DELIVERABLE D3.1:
DEPLOYMENT AND MOORING SYSTEM RISKS AND REQUIREMENTS

ADVANCED TIDGEN® POWER SYSTEM
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Purpose

This document is the technical report deliverable, D3.1, for the Advanced TidGen® Power System project:

Award No.:	DE-EE0007820, effective 11/1/2016
Project Title:	Advanced TidGen® Power System
Prime Recipient:	ORPC Maine
Principal Investigator:	Jarlath McEntee, P.E.

The document provides details regarding deployment and mooring system preliminary design for Task 3 of the Advanced TidGen® Power System project.

Anticipated Completion (Quarter)	Task (# and Name)	Associated Milestone #	Deliverable Type (Report, Presentation, Data)	Description of Deliverable or Data Content	Data Format	Protection	Expected File Size	Special Requirements	Where to submit the deliverable (PMCD, MHK-DR)
3	Task 3: Advanced Deployment, Retrieval, & Mooring Design	n/a	Report	D3.1: Technical report on deployment and mooring system design requirements and subsystem risk analysis	pdf	Protected	<20MB	None	MHK-DR

1 Introduction

A primary goal of the Advanced TidGen® Power System project is to adapt ORPC's buoyant tensioned mooring system (BTMS) to the Advanced TidGen® turbine generator unit (TGU). The TGU, as determined at the System Definition Review held in June 2017, is a dual-driveline, stacked system that implements hydrodynamic improvements for turbine design, turbine-turbine interactions and turbine-structure interactions. A major challenge for mooring and deployment system design will be to account for the substantial increases in loading incurred from increased power production and the resulting system drag during operation. Figure 1 shows the current system as presented for the Preliminary Design Review held in October 2017. This document addresses major risks, preventative measures, and mitigation strategies that have influenced this design and continue to drive development work toward the next design iteration.

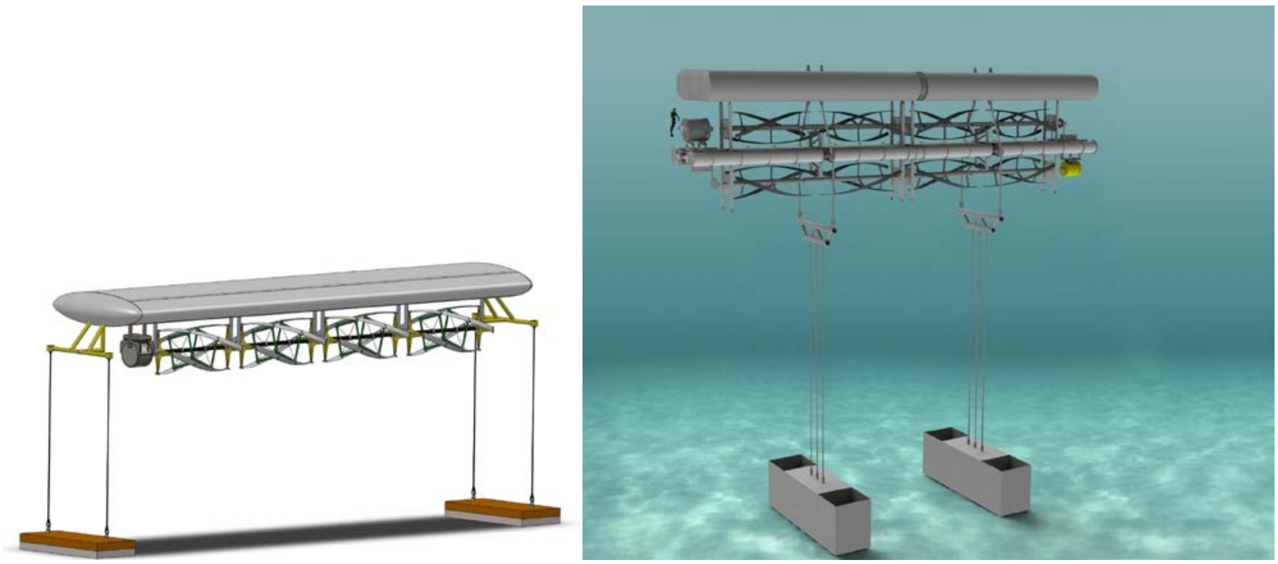


Figure 1. (Left) Single row TidGen® concept with a four-line, gravity anchor BTMS as part of original proposal. (Right) Evolved stacked concept with two lines, each with additional lines for redundancy. Preliminary design analyses were performed to address risks affecting safety, performance and longevity.

2 Risks and Mitigation

ORPC worked with Maine Marine Composites (MMC) for performing preliminary analytical studies of various mooring line configurations as well as sensitivity studies for issues such as anchor misalignment. ORPC utilized Proteus DS, a dynamic analysis software package provided by DSA. MMC supplemented these studies with OrcaFlex models to aid in final determination of the BTMS configuration. MMC has been contracted to complete the detailed design of the mooring system.

Figure 2 depicts several mooring system configurations that were examined. The mooring system was assumed to consist of two to six sets of lines, each of which can be constructed of steel chain, wire rope, or synthetic rope. Gravity anchors were used. Main functionality of the mooring system is to maintain proper depth within the water column and orientation to high-speed flow.

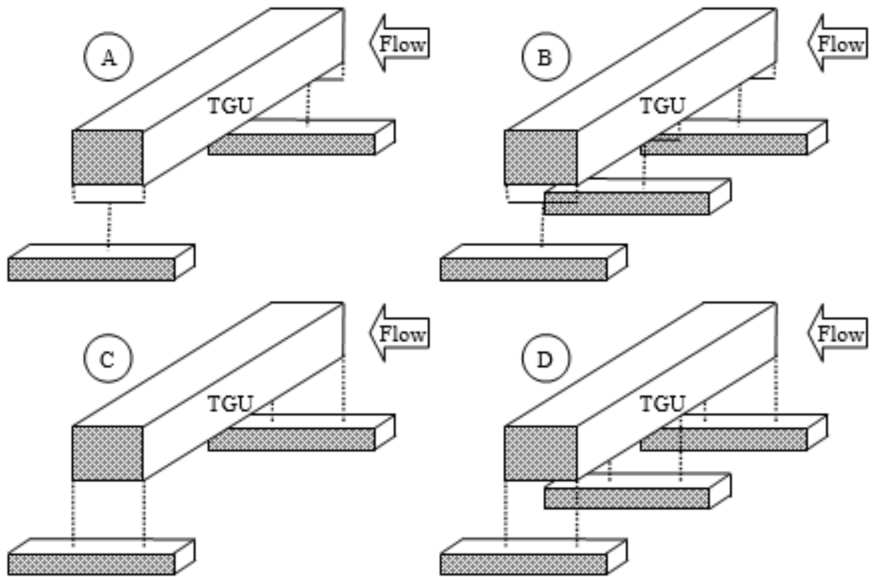


Figure 2. Mooring system configurations modeled in dynamic analyses:
(A) Two gravity anchors (mooring blocks), two mooring lines with spreader bars
(B) Three gravity anchors, three mooring lines with spreader bars
(C) Two gravity anchors, four mooring lines directly to TGU
(D) Three gravity anchors, six mooring lines directly to TGU

The following overviews the major risks identified during preliminary design and mitigation strategies that could be implemented to address them.

2.1 Attitude and Depth of TGU for Maximum Power Output

Risk

If the TGU is not oriented properly with respect to the flow, the electrical power output will be reduced. Factors that affect the alignment of the TGU are:

- Unequal length of mooring lines
- Misalignment during deployment or during periodic retrieval/redeployment operations
- Uneven depth of gravity anchors
- Misalignment of gravity anchors (one end lower than another)
- Uneven settling of gravity anchors
- Anchor slippage
- Non-catastrophic collision damage
- Non-catastrophic structural failure
- Cumulative tolerance errors

There are two ways to guarantee that the TGU alignment is correct: (1) to manufacture and deploy all components within tight, predetermined tolerances, or (2) to allow the mooring system to be adjusted at the deployment site. The cost of each must be measured against its benefits.

Mitigation

There are two issues, how much misalignment is tolerable, and how much misalignment there actually is. Misalignment in the pitch direction will have a relatively small impact on performance, whereas misalignment in yaw might result in a much greater impact on performance. If the TGU misalignment is significant, steps must be taken quickly to correct the situation, and this may be expensive. A cost-effective maintenance strategy will have identified which small alignment errors can be ignored during operations and, as needed, corrected during periodic inspections.

As the design matures, 3D CFD simulations can aid in determining orientation and attitude sensitivity to performance. Field testing can verify model predictions and refine energy production estimates. The following parameters for the TGU should be investigated:

- Depth: Vertical distance from mid-point of rotor shaft to mean low tide
- Roll: Rotation around direction of maximum flow
- Pitch: Rotation around rotor shaft axis, measured relative to horizontal plane
- Yaw: Rotation around vertical axis measured relative to max. flow direction

If the entire system is preconfigured and deployed as a unit, the depth and orientation of the gravity anchors will play a major role in the alignment of the TGU. Accordingly, a goal of the project will be to develop a set of specifications for the depth and alignment of the gravity anchors. The following parameters for gravity anchors should be investigated:

- Depth: Vertical distance from mean low tide to top of padeye on gravity anchor
- Relative depth: Vertical distance from top of padeye of one gravity anchor to the next
- Relative horizontal offset: Horizontal distance between corresponding padeyes on adjacent anchors (i.e., between forward padeyes or between aft padeyes)

Two strategies for detecting alignment problems are identified below:

a. During deployment/redeployment a multibeam sounder system such as the Furuno WASSP should be used to monitor the locations and orientation of the gravity anchors. The sounder must be accurate enough to measure distances within the ranges of tolerances for the TGU and anchor alignment tolerances listed above.
b. IMUs mounted on the TGU will be used to monitor the attitude and depth after installation and during normal operation. Values from the IMUs should be checked and logged on a frequent, regular basis to detect alignment problems and detect trends toward alignment problems efficiently. The magnetic sensors in the IMU can be used to measure the yaw orientation of the gravity anchors accurately. To monitor relative sinkage of one gravity anchor versus another, the IMUs must have an accurate depth (altitude) sensor based on average water pressure or the equivalent. Depth sensing must be accurate enough to discriminate to within the depth and relative depth specifications listed above.

IMUs include micro-machined (MEMS) sensors to measure 3-axis linear acceleration and rotation velocities in the IMU box coordinate system. Further, they usually include 3-axis magnetometers to measure the earth's gravity field. A control algorithm based on a Kalman filter is used to integrate the signals from the accelerometers and rate gyros to estimate linear velocities and positions. Sometimes IMUs include pressure sensors, typically to measure the height of a flying drone in air. The sensitivity of the IMU altimeter is often limited to the expected range of pressures for flying drones, e.g. air pressure at sea level plus or minus perhaps 50%, an accuracy of about 1% to 10% of full scale. For this application the pressure sensor must measure pressure changes corresponding to depth variations of a fraction of a meter with background pressures corresponding to 100 m, an accuracy of 0.1% depending on how accurate the depth measurements need to be.

Mitigating Alignment Problems: Below are strategies that can address the factors affecting misalignment:

(1) Mooring lines should be pre-stretched during production and then should be measured at the production facility. Any lines that are outside tolerance should be repaired by the line production shop before they are shipped to ORPC.

(2) The depth and orientation of the TGU is dependent on the dimensions of the mooring lines components and the alignment of the gravity anchors. As the system is deployed the gravity anchors will be set on the seafloor. It is recommended that localized geophysical preparation work has been done, else the individual anchors may be placed at significantly different depths.

(3) To guarantee that the anchors are placed properly, their orientations and depths must be monitored during deployment/redeployment. Depending on the precision required in the depth measurements, the absolute alignment and depth might be measured using a multibeam sonar device such as the Furuno WASSP S3.

(4) Without thorough geophysical testing under each gravity anchor, it is difficult to know if the subsurfaces are uniform, and thus if settling will be uniform. To detect uneven settling or uneven anchor slippage, anchor line tensions can be monitored. Tension sensors have to be accurate and well calibrated so that minor changes in tension over multiple tide cycles can be detected.

(5) To further guarantee that the anchors remain placed properly, their orientations and depths can be monitored on a regular basis using a multibeam sonar device.

(6) It is difficult to predict the effect of non-catastrophic impact damage on the mooring system. Some sort of acoustic signature analysis methodology could be employed to detect such damage rapidly. A passive strategy is to include redundant lines, and to remove the device if catastrophic damage occurs. Catastrophic failures are addressed in the next section.

(7) The TGU and mooring system are complicated devices and it is quite possible for cumulative misalignment of components to add to exceed the acceptable range for alignment. Accordingly, periodic inspections by ROVs and perhaps divers would be in order, coupled with periodic remote measurement such as multibeam sonar. Alternatively, a conditional monitoring system could identify when alignment tolerances have been exceeded over time. Cost benefit analyses comparing periodic inspections vs. passive/redundant reaction strategies should influence the appropriate maintenance program. Onshore maintenance should include a thorough inspection of all parts, replacement of parts that are observed to wear or could be predicted to wear, and tests and possible replacements of all sensors, wiring and data collection devices.

2.2 Catastrophic Mooring Failures

It is not cost effective to build a mooring system that cannot ever fail under any circumstances. The recommended strategy is to reduce the cost of a mooring failure by building in redundancy and tolerance to damage from the mooring system.

Risk

A mooring line can break due to:

- Long term effects such as metal fatigue, corrosion, abrasion, and galvanic action.
- Contact with:
    - Mega fauna such as whales or sharks
    - Large objects adrift in the high current water column such as waterlogged trees, flotsam and jetsam from commercial or recreational boats
    - Anchor chains from boats
    - Drag lines from boats

Mitigation

The damage from a broken mooring line can be minimized by redundancy. Completely redundant mooring lines will have adjacent but separate fairleads, separate lines and separate anchors; that is, there will be no potential single point of failure. Recognizing the value of redundancy, rules from standards-making organizations have reduced design margin requirements for each redundant line than they do for single, non-redundant lines. For example, from 2 (ABS, 2013), a non-redundant mooring line must be designed with a safety factor of 2.0, whereas a non-redundant line can be designed with a safety factor of 1.67, all the way down to 1.05 for a transient incident if one of the lines is broken. Depending on the cost of retrieval/repair/installation, it may make economic sense to use completely redundant lines.

Table 2. Design safety factors for steel mooring lines.

Safety Factors for Steel Mooring Lines or Tendons

Loading Condition	*Redundancy of the Stationkeeping System*	*Design Condition of the Stationkeeping System*	*Safety Factor*
Design Load Cases	Redundant	Intact	1.67
		Damaged condition with one broken line	1.25
		Transient condition with one broken line	1.05
	Non-redundant	Intact	2.0
Survival Load Cases	Redundant or Non-redundant	Intact	1.05

The design should be able to handle the loss of a single mooring line sustaining only minimum additional damage and without triggering a series of cascading failures. To assure this, simulations of the system in its damaged state should be run. Barring a second catastrophic event, the system should remain intact, possibly remaining able to convert current to electricity, albeit at a reduced rate.

The design should include the ability to degrade smoothly, dropping from full functionality to a dormant standby state without a complete loss. That is, the design should include provisions for remote decoupling of the umbilical line, for braking smoothly to avoid sudden stops, and so on.

All of these plans should be analyzed in worst case conditions, wind, wave and current conditions corresponding to a multi-century return period.

Detecting Mooring Failures: If individual load cells can be placed in series with the mooring lines, then the load imbalance can be detected and relayed shore-side. If load cells are too unreliable or too expensive, acoustic signatures can be used to detect a problem state, and divers or an ROV can be dispatched to investigate further.

2.3 Component Failures

The best approach to avoiding component failures is to use periodic inspection and 24-hour sensor monitors to catch failures as they start. A series of considerations and suggested inspection criteria are listed in API RP 2SI.

Fairlead Failure

The fairlead system and local structure has to be strong enough to support the maximum loads applied to them without any permanent deformation. If the hinge or swivel mechanisms are not oriented properly, high levels of abrasion can occur. This was observed during previous ORPC tests and also in the analysis of mooring system failures due to off-axis chain bending during normal operations on oil platforms.

Gravity Anchors

Risks for gravity anchors include failure of the padeye, anchor drag, uneven settling of the anchor, and degradation of concrete. Preliminary analyses reviewing operation and stability with uneven anchors should be performed. A monitoring system should sense mooring line tensions and see if the sum/difference changes over a tide cycle.

Mooring Lines

Risks for mooring lines include single point or line failure, multiple line failure, long term abrasion or corrosion damage, damage from extreme events (snap loads), failure of mooring due to abrasion at anchor shackle or TGU shackle or connection, and failure of mooring due to corrosion. A maintenance plan should address expected damage from line/shackle/fairlead failure. Pre-deployment and post-deployment inspections for the project installations should inform maintenance requirements. Snap load inhibitors could be incorporated in the design.

Umbilical Failure

The primary umbilical failure would be due to higher stiffness than mooring line. Bend restrictors should be sized according to depth changes during the tide cycle, and a deployment strategy should account for umbilical line length requirements.

Component Lifecycle

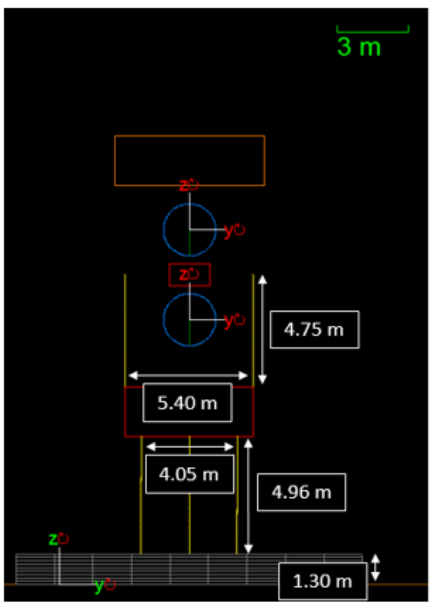
All components should be selected and design to anticipate risk of abrasion, corrosion, snap events and fatigue loads. If chain is used, expected corrosion can be calculated and compared to inspections and detection strategies for loss of material.

Unplanned Dynamical Behavior includes Vortex-Induced Vibration (VIV) on the mooring lines and buoyancy pod. Mooring line design can include various strategies for minimizing VIV, including placement of redundant lines. System modal analysis can identify what frequencies matter, and a conditional monitoring system may include acoustic signature analysis for validation during the test system deployment.

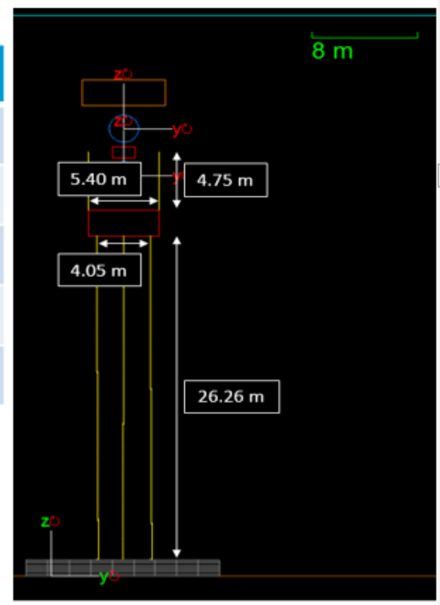
3 Preliminary Design Analyses

Several design analyses have been performed to address the risks and recommendations identified above. The initial mooring line configuration was chosen based on TGU orientation sensitivity to uneven settling or displacement of anchors. The original concept had two lines per anchor, four lines total. As presented at the System Definition Review, OrcaFlex models showed that in the event of anchor displacements of 1m (either vertical translations, or angular displacement if the fore or rear of an anchor is shifted) the overall TGU pitch was on the order of 6 degrees under expected loading conditions for the original concept. By adopting a configuration of one line per anchor, however, the system pitch was reduced by a factor of 3. The pitch of the system was considered critical to the power production of the system, as the central nacelle between drivelines could interrupt flow if tilted at too great an angle.

Subsequent analyses examined snap events and fatigue loading of a two-line configuration with line redundancies. Figure 3 shows two OrcaFlex models that were examined at operational limit states of the TidGen® preliminary design, for both Cobscook Bay (max design velocity of 2.2 5 m/s) and Western Passage (max design velocity of 3.5 m/s). Drag and lift values for the turbines were derived from internal computational fluid dynamics models. Note that subsystem testing in budget period 2 will aim to verify these model assumptions.



Case	Description
Static	Freewheel, 2.25m/s
Failure 1	Primary mooring line snap
Failure 2	Fore bridle line snap
Failure 3	Aft bridle line snap
Fatigue	Static with oscillations



Cobscook Bay

Western Passage

Figure 3. OrcaFlex model parameters examining limit state conditions.

Figures 4 and 5 show predicted loading for failure of the bridle lines and the effect of fatigue loading due to turbine rotation. Mooring lines were chain, chosen for price and benefits of stiffness for a 2-line configuration. Takeaways were that snap loads are the driving factor for line sizing, and that integrating a snap load suppressor in the mooring lines would benefit in both cost and risk reduction. MMC has a potential design solution, although ORPC is investigating alternative products. For fatigue, the system is seeing approximately +/- 10% oscillation in line tension. This presents a concern for increased abrasion rates due to dynamic tension.

Line Snap

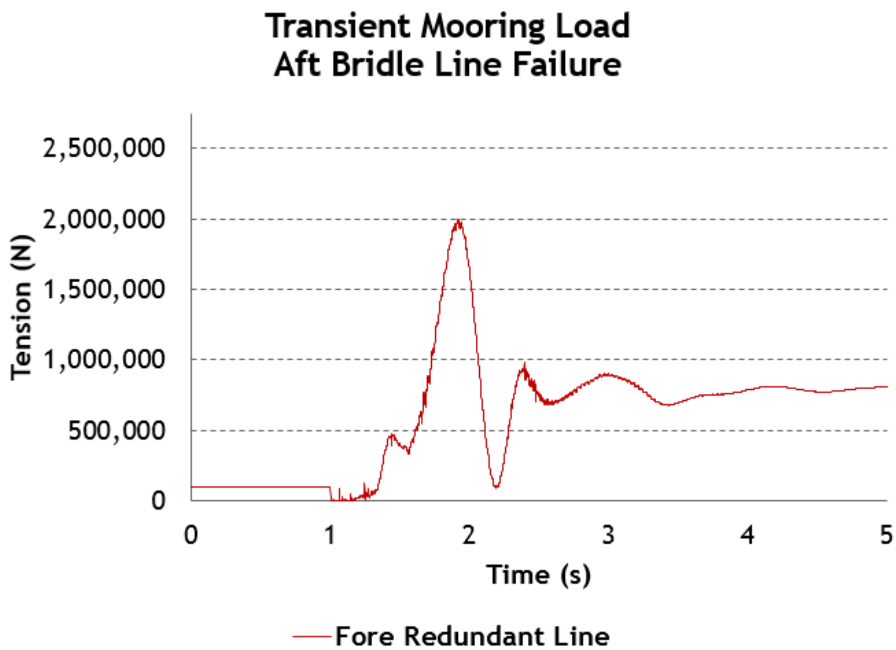


Figure 4. OrcaFlex model of snap loading tension on bridle lines.

Line Fatigue

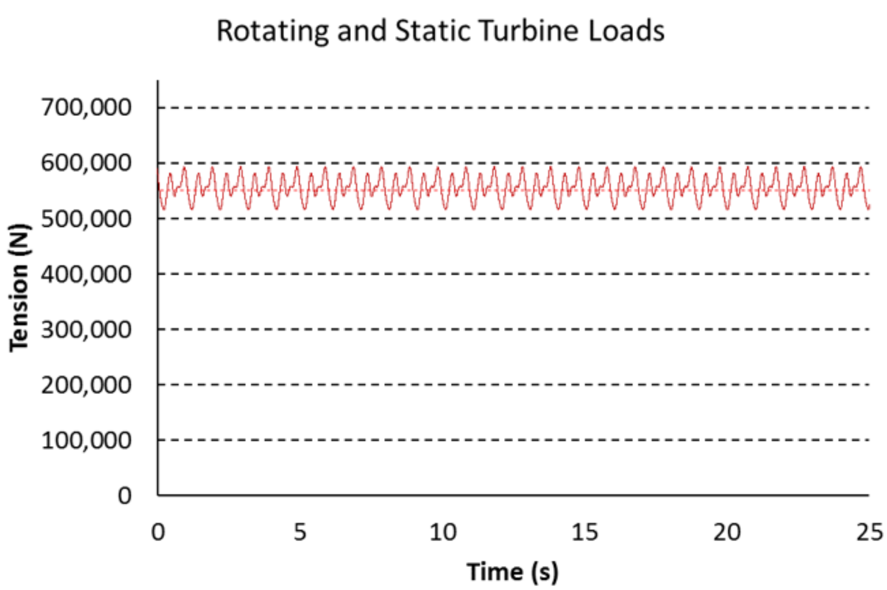


Figure 5. OrcaFlex predictions of fatigue loads on mooring lines due to turbine rotation.

Continuing design effort requires investigation of mooring line suppressors, and completion of studies for the following operational load cases:

- ULSa loadings
- ALS loadings
- Shutdown loadings

- Off-axis flow condition
- Flow shear condition

System buoyancy will be optimized to reduce anchor weights. Conservative estimates of coefficients of friction between the anchors and a bedrock seabed assumed for Western Passage have estimated initial anchor sizes as much as 270,000 kg each. The primary drivers are horizontal loads and a low estimate for coefficient of friction.

REVISION HISTORY

Revision	Date	Description	Author	Reviewer
00	10/26/17	Initial	C. Marnagh	J. McEntee