High cycle dynamic testing of marine hydrokinetic blades

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ABSTRACT: River and tidal current energy can play a substantial role in the de-carbonisation of Europe's electricity production. In recent years several companies have been developing technology to harness the power of the world's waterways. One such developer is the Ocean Renewable Power Company (ORPC) who have developed a range of marine hydrokinetic devices to provide reliable electricity to remote communities who are normally dependent on local diesel-powered electricity generation. The latest generation of ORPC devices use high efficiency carbon fibre reinforced epoxy foils to extract energy from flows with diurnal variations in flow speed, subjecting the device to a wide envelope of blade loading. Technology to harness water current energy is still at a relatively early stage of development, hence de-risking of components plays a vital role on the road to commercialisation. In this study, planned testing of a demonstrator foil from the ORPC device in a novel dynamic loading setup is presented where the load will be generated by the rotation of an offset mass by an electric motor fixed to the blade. Such a test setup will allow for efficient testing up to very high cycle numbers not normally achieved in classic hydraulically actuated testing. Dynamic modelling of the blade response will be used to help predict the natural frequencies and relate the frequency of rotation to the load response in the blade. Data generated from the testing will contribute to the modelling and validation of future tidal blades, as well as the overall goal of electricity de-carbonisation.

KEY WORDS: CERI/ITRN 2022; marine energy; renewable energy

1 INTRODUCTION

Tidal flows are created by the changing gravitational pull of the sun and moon as the earth rotates causing predictable flows of water. Tidal energy is the utilisation of these moving masses of water to generate electricity. Tidal flows are an ideal source of renewable energy because their periods and durations are easy to predict accurately, allowing grid operators to effectively plan grid generation. Tidal energy devices are very site-sensitive due to the localised nature of the water current in a specific location, hence tidal energy devices are best suited to sites with a natural means of increasing the local water flow. For example, the fastest water currents may be found in bays where the surrounding landscape naturally funnels the water or between relatively close islands which would have the same effect.

Unlike the wind power industry which has arrived at a 'standard' 3-bladed horizontal axis design, the tidal energy industry is generally at an earlier stage of technical development which sees a variety of design philosophies coming to market. With this range of designs it is essential that testing of key components takes place in order to prove and qualify designs prior to field deployment. This testing is essential to increase confidence and investment in the industry.

Ireland has a strong development potential of 3000 MW across several sites in Irish waters [1]. Figure 1 shows the variety of tidal energy devices under consideration which including 'sea-snakes', underwater tidal stream generators, paddle generators and kite generators [2].

Figure 1. The wide variety of tidal energy devices under development [2]

2 CRIMSON PROJECT

2.1 Project Overview and Facilities

In an era where single point thermal generation of electricity appears to have peaked [3], the industry must look at all available options in the move to distributed generation. One such company contributing to the solution is the Ocean Renewable Power Company (ORPC) with their development of marine hydrokinetic (MHK) devices. The latest work in MHK development is part of the wider CRIMSON project [4] which comprises NUI Galway, ÉireComposites, Consiglio

Nazionale delle Ricerche (CNR), and Mitsubishi Chemical Advanced Materials (MCAM).

CRIMSON stands for the **C**ommercialisation of a **R**ecyclable and **I**nnovative **M**anufacturing **S**olution for an **O**ptimised **N**ovel marine turbine and has the objective to develop, test and manufacture MHK devices using recycled carbon fibre material.

The project draws from the expertise of experienced players in the fields of materials recovery and production (MCAM), advanced composites manufacturing (ÉireComposites), MHK turbine development, installation and operation (ORPC) plus the research expertise, resources and facilities provided by NUI Galway and CNR.

NUI Galway will lead the work package on structural testing of the MHK turbine assembly with the demonstrator foil, once received from manufacturer ÉireComposites. Testing will take place in the Large Structures Test Laboratory located in the Alice Perry Engineering Building at NUI Galway, see Figure 2 and Figure 3. The test lab is under the management of the Sustainable and Resilient Structures Research Group (nuigalway.ie/structures) and has overseen the testing of several marine renewable energy devices in recent years, including static and fatigue testing of the world's largest tidal turbine blade in 2020 which saw a peak load of 1 MN borne by the blade [5].

Figure 2. The Large Structures Test Laboratory at NUI Galway operated by the Sustainable and Resilient Structures research group

2.2 *Existing developments in marine hydrokinetic devices*

OPRC have a track record of MHK design, installation and operation, most notably through the ACCORD project [7] in 2018. In 2019 ORPC deployed its RivGen power system in a river feeding Iliamna Lake beside the remote Alaskan village of Igiugig. Igiugig village operates in own electrical micro-grid, fuelled by diesel electric generators. The diesel for these generators is delivered by air periodically to the village's airstrip, from where it is transported to the generating station.

Igiugig has seen its fair share of attempts at de-carbonising its electrical grid by well-meaning developers but none have seen the success of the RivGen device. In October 2020, the RivGen device was announced as being the longest operating river current energy converter in the US [8] during which it dealt with frazil ice debris strikes from the spring break up of ice in Alaska's largest lake. ORPC is now looking at further deployments in the Americas and Europe. Figure 4 shows the RivGen system on-site in Igiugig, prior to its immersion.

Figure 3. A sample installation of hydraulic actuators at the Large Structures Test Laboratory, NUI Galway.

2.3 *RivGen Power System*

The RivGen power system comprises a horizontal shaft mounted on specially designed bearings with an electrical generator at one end. Three blades are mounted on this shaft in a helical pattern as if they are wrapped around the shaft. Helically twisted blades are a development that levels out the torque response from the shaft as it rotates and are an improvement from previous iterations with straight blades. Manufacturing helical blades represents enormous challenges over straight blades and it is a challenge for which carbon fibre is particularly suited.

The existing blade design uses a high performance carbon fibre material combined with ÉireComposites' proprietary CPET (composite powder epoxy technology) giving a high performance hydrodynamic blade with excellent saltwater immersion characteristics [9] [10].

Figure 4. RivGen power system on-site, ready for commissioning in Igiugig, Alaska [6]

2.4 CRIMSON project goals

The CRIMSON project aims to build on the progress made by past developments with the ACCORD project by placing additional focus on sustainability in the material selection process. The stated aims of the project are to "bring to market a reliable, sustainable marine energy turbine through the application of novel materials and technologies over the complete life cycle of the product" [4]. Since the project kick-off in 2021, work has begun at ÉireComposites on testing recycled carbon fibre (rCF) material received from MCAM to evaluate their suitability for use in such a high performance application. It is hoped that breakthroughs made in CRIMSON in the use of rCF material will pave the way for its use in other applications and industries. Ultimately, the best outcome for the test programme is that rCF material can be depended on for the key turbine components.

ÉireComposites will manufacture a demonstrator turbine blade which be sent to the Large Structures Test Lab at NUI Galway for a full test programme to validate the design lifetime.

3 METHODS

3.1 Aim and objectives

The overarching aim of this paper is to lay out the work planned at the Large Structures Test Lab at NUI Galway to evaluate the novel tidal bade.

In order to achieve this aim, the following key considerations will be discussed:

- Load prediction and modelling plus and overview of the planned suite of testing
- Data collection and the instrumentation planned for this purpose
- The proposed dynamic, static and fatigue testing

3.2 Load prediction and modelling

Modelling of the test assembly by researchers in the Sustainable and Resilient Structures research group in conjunction with ORPC will output the loads, displacements and strains expected during at operating speeds. The performance of the carbon fibre blades will be monitored under a controlled maximum strain type setup. This means the blade must be able to perform at operational conditions without exceeding the materials maximum strain limit. The testing outlined in the following sections is expected to confirm the stains predicted by the computational modelling.

3.3 Testing overview

Testing of the blade will be guided by industry standards DNV GL ST-0164 and IEC62600-3, as with previous test programmes in the Large Structures Test Lab. Loading information will be informed by design analysis carried out by ORPC in co-operation with ÉireComposites and MCAM.

The test programme will aim to validate the blade's design lifetime by replicating 20 years' worth of loading in an accelerated test programme of static and fatigue testing as well as a dynamic analysis of the blade's natural frequency and damping behaviour.

A representative blade of the newly-developed turbine design will be installed in the Large Structures Test Lab in a similar fashion to Figure 5.

Testing will commence with a dynamic analysis to determine the blade's natural frequency and damping coefficients. The blade will then be statically loaded incrementally up to its maximum operational load during which displacement and strain sensors will be compared to expected performance.

Fatigue testing will follow and will be provided by a novel 'rotating mass' arrangement, further described in Section 3.7.

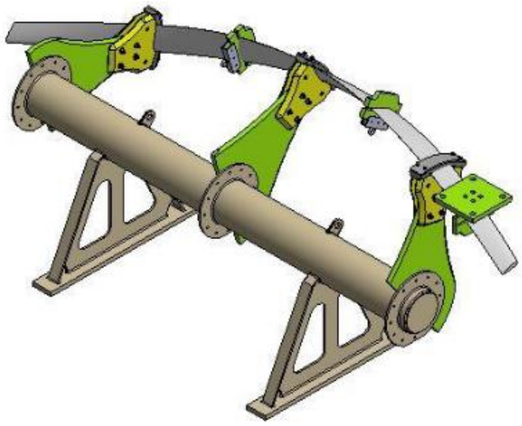

Figure 5. Representative test fixture

3.4 Instrumentation

Enormous amounts of data can be collected from test of this scale so it is crucial to know what should be recorded and what can be left out, or inferred from collected data.

Single axis accelerometers will be rigidly mounted on key parts of the blade span to record the frequency and damping response of the blade to excitations. A minimum of 3 accelerometers will be required to collect data in the x, y and z axes. Endevco piezoelectric sensors with a range of 1-8000 Hz and sensitivity of 100 mV/g will provide ample granularity of data.

Displacement will be recorded using linear variable displacement transducers (LVDTs) installed at the blade tip and mid-span locations as well as at the mounting brackets to record any movement and the fixed points. The displacement range required of the LVDTs will be determined in prior analysis of the blade design and material performance.

Loading will be recorded using suitably sized load cells connected to the main data acquisition system. In the case of hydraulically actuated testing the load cells are already incorporated in the hydraulic actuator assembly, as shown in Figure 6.

Figure 6. In-line load cell mounted on a hydraulic actuator at the Large Structures Test Laboratory, NUI Galway

Strain will be monitored using linear and rosette electrical resistance strain gauges from the Tokyo Measuring Instruments Lab. Analysis of the blade design by ORPC and ÉireComposites will reveal the expected locations of maximum strain to guide the positioning of the strain gauges.

3.5 *Dynamic analysis*

A dynamic analysis of the blade will be conducted prior to any loading of the blade. This will involve fixing the blade to its hub supports in a manner representative of what will be applied in the field. The blade will be excited by means of a hammer strike while the acceleration response will be recorded. Post processing of this data will reveal the blade's natural frequency and damping characteristics.

3.6 *Static testing*

The purpose of static testing is to prove the blade's capability to reach its maximum operational load without any obvious failure or breaches of design limits. Static testing commences by applying loads incrementally to the blade until the maximum operational load is reached. At each loading increment, the blade will be held for a defined time period as defined in [13] and [14] and observed for any discrepancies from expected behaviour. When the test assembly has held the operational load for the required dwell period without any major issues, the static test will be considered complete and allow progression to fatigue testing.

Load may be applied to the blade using a choice of electronically controlled hydraulic actuators available in the test lab at NUI Galway. A displacement controlled loading regime will be used to mitigate the risk of damage to the blade or personnel in the event of unexpected behaviour. Once static testing has been passed satisfactorily the blade can progress to fatigue testing.

3.7 *Fatigue testing*

A large part of the research impact of the testing work packages lies in the novel test method planned for fatigue testing. It is proposed to test the blade to 10,000,000 cycles during testing. Achieving this number of cycles with standard electrically powered hydraulic actuators would require a prohibitive amount of laboratory time as well as a huge amount of energy. To overcome this, a rotating mass will be used to generate the required load at a suitably high frequency. In a first order system, the force generated by a rotating mass is described by equation (1) where F is the force in Newtons, m is the mass of the rotating mass in kg, ω is the angular velocity of the mass in rad/sec and r is the radius at which the mass is mounted, in metres

$$F = m\omega^2 r \tag{1}$$

This rotating mass then generates a response in the "fixed" blade which interacts with the initial excitation causing a second order response.

A geared electric motor with inverter has been sourced to rotate the mass at a controllable and measurable rate. Loading data will be provided by a load cell mounted between the electric motor and the blade. The data acquisition system will simultaneously monitor load, displacement and strain data as they are generated.

Figure 7. 3 phase electric motor with gearbox used to rotate a mass at a measurable, controllable rate [15]

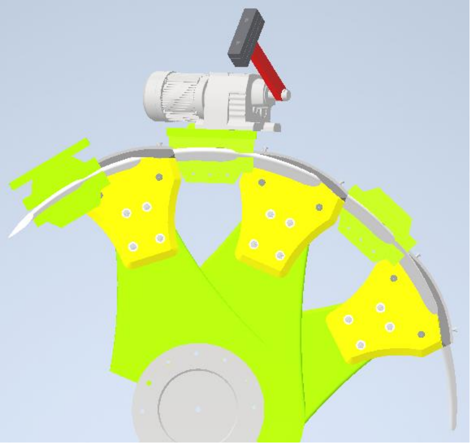

Figure 8. Representative test fixture with rotating mass fatigue test equipment mounted on the blade.

4 DISCUSSION

4.1 *Expected outputs*

Testing on this scale generates vast quantities of data which will be used to confirm assumptions and validate the design.

Static testing of the blade up to its maximum operational load will yield valuable data on the load-displacement response of the blade and give an effective means of comparison to the modelled blade. Results at this stage can be used to fine tune the fatigue test programme before it starts.

The instrumentation used in fatigue testing of the blade will reveal how the displacement response of the blade changes as the test develops. A divergence in displacement about the neutral axis as the cycles increase would indicate that the testing is having a weakening effect on the blade structure, as expected, and this data can in turn be used to estimate residual fatigue life in the blades. If the blade successfully survives the fatigue programme, a final static test to failure may be done to determine the remaining capacity of the blade.

An earlier generation of the foil was tested previously at the facility in NUI Galway, which was performed using two vertical actuators, as shown in Figure 9. The actuator at the cantilever section was attached directly to the foil, while the actuator at the mid-span section used a wire rope connection to load the foil towards the centre of rotation. A comprehensive set of static tests, along with low-cycle fatigue testing, was performed. The full details of the results from this testing programme for the device are given in [12].

Figure 9. A helical foil installed at the Large Structures Testing Laboratory undergoing structural testing using two actuators.

A comprehensive static testing programme was first completed on the helical foil, where the deflection and strain along the foil under the maximum static load profile is given in Figure 10. The maximum deflection is at the cantilever tip of the blade of 23 mm, where the mid-span deflection was approximately 4 mm. The maximum strain on the foil is approximately -1.2×10^{-3} in compression and approximately 1.05×10^{-3} in tension, Figure 11. These strains aligned well with the predictions used in the foil design and were lower than the conservative strains given in the DNVGL-ST-0164 standard.

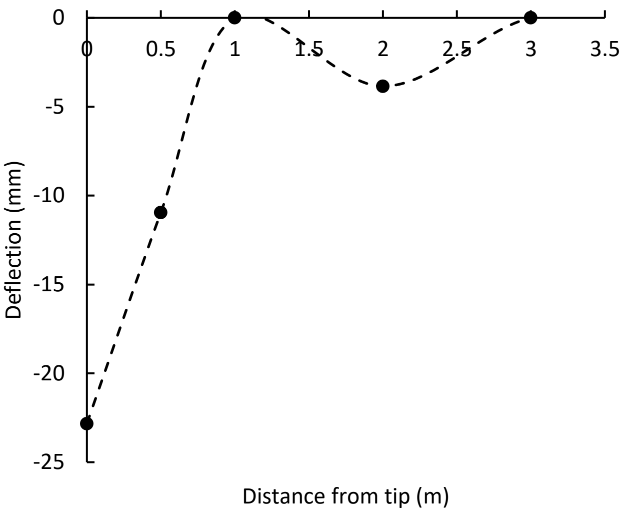

Figure 10. Selected testing results from the structural testing of a helical foil under the maximum static load, showing the foil deflection

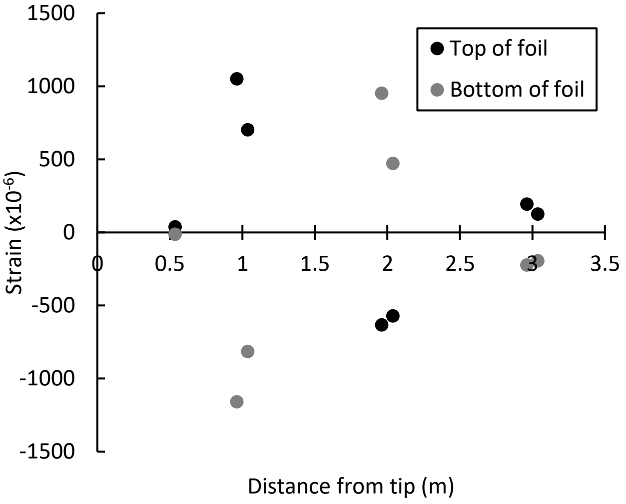

Figure 11. Selected testing results from the structural testing of a helical foil under the maximum static load, showing the strain at the top and bottom outer surfaces along the length of the foil.

4.2 Impact of this research

The purpose of the test programmes was to prove the structural integrity of rCF material of the MHK blades for an operational lifetime in a laboratory environment using recognised international standards (DNVGL-ST-0164 and IEC-TS-62600–3). The net result of the CRIMSON project will be a contribution to marine hydrokinetic energy as a serious player in the de-carbonisation of electrical grids in Europe. As an ever increasing amount of virgin carbon fibre material is produced every year it is imperative that industry and research should combine to improve its environmental impact. By their nature, carbon fibre parts are often designed for high impact, high value components so using a recovered (recycled) material will naturally experience roadblocks to commercial application. Funding mechanisms such as the Horizon 2020 Fast Track to

Innovation help companies and research institutions to prove the capabilities of these materials.

5 CONCLUSION

This paper summarises the planned test programme of a recycled carbon fibre blade for a novel tidal turbine design. The work is funded as part of the CRIMSON project which brings together the capabilities of several companies and institutions operating in the tidal energy field. A new tidal turbine blade will be design using data and modelling techniques optimised for the inclusion of recycled carbon fibre. A full-scale test programme will then be carried out at NUI Galway on a demonstrator blade with the intention of qualifying the blade for its 20 year design life. The long term goal for projects such as CRIMSON is the widespread of adoption of tidal energy as a means of producing environmentally-friendly electricity in Europe.

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