Proceedings of the 3rd Marine Energy Technology Symposium
METS2015
April 27-29, 2015, Washington, D.C.

OCGEN® MODULE MOORING DESIGN

Cian Marnagh
Ocean Renewable Power Company
Portland, ME, USA

Jarlath McEntee
Ocean Renewable Power Company
Portland, ME, USA

James Donegan
Ocean Renewable Power Company
Portland, ME, USA

Milo Feinberg
Ocean Renewable Power Company
Portland, ME, USA

Michael MacNicholl
Maine Marine Composites
Portland, ME, USA

[1]Corresponding author: cmarnagh@orpc.co

INTRODUCTION

Ocean Renewable Power Company, LLC (ORPC) has successfully completed the OCGen® Module Mooring Project (Project).The Project made a significant step in the development of designs, methodologies and practices related to floating and mooring of marine hydrokinetic (MHK) devices. Importantly for ORPC, the Project provided a sound basis for advancing a technically and commercially viable OCGen® Power System. The OCGen® Power System is unique in the MHK industry and, in itself, offers distinct advantages over MHK devices that are secured to the seabed using fixed structural frames. Foremost among these advantages are capital and operating cost reductions and increased power extraction by allowing the device to be placed at a more energetic level of the water column.

This Project required an extensive research, design, development, testing, and data collection and analysis effort conducted with respect to a positively buoyant, submerged MHK device secured to the seabed using a tensioned mooring system. Although the Project was based on ORPC's OCGen® Power System, it has wide applicability to other MHK systems and to other ocean-based technologies, including offshore oil and gas.

Different analytic tools were evaluated for their utility in the design of submerged systems and their moorings. Three analytical approaches were evaluated: basic computational fluid dynamics (CFD), an ORPC developed lumped-parameter modeling effort, and use of commercial mooring analysis codes. These analytical efforts were supported by a limited scale model test effort. Commercial mooring codes offered significant advantages over the other approaches, in that a well developed and validated code offered higher confidence in the analysis results. Scale model testing was shown to have been qualitatively valuable by rapid testing of selected mooring configurations.

Deployment and testing of a prototype OCGen® system provided significant data related to mooring line loads and system attitude and station keeping. Mooring line loads were measured in situ and reported against flow speeds. The data set generated was one of the few data sets available for such mooring systems. The data will prove useful for additional validation work of newer design approaches.

The most important overall measure of the technical and economic effectiveness of the methods and techniques used in the Project was the full demonstration of the stability of the OCGen® device in reversing tidal currents and the efficacy of the tensioned mooring system. There was no doubt after completion of this Project, that the basic design assumptions of ORPC's OCGen® Power System have been technically and operationally proven and that both capital and installation costs associated with the tensioned mooring system are significantly less than those incurred in ORPC's fixed frame power system, the TidGen® Power System.

Costs of concrete and welded steel anchors were lower than the construction for the tubular space frame structures used for the TidGen® device. While overall masses may be equivalent between the anchors for OCGen® and the bottom support frame of the TidGen® device, the mass for the OCGen® anchors was mostly concrete as opposed to high quality steel. Costs of mooring lines were small compared to other project costs.

Installation costs for the buoyancy OCGen® system were much lower than for a piled foundation used for the TidGen® Power System. Installation for the TidGen® Power System would not be expected to be less than ten days of on-water work at the deployment site with expensive lift and barge assets. Deployment of the OCGen® system took place in two days with the majority of the assembly work conducted in protected near shore environments. Actual deployment of the system at the site took approximately six hours.

A further advantage of the OCGen® anchor system was the reduced environmental impact of the installation of the two concrete anchors in comparison to the steel framed bottom support structure with concrete piles for TidGen® Power System. Whereas installing a piled structure for the TidGen® device required hydroacoustic monitoring and observations of endangered species and marine mammals, it was determined by regulators that the tensioned mooring system required no such monitoring.

Approaches Used

ORPC developed analytical tools for the design of an OCGen® TGU, mooring lines and anchoring system. While multiple design tools were evaluated, the primary design tool selected was a commercial mooring code, OrcaFlex, due to its ability to analyze a wide variety of situations and arrangements in a time efficient manner.

From the analytical work performed, it was clear to ORPC that the prototype and full-scale OCGen® power systems should comprise the following basic elements: a set of cross-flow turbines; a buoyancy pod or chamber arranged above the cross-flow turbines, so that the center of buoyancy of the combined system was above the center of mass of the combined system in order to have basic stability; mooring line attachments to be placed on the buoyancy structure at some vertical location between the center of drag of the turbines and the center of drag of the buoyancy pod; a set of synthetic mooring lines utilized as tension leg moorings attached from the TGU to the moorings; and a set of mooring blocks on the seafloor, which obtain their holding power primarily by weight alone (Figure 1).

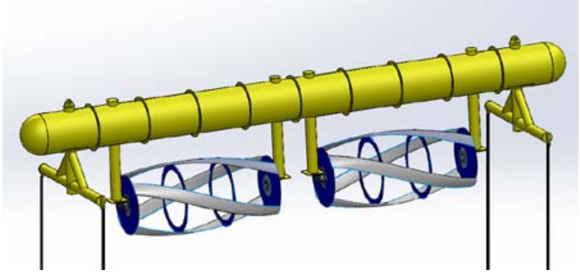

FIGURE 1. PROTOTYPE OCGEN® ARRANGEMENT, SHOWING THE TGU, WITH SPHERICAL END CAPS AND SINGLE VERTICAL SUPPORTS FOR TURBINES AND MOORING LINES.

With these elements in mind, a prototype OCGen® Power System was developed. The intent was to construct, deploy, operate, and retrieve this system within ORPC's Federal Energy Regulatory Commission-licensed site in Eastport, Maine.

Bathymetry information for this site showed little variation in elevation within the approximate footprint of the turbine. Based on this information, the mooring and anchor design was performed assuming a flat seabed. The water depth at the site was 25 m (82 ft).

At the OCGen® deployment location, the tidal flow was known to have different yaw angles during the ebb and flood tides. The magnitude of the maximum tidal flow was taken as 2.4 m/s for the design of the OCGen® prototype.

Mooring System Modeling

OrcaFlex was used to calculate mooring line tension at the top end of the line for different flow speeds and flow directions (Figure 2).

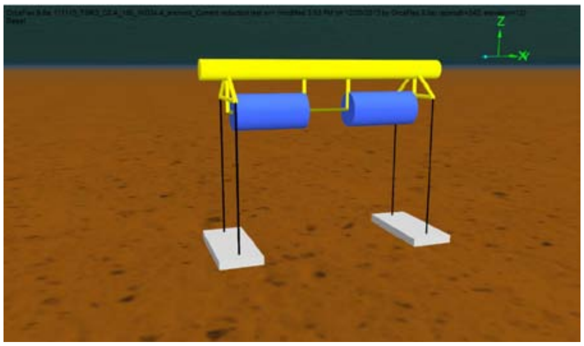

FIGURE 2. ORCAFLEX MODEL OF THE PROTOTYPE OCGEN® POWER SYSTEM

Mooring Lines

Line tensions were taken at the top end of the line, at the connection point to the structure, where the maximum tension occurred. The maximum mooring line tension was 64.95 kN, and occurred in both forward lines under a head-on current with a maximum turbine tip speed ratio (TSR) of 3.0. Since the mooring system and structure were symmetric, the same maximum tension would occur in the two aft lines when the tide flow was reversed.

Displacements predicted by the model were determined. Results showed only a slight rotation of the model. The mooring configuration allowed very little rotation in yaw. For the most extreme case of a 20 degree offset current, the yaw of the model was approximately half a degree. The maximum roll was less than 1 degree. Maximum movement in the flow direction was 8.25 m, resulting in a forward mooring line angle of 43.5 degrees from vertical. This large motion in the flow direction is expected as the design balanced drag from buoyancy pods and turbine against the buoyancy forces.

Consideration of vortex induced vibration for the mooring line indicated that it is not particularly likely for these line lengths. The expected shedding frequencies were less than 6Hz for water speeds of 2.5 m/s, and the fundamental vibration frequency for the mooring line was predicted to be greater than 11Hz.

Design of the Anchors

The bathymetry information for this site showed little variation in elevation within the approximate footprint of the turbine. Based on this information, the mooring and anchor design was performed assuming a flat seabed. The water depth at the site was 25 m (82 ft).

The anchor design consisted of two concrete clump weight anchors. Each anchor has a 1.5-ft high steel skirt surrounding the perimeter with 1.5-ft high steel shear keys. The shear keys and skirt provided additional lateral holding capacity by engaging the soil contained within them.

Modal Analysis (PCCI)

OrcaFlex was used to determine the natural frequency of the overall system. The natural frequency was calculated for the model in two static state cases: no current and 2.4 m/s at 180°.

The mode shape for mode 1 consisted of rigid body oscillation in the fore and aft direction; mode 2 was oscillation about the vertical axis, and mode 3 was oscillation from side to side.

The longest modal period calculated for the moored structure was 11.2s. This was much less than the shortest expected period of variation in current of 60s; therefore, ORPC expected no dynamic amplification of the oscillations of the turbine due to resonance with the current variations. For flows with shorter periods, we expected the length scale of the flow to be small enough as to not affect the entire structure simultaneously.

OCGen® Height

A plot of OCGen® height as a function of water speed is shown in Figure 3. Of note was the behavior at slack water, v = 0m/s. There was a slight but noticeable bi-stable condition in the data, which indicated different OCGen® heights at low and high slack water events. OCGen® height was calculated using an on board self-contained pressure transducer. The variation in height of the system during deployment is approximately 1m out of 11m. This behavior is expected, and we found that these motions are both predictable and stable.

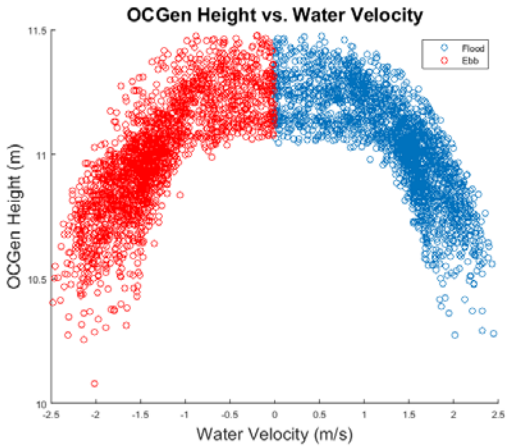

FIGURE 3. OCGEN® HEIGHT IN THE WATER COLUMN FOR ALL DATA. THE DIFFERENCE IN HEIGHT BETWEEN HIGH AND LOW TIDE SLACK WATER EVENTS IS EVIDENT IN THE BIFURCATING DATA AT ZERO WATER SPEED.

OCGen® Mooring Line Angle

Mooring line angles, defined as the angle made with the vertical, were estimated from the TGU height data. Due to the bi-stable condition at low and high slack water of the TGU height, a calculation of mooring line angle at these locations proved difficult. This can be seen in Figure 4 where the line angle at slack water appears to vary between 0-10 degrees from vertical, which was known to be untrue. The turbine never experienced flows of the maximum design case of 2.5m/s, and therefore the predicted maximum mooring line angle of ~45 degrees could not be validated, but the trend shown in figure 4 is consistent with expectations.

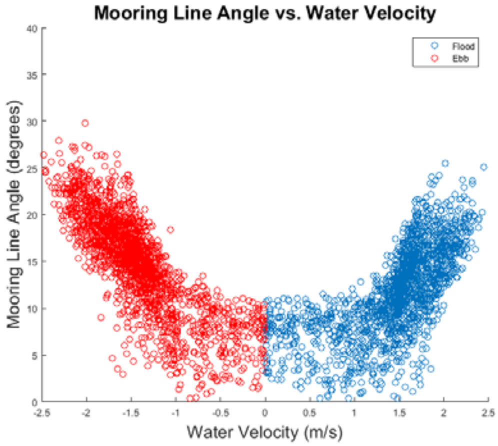

FIGURE 4. OCGEN® MOORING LINE ANGLES IN THE WATER COLUMN AS A FUNCTION OF FLOW SPEED. THE ESTIMATED 25° MOORING LINE ANGLE AT PEAK FLOW WAS MORE TRUSTWORTHY THAN THE ANGLE AT SLACK WATER.

Mooring Line Loads

Each of the four OCGen® mooring lines was equipped with a load cell, which measured the load experienced by each mooring line at three second intervals. Plots of the loads are presented in various formats (Figure 5 and 6).

Along with the raw data plots, averaged data using 3 minute block averages are also presented. The data represent results for two different operating conditions, the first with the turbines on not rotating, the second with the turbines rotating.

Note that loads for the zero flow condition were not equal, indicating difference in mooring line length, probably due to different degrees of mooring block settling at each mooring line.

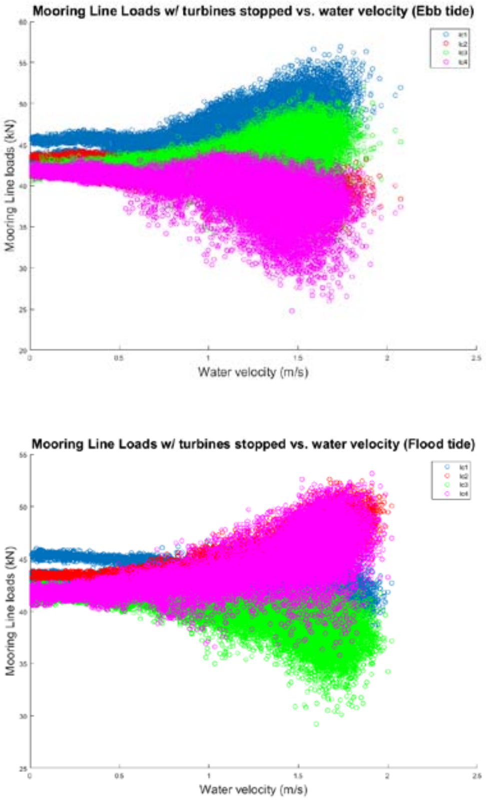

FIGURE 5. RAW OCGEN® MOORING LINE LOADS FOR EBB AND FLOOD TIDES; OPERATING STATE 1 (TURBINES NOT ROTATING). NOTE THE OFFSET OF LOADS AT V = 0M/S. THIS IS DUE TO DIFFERENCES IN MOORING LINE LENGTHS, PROBABLY DUE TO DIFFERENCES IN MOORING BLOCK SETTLEMENT AT EACH MOORING LINE.

Loads on the upstream lines increased with increasing water speed. Loads on the downstream lines decreased with increasing water speed for this water speed range. Comparison of loads for the mooring lines for the different operating conditions showed that the loads for each of the operating conditions were not greatly different. This indicated that the loads from the drag of the buoyancy system may be of greater significance than the loads created by operation of the turbine.

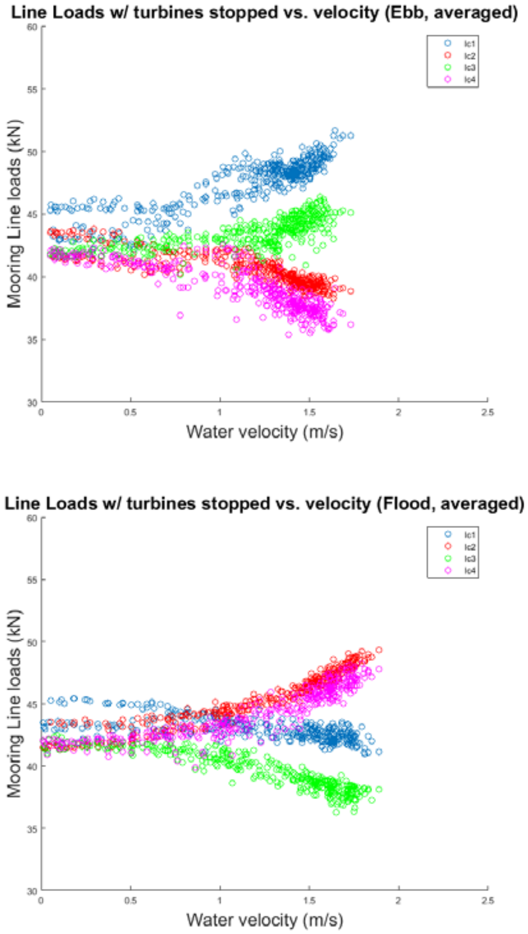

FIGURE 6. AVERAGED MOORING LINE LOADS FOR EBB AND FLOOD TIDES; OPERATING STATE 1 (TURBINES PRESENT AND NOT ROTATING). DATA IS AVERAGED IN 3 MINUTE BLOCKS.

Scour Inspection

After installation of the OCGen® prototype mooring system, video and dive inspections of the mooring system were performed at the beginning of the installation and just prior to removal.

Findings of the inspection showed that while the anchors were intended to self-embed under their own weight; they did not in fact do so. The anchors remained on top of the seafloor, except for one side of one anchor. Mooring block movement over the course of the deployment was very limited, consisting of 1 to 2 in. of movement on either block (Figure 7).

The fact that the mooring blocks did not self-embed fully and that the moorings did not move significantly indicated that the design process for the mooring blocks produced conservative results in this case. The requirement for self-embedment may be relaxed in future design iterations.

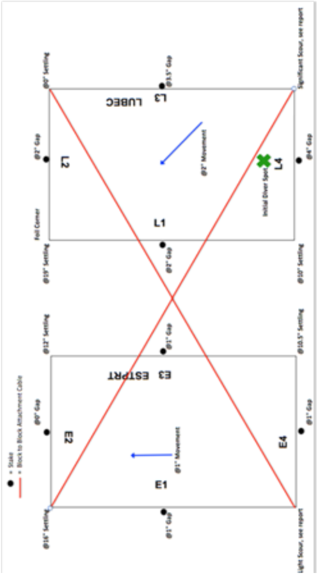

FIGURE 7. RESULTS OF MOORING MONITORING DURING DEPLOYMENT OF OCGEN® PROTOTYPE MOORING SYSTEM.

Comparison of Experimental Data with Models

A comparison of empirical results from the deployment and analytical results predicted by design tools was made. Some calibration of the OrcaFlex models was required in order to provide a reasonable match between the model results and the data. This calibration was primarily related to the load difference between the mooring lines at slack water. These load differences were most probably related to differences between the heights of the moorings off the seafloor, and were modeled as such in OrcaFlex (Figures 8 and 9).

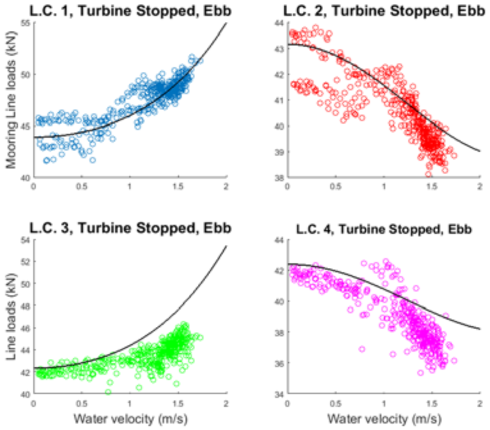

FIGURE 8. OPERATING STATE 1 (TURBINE STOPPED). EBB TIDE MOORING LINE LOADS ALL FOUR MOORING LINES WITH ORCAFLEX RESULTS. DATA WERE AVERAGED OVER THREE (3) MINUTE TIME INTERVALS. BLACK LINES REPRESENTED THE ORCAFLEX RESULTS.

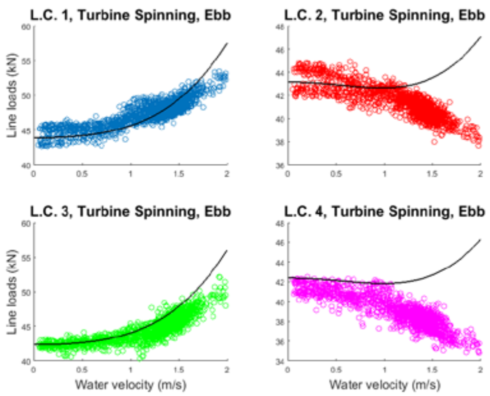

FIGURE 9. OPERATING STATE 2 (TURBINE SPINNING). MOORING LINE LOADS WERE COMPARED FOR ALL FOUR MOORING LINES WITH THE ORCAFLEX RESULTS FOR THE EBB TIDE. DATA WERE AVERAGED OVER THREE (3) MINUTE TIME INTERVALS. BLACK LINES REPRESENTED THE ORCAFLEX RESULTS.

CONCLUSIONS

In general the correlation between measured load and predicted load for the upstream mooring legs was good. Correlation between the OrcaFlex results and the measured downstream legs was weaker. The OrcaFlex models predicted an increase in downstream mooring line loads with increasing water speed, and this increase is not seen in the data. The expected increase in loads, as predicted by OrcaFlex, was due to the increase in line extension required on the aft line as the TGU translated further with increased flow speed. The fact that this deviation occurred indicated that the model for the mooring line was more compliant than was actually the case.

Overall, the OCGen® module mooring design project, utilizing design techniques such as Orcaflex models, resulted in an innovative tensioned mooring system that allowed operation in an energy rich environment while significantly reducing environmental footprint and costs over traditional bottom mounted MHK devices.

ACKNOWLEDGEMENTS

This Project was funded in part by the U.S. Department of Energy under award DE-EE0002650 and by the Maine Technology Institute.