THOR-QCS

WES Quick Connection Systems Stage 1 Public Report

TTI Marine Renewables Ltd

This project has been supported by Wave Energy Scotland

1 Project Introduction

This is a high-level public report issued under the Wave Energy Scotland (WES) Quick Connection System programme for the THOR-QCS (**T**ensioned (mooring) **H**ook-up **O**peration and **R**etrieval) system developed by TTI Marine Renewables Ltd. The project was led by TTI Marine Renewables Ltd (Scotland), with wider support from the wider Tension Technology International Ltd group of companies.

The THOR-QCS system is a marine operations tool designed and developed to give significant cost, time, operational and safety benefits to the mooring hook-up and disconnection operations for a wave energy convertor (WEC) and other floating marine energy convertors.

The mooring system for a floating Wave Energy Convertor (WEC) typically requires a degree of pretension in the system to achieve acceptable system responses, regardless of the mooring line type, number of mooring lines or general mooring configuration (even “slack” moorings have significant tension in the system due to chain catenary weight). Hooking up (connecting) and disconnecting the mooring system whilst generating sufficient pretension is typically a complex marine operation requiring numerous temporary phases, which has an economic cost to the project. The alternative is to permanently deploy tensioning equipment on the WEC (which is what O&G installations typically do) but this then results in significant CAPEX expenditure for hardware that is only used at start-of-life and possibly at major service intervals or failure cases. This negatively affects Levelised Cost of Energy (LCoE).

The existing installation strategy typically uses a Multicat type vessel to pull and push the WEC into various positions to "generate slack" in the mooring system such that the connections can be established. This often requires a temporary mooring for the vessel to give a reaction force and then using vessel winches to manoeuvre the WEC or pull-in mooring lines. These temporary phases are often more complex than the actual WEC mooring, and therefore have a cost, and the various stages require coupling between vessel and WEC which has safety and operational constraint implications.

The THOR-QCS system integrates commercially available off-the-shelf (OTS) hardware, bespoke hardware, and a novel marine operations approach to facilitate the mooring hook-up and disconnection operations for WECs. The approach is also deemed to be valid for other offshore floating renewable devices and perhaps more general marine operations also.

A bespoke tool under development is designed to be temporarily installed between a mooring pennant connected to the WEC and a part of the pre-installed mooring system. The tool is deployed from a workboat but once in the water is self-supporting. The tool provides a self-reacting pull-in force between the parts of the system such that the main mooring line can be connected whilst under zero tension. The tool and system aim to satisfy the high-level requirements of:

- No crew transfer to WEC from workboats and no personnel on board the WEC,
- No diving operations,
- Health and safety of all marine operators is paramount consideration,
- No personnel working on tensioned lines,
- Avoiding tight mooring of WEC to workboat (hipping-up) to minimise risk to vessel, WEC and personnel),

- A large weather window and short duration operation, allowing safe operation in higher sea-states,
- Minimise requirement for permanent mooring tensioning hardware and complex hardware in splash-zone. Each line is likely to require the hardware for permanently installed equipment so the Bill of Materials, CAPEX and effect on levelized cost of energy (LCOE) is significant,
- Minimise requirement for workboat size, winch and crane capacity thus minimising operational expenditure (OPEX) and maximises availability,
- Be lightweight for easy handling and be buoyant for easy handling.

2 Description of Project Technology

Figure 1 is a schematic diagram for the THOR-QCS tool sub-systems and its interfaces to the wider WEC mooring system. The actual mooring connector is shown as an overlapping system since it is not an intrinsic part of the THOR tool but is a necessary part of the overall process of using the THOR tool and hardware options are available for this component, which were examined. Due to reasons of confidentiality the THOR-QCS system is only described at system level and a breakdown of materials and components is not shown or described in this report.

As outlined in the introduction the THOR-QCS is a tool to pull a pre-laid mooring and WEC mooring pennant together such that the long-term mooring can be connected in a tensioned system. There are four key sub-systems in the THOR tool:

1. Structure: to provide tensioning load path and to mount buoyancy to allow the tool to float

2. Buoyancy: to provide the necessary floatation to the system,

3. Pull-in actuator: to provide the tractive effort to pull both free ends of the mooring system together to allow the connections to be made,

4. Control and energisation: to provide power to the pull-in actuator, monitor feedback signals and command the system to haul-in and suchlike,

5. Additionally, there are pull-in line contacting components, to affect the required rope path, and

6. There are also ancillary sub-systems/components which may comprise, for example, temporary connections at bollards or pad eyes, connector handling components and tow-points.

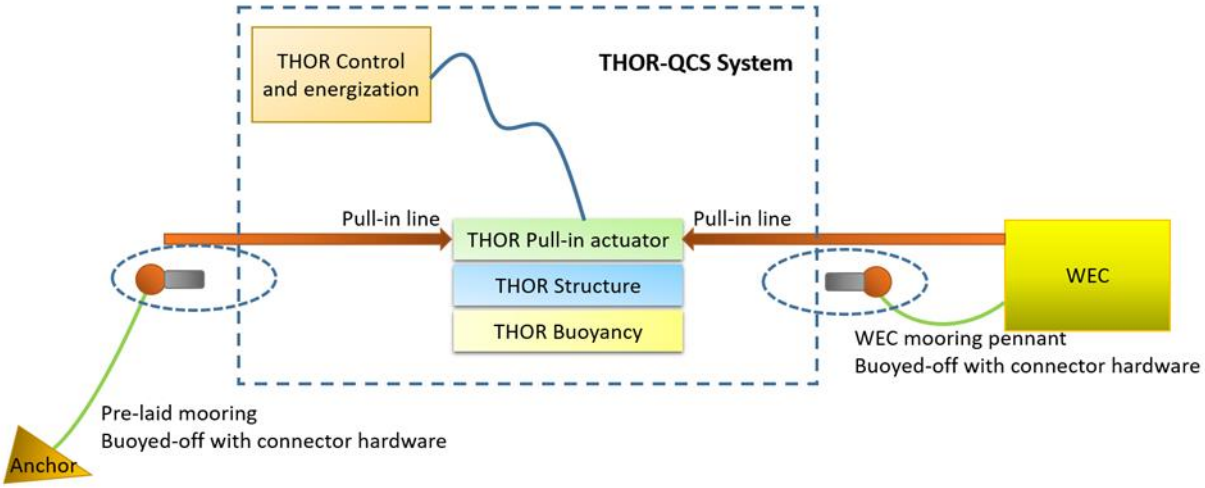

Figure 1 THOR-QCS system diagram

3 Scope of Work

Work tasks which have informed the Stage 1 concept design and outcomes include:

1. Design envelope and concept definition study, considering range of mooring system types, WEC scales and installation scenarios. The purpose of this study was to define range of rope pull-in lengths and forces to achieve required mooring system pre-tension. Simulation and analysis were conducted using Orcaflex for still water scenarios. This study largely informed the design requirement for a twin pontoon rotary pull-in mechanism, instead of a linear actuator, and the system scale for 1st generation product design. This task also informed the design of the Long-term mooring for the range of WEC scales considered.

2. Storyboarding of baseline operational procedure (without THOR QCS type system), for comparison with New Storyboarding with THOR-QCS.

3. Hardware landscaping report to inform availability, suitability, and cost of commercially available OTS components which could be integrated within the THOR QCS.

4. Development of qualification register including FMECA (Failure Mode, Effects and Criticality Analysis). This formed part of a systems engineering approach in line with DNV-GL-RP-A203 and informed proposed qualification activities for proposed Stage 2 and Stage 3.

5. Concept design including material specifications, components, dimensions, mass distribution and cost. The design was iterated and optimised based on outputs from other parallel activities and was informed by outputs from Orcaflex analysis, hardware landscaping, operational requirements, technical risk mitigation and cost. The concept was then detailed in 2D and 3D CAD design drawings,

6. Further modelling of critical operations within Orcaflex to assess peak loads and velocities and inform concept design including buoyancy and stability. Detailed modelling was not a requirement within Stage 1 WES guidance, but early in-depth modelling did significantly help inform Stage 1 concept design, which was planned to be revisited within FEED activities proposed for Stage 2

7. Qualitive assessment including initial cost-benefit of THOR-QSC compared to conventional approach.

4 Project Achievements

Stage 1 resulted is the successful completion of all the activities identified in the scope of work outlined in section3. The project deliverables are summarised in Table 2 below. Apart from the Public report (D02), all other deliverables are confidential. For more detailed information of the THOR-QCS project from interested parties, TTI Marine Renewables Ltd should be contacted directly.

Deliverable	Milestone	Title
D00	M1	Intermediate Update Report (Concept Definition)
D01	M2	Confidential Final report
D02	M2	Public Report
D03	M1	Baseline Storyboard
D04	M2	New Product & Process Storyboard
D05	M2	Stage 2 application pack
D06	M2	Concept General Arrangement Drawing & BoM (Breakdown of Materials)
D07a	M2	WP2.1 Hardware Landscaping & Down Select
D07b	M2	WP2.3 Concept Design Report
D07c	M2	WP2.2 Qualification Plan
D07d	M2	WP3.2 Simulation Report
D07e	M2	WP3 Qualitative Benefits Report
D08	M2	High-level plan for physical testing activities proposed in Stage 3

Table 1: Stage 1 deliverables

The culmination of Stage 1 was a costed and feasible concept design which can readily be manufactured from a combination of bespoke and OTS components. Studies included a comparison between the steps undertaken in conventional mooring system hook-up and tension operations with an alternative approach which includes the THOR-QCS approach. Adoption of the THOR-QCS approach would remove the current need for workboat personnel to carry out potentially risky operations. This can potentially broaden available weather windows. Combined with the ability to be used with smaller work vessels and perceived reduction in operation durations will have a beneficial effect on project economies. A quantitative comparison has also been included which clearly demonstrates the cost benefit of the THOR-QCS approach, when compared to a workboat which has to deploy its own temporary mooring in order to hold station.

Early Orcaflex modelling for a range of mooring system types and WEC scales was particularly useful in deriving the tools required mooring line pull-line length and forces. More detailed dynamic modelling was then conducted to assess couple dynamics s of the tool, mooring system and WEC in waves. This was used to inform the buoyancy requirements of the tool and assess dynamic forces and velocities imposed on the system. Initial finite element modelling was also conducted to size and design key sub-systems.

Stage 1 would have benefited from earlier integration of mechanical design and naval architecture aspects of the tool, which would have resulted in more efficient design spiral and final design convergence.

5 Recommendations for Further Work

As part of Stage 1 activities, a qualification plan (Deliverable D07c refer to Table 1) has been developed in accordance with DNVGL-RP-A203 which was informed by residual technical risks and recommended mitigations identified in the completed FMECA and Technical Risk Register. The plan outlines the system and subsystem qualification tests and complementary design, engineering and simulation activities proposed for Stage 2 and Stage 3 (under a possible WES programme framework or alternative). The qualification plan outlines full-scale sub-system and system sea trials for Stage 2 and Stage 3 respectively. The plan forecasted that some sub-systems would have progressed towards TRL 5 in Stage 2, completing Q3 2021. Thereafter, Stage 3 would demonstrate full system performance taking THOR-QSC towards TRL 7 by mid-late 2022.

The Stage 2 application (D05, Reference Table 1) outlines the proposal for further work. Key to Stage 2 would be the proposed partnering with experienced marine contractor and separate marine operations modelling specialist. The nominated marine contractor (identified as a potential end-user) would be tasked with the field testing of key sub-systems at Stage 2, prior to full system implementation and field testing at Stage 3. The marine operation specialist was tasked with carrying out reliability, availability, and maintainability (RAM) modelling as part of the marine operations assessment phase, for both test cases identified (e.g., WEC and FOWT test cases). A combination of commercial software and algorithms developed in-house by the marine operations specialist would be used. The specific level 1 work packages outlined within a Stage 2 application included:

- WP01 Project Management
- WP02 Systems Engineering
- WP03 Conceptual Design
- WP04 Dynamic Model Development & Implementation
- WP05 Marine Operational Analysis & Benefit Assessment
- WP06 THOR Key Sub-systems Wet Test
- WP07 Stage 3 Physical Testing (Programme & Design)
- WP08 Commercialisation & Exploitation

6 Communications and Publicity Activity

There is currently no active public promotion, and this is under review.

7 Useful References and Additional Data

TTI Marine Renewables Ltd was the principal author of WES Mooring & Foundation Landscaping report, which is available for download from the Wave Energy Scotland knowledge library https://library.waveenergyscotland.co.uk/. As part of this mooring and foundation landscaping study, TTI conducted a Voice of Customer (VOC) survey to better understand the requirements and priorities of the sector. Specific questions relating to WEC connection and disconnection, helped inform the requirements of the THOR-QCS system.

The Qualification Plan has been developed in accordance with **DNVGL-RP-A203**, which is particularly relevant for the systematic development path of "new" technologies. The objective of the qualification plan is to generate a suite of activities which can be applied to reduce the uncertainties in the product and the likelihood of failure, according to the failure modes set out in the FMECA. The aim is to cost effectively generate the most reliable evidence. The qualification plan outlines qualification activities for Stage 2, while also outlining those which may be conducted at Stage 3 (which will be confirmed on the completion of Stage 2, when mitigations for residual technical risks will be re-assessed).

This qualification plan is a working document and will be maintained through ongoing product development activities.

Publicity Material

[Please supply WES with any logos, images and video files that are non-confidential and available for WES to use to promote WES supported projects. Files should be uploaded to the Objective Connect milestone folder. Use the table below to summarise the publicity material.]

Filename	Media Type	Description