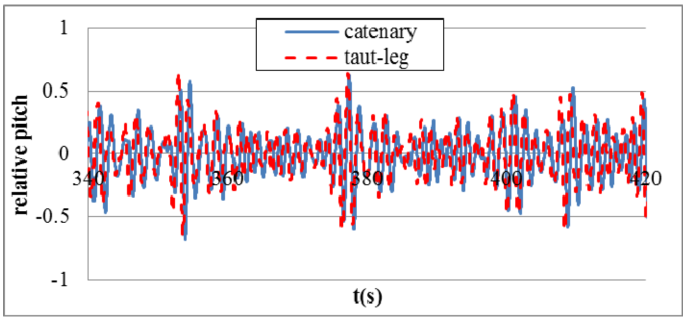

Figure 13. Pitch motion (normalised by the maximal significant height of pitch motion)

5.3 *Further comparisons*

Table 2 andTable 3 show the detailed comparisons of the loads and motions. For an optimised mooring system, it is important to have a reduced maximal loads on the mooring lines and anchors, and the maximal excursions of the device. Hence for comparison of the loads and surge motions, it is important to compare their maximal values. While the heave and pitch motions of the device are more for power conversion, and their statistical values may be more important, hence their significant values are compared (‘significant value’ means the average value of the largest 1/3 heights of the motions). From the tables, it can be seen that the taut-leg mooring has reduced the loads on mooring lines and the excursion of the device in both extreme and operational waves. If power conversion is considered, the heave and pitch motion are actually improved in the taut-leg mooring than that in the catenary mooring, which means the taut-leg mooring may improve the power conversion.

Table 2. Loads and motions in extreme waves (Hs=10.76m/Te=13.0s)

Parameters	criterion	Catenary	Taut
L1	Maximum	1.00	0.32
L2	Maximum	0.61	0.32
L3	Maximum	0.63	0.31
Surge	Maximum	1.00	0.60
Heave	‘H1/3’	1.00	1.07
pitch	‘H1/3’	1.00	1.11

Table 3. Loads and motions in operational waves (Hs=4.95m/Te=8.97s)

Parameters	criterion	Catenary	Taut
L1	Maximum	0.360	0.175
L2	Maximum	0.215	0.170
L3	Maximum	0.224	0.156
Surge	Maximum	0.958	0.549
Heave	‘H1/3’	0.483	0.540
pitch	‘H1/3’	0.627	0.709

6 DISCUSSION

The reduction of loads in the mooring system has many benefits which may lead to the overall goal of reduction of the total cost of energy however these must be balanced against the costs of the implementation of the load reducing technology in this case through the elasticity of the materials used. There are many factors to consider in marine renewable array mooring design and often conflicting ones so a full analysis of the mooring design and associated costs including installation and decommissioning costs before the optimum system can be chosen and the benefit to the cost of energy realised. For example, the load reduction seen in these tests can lead directly to a reduction in the size of the anchor used in the case of gravity anchor however the additional uplift forces preclude the use of drag embedment anchors, currently the most cost effective anchoring means where soil conditions allow. Equally the layout tested here was chosen as one which would lead to lowest line loads and maximum benefit from the Seaflex component, however in an array deployment the layout is less compatible with other cost reducing options, the sharing of anchors between machines. So even where gravity anchors are used the benefit of reduced size of anchors may be tempered by a need for a greater number of them.

The layouts chosen also do not allow direct load comparison between the equivalent catenary mooring and elastic taut designs however they do allow a greater insight into how far the application of this technology could take the load reduction against existing practical design. A more direct equivalent catenary version of the taut layout, i.e. three single catenary lines on the same headings as the taut mooring lines and with no connections between them would be an interesting further comparison but does not show as well what could be achieved against what would be the current alternative.

It is also important to acknowledge and understand the limitations of the testing in terms of the range of load cases investigated and how this dataset would relate to a full mooring study leading to a satisfactory level of risk mitigation for the developer, usually accompanied by either a third party design verification or certification by a suitable body such as a classification society. Constraints around time and budget of course place restrictions on the depth and breadth of possible testing within this project so the limited set chosen is by no means comprehensive and is insufficient to prove the configuration is survivable in all reasonable conditions. The chosen tests are based on experience of full investigations by PWP on the catenary mooring systems and whilst they cannot be guaranteed to represent the worst case scenario for the elastic taut mooring, it is reasonable to assume the tests are likely to be fairly close to worst case for sites similar to those evaluated by PWP to date. A full analysis would look at a much greater range of angles of incidence of both waves and tidal flows and reduce the potential for doubt as to the worst case which arises from the fact that different mooring layouts and sources of compliance will react differently to particular combinations of waves and tidal flows. E.g. it is reasonable to assume in the case of this taut mooring that the wave frequency loading will be distributed across both front lines whereas in the catenary the single front anchor line is doing the vast majority of the work and it is easy to imagine that a wave and tide combination more from one side would lead to higher individual line loads on the up-weather side in the taut mooring.

However given the above, the benefit seen in the load cases chosen is of sufficient magnitude (up to ~70%, and without negative effects in surge excursion or pitch and heave motions) to show the considerable potential of this technology to play a part in the mix of mooring options and to warrant further investigation. By this we suggest further research effort to better characterise and simulate the behaviour and longevity of these materials, cost reduction effort on the part of the manufacturers and more detailed consideration on the part of the mooring designers of marine energy systems such as Pelamis to arrive at the optimum mooring solutions for device arrays to lead to minimum overall cost of energy.

7 CONCLUSIONS

The spring and hysteresis characteristics of the Seaflex elastic element can be modelled with good similarity at small scale using a combination of inelastic cords and O-ring cords. However, a degree of O-ring creep must be taken into consideration in the model tests;

Experiments using elastic elements combined with a new mooring layout reduced mooring loads considerably. For example, the maximum dynamic force in original catenary mooring can be reduced by 70% using the taut mooring. The taut-leg mooring also reduced the device excursions.

These benefits of the taut-leg mooring must be weighed against the potential cost increases due to the incorporation of the elastic elements and the provision of anchors capable of taking their vertical loads. Anchors of appropriate vertical and horizontal holding capacity are being investigated in the GeoWAVE project.

The application of the taut-leg moorings to the Pelamis wave energy converter does not significantly change the angular motions of the machine, which are the main motion modes for power conversion. Therefore, the new mooring system will not have negative effects on the Pelamis power conversion.

ACKNOWLEDGEMENTS

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