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Development of the world's first regenerative hydraulic tidal blade test centre: FASTBLADE

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***Abstract*—The structural lifetime fatigue testing of tidal turbine blades is currently a challenge faced by the tidal industry. Due to the high stiffness and short length of composite tidal blades, it is not possible to perform resonant fatigue testing in the same way as wind turbine blades. Tidal blades have too high a natural frequency which, if tested resonantly, would result in internal heating of the composite and lead to premature failure. The aerospace industry uses conventional hydraulic systems to fatigue test composite structures such as wings. Although this approach would technically work for tidal blades, testing using this method is economically unviable for an emerging sector. FASTBLADE has been designed to specifically address the challenge of providing lifetime fatigue testing of tidal turbine blades in a cost effective and timely manner. The facility uses a Digital Displacement® hydraulic system to enable energy recovery between loading cycles at high flow rates without compromising on the quality, control or confidence in certification of tidal blades. The paper evaluates the choice of instrumentation and facility equipment designed to enable the fast and yet robust fatigue testing of tidal blades. The 70 tonne reaction frame, capable of 1 MN fatigue loads and 2 MN static loads, combined with 800 lpm of reversible hydraulic flow, will revolutionise the structural testing capabilities within the UK. FASTBLADE will provide training for students and apprentices, deliver cutting edge research outputs, and enable the tidal sector to make the next step toward commercial success with the delivery of larger and certified blades.**

***Index Terms*—Composites, Tidal Energy, Structural Testing, Instrumentation, Fatigue Testing, Regenerative Hydraulics, Full Scale, Construction, University of Edinburgh, Babcock, FASTBLADE**

I. INTRODUCTION

THE objective of the FASTBLADE project is to develop an accelerated structural composite fatigue testing facility with a specific focus on tidal turbine blades. FASTBLADE started in 2017 as the Structural Composites Research Facility, when The University of Edinburgh was awarded a £1.8M equipment grant from the UK Engineering and Physical Sciences Research Council. Since the award, the project team has collaborated with numerous partners from industry, academia and the government to develop FASTBLADE into a £4.1M industrially relevant facility.

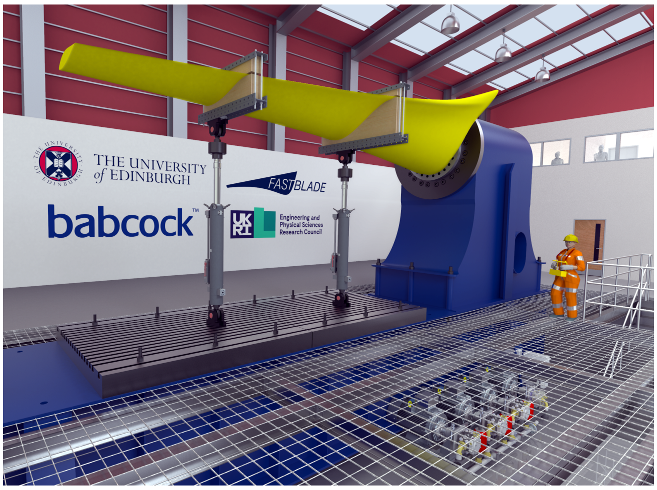

Fig. 1. Rendered Image of the FASTBLADE Facility. [1]

A. Sector Requirements

Structural testing is key to reducing design uncertainty to advance technology beyond state-of-the-art. Tidal turbine blades are mainly manufactured from glass or carbon fibre reinforced polymeric composite materials. There is little understanding of how these tidal blades fail under fatigue loading and what the underlying factors governing failure are.

B. Existing testing capabilities

Hydraulic actuation is currently utilised for fatigue testing of tidal turbine blades, as the natural frequency of the blades is too high to use the resonant excitation techniques employed for wind blade testing [2], [3]. Currently, there is no facility capable of lifetime fatigue testing stiff and slender structures as efficiently as FASTBLADE, as they rely on conventional hydraulic systems.

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The aerospace industry uses conventional hydraulics for fatigue testing at even greater scales than tidal blade testing. Although techniques used by the aerospace sector would work for the tidal industry, they are prohibitively expensive and are generally part of a long term dedicated facility for the testing of a single aircraft. In addition, due to the only slightly accelerated level of testing carried out, structural fatigue testing can last years [4].

C. *Novelty*

The regenerative hydraulic pump-motor system used in FASTBLADE has never been applied to structural testing systems before and represents a new level of ambition for the technology. A substantial amount of system design and optimisation has been required for its successful deployment. Existing hydraulic equipment has been reconfigured, and common practice has been re-evaluated for new techniques in load control, oil cooling and other fundamental operations, all of which are affected by the new modes of operation introduced by the Danfoss DD® pump system [5].

II. Facility overview and capabilities

The FASTBLADE facility has been designed to maximise functionality, flexibility and future expandability. In order to achieve this, it is being constructed in a high-roof warehouse at the Rosyth Dockyard, Fife, Scotland. The dockyard setting allows for excellent road links for large blade deliveries, while also giving the option of receiving deliveries by sea if clients require. The warehouse is approximately 18 m wide and 38 m long with a 9 m high x 12 m wide access door. Having a large open space available improves our ability to simply and safely offload, instrument and test specimens up to 16 m in length and 3 m in diameter.

The FASTBLADE facility can be divided into four main components, (1) the reaction frame, (2) hydraulic pump-motors, (3) hydraulic test actuators, (4) measurement, data logging and control hardware systems.

The reaction frame developed and fabricated by Babcock International Group, reacts against the forces between the hydraulic actuators and the test specimen. The reaction frame is designed to close the load path between the actuators and the test specimen to avoid costly civil foundations. The reaction frame is installed below floor level in a pit to maximise the space available for the pair of tandem cranes with a 7 m hook height, which will offload and install specimens. The pit also provides a convenient way of isolating the hydraulic system from personnel working on the blade and acts as a hydraulic bund to contain any oil in the case of a leak.

The load capacity of the reaction frame and strong wall combination are rated for 2 MN and 11 MNm in a static test and 1 MN and 5 MNm in a high cycle fatigue test. It is also possible to remove the support wall and install alternate test fixtures as required for specific tests, which may exceed the load capacities of the standard reaction frame setup, but would still benefit from the regenerative hydraulic system.

FASTBLADE also contains mechanical and electrical workshops, changing area, showers, plant room, control room, staff offices, teaching and client spaces as well as a small kitchen. Clients will be able to work with FASTBLADE staff with their own space on-site to monitor and contribute to the testing.

A. *Developing partnerships*

The technical and logistical challenges of delivering a facility such as FASTBLADE has necessitated close collaboration between many different industries. The University of Edinburgh has worked in partnership with Babcock International Group [6], who are designing and manufacturing the reaction frame and managing the construction works.

NI [7] has supplied the data acquisition and control system hardware along with providing support on software development for the custom control and data acquisition system required for the unique hydraulic and testing system. Instrumentation such as load cells are being supplied by Applied Measurements [8], who have developed custom load cell housings for connection to the hydraulic actuators. The actuators are being supplied by FOX-VPS [9]. They have spent considerable effort designing and delivering fatigue-rated actuators without any of the servo valve complexity normally present on such a cylinder.

MatchID are supplying the digital image correlation software which FASTBLADE will use to perform multi-camera 3D DIC measurements of the blade. MatchID collaborated closely to trial this system at The University of Edinburgh on a smaller scale test which has been published in a MatchID application note. [10]

III. Hydraulic system

FASTBLADE is the world's first facility with regenerative hydraulic actuation, designed to deliver lifetime fatigue testing of stiff and slender structures such as tidal turbine blades. Testing of these structures requires long actuator strokes (1000 mm) and high forces (1000 kN) that ultimately require large flows of hydraulic oil at high pressure.

The hydraulic system consists of four hydraulic pumps connected via high-pressure supply lines to four hydraulic actuators. The four hydraulic pump-motors are capable of supplying a total of 800 litres per minute of hydraulic oil at up to 420 Bar. However, the system is initially limited to 280 Bar due to issues with the availability of the higher pressure rated auxiliary equipment. There is also a low-pressure return line from each cylinder to a vented oil reservoir. Manifold blocks and interconnection lines provide a common pressure feed from all pumps to all cylinders. Furthermore, the manifold blocks include numerous spare ports for additional hydraulic actuators. This hydraulic network has also been configured with valving to allow rapid configuration changes between fatigue test mode (low load and high reliability) and static test mode (high loads and low cycles).

The system does not feature a ring main as is standard. Instead flow will oscillate back and forth within the supply lines. This is made possible by the Danfoss DD® pump's ability to rapidly switch from pump to motor mode. The pumps are the result of over two decades of engineering development at Artemis IP and the latest models for FASTBLADE have been commissioned on a demonstration rig.

A significant challenge of the FASTBLADE system is that the hydraulic control is all performed at the pump-motors rather than at a servo-valve at the actuator. This means that the compressibility of the oil, the expansion of pipes and the damping of the flow are all vital to the optimal performance of the system.

In order to develop the hydraulic circuit and confirm the performance of multiple pumps in parallel, a full Simulink model of the hydraulic circuit has been developed. The model incorporates a full Simscape fluids hydraulic network including pipes, joints, valves and actuators. This is connected to a Simscape Multibody representation of a composite tidal turbine blade. Extensive work was carried out to identify the optimum hydraulic network for various blade parameters.

Due to the cyclic nature of the pressurisation of the entire hydraulic network, a large proportion (approximately 15% to 40%) of the pumping capacity is lost in the compressibility of the oil and expansion of the pipes. A system response and efficiency study was carried out to select the optimal supply line pipe diameter. The study indicated that a lower than normal pipe diameter provided the greatest system response due to the reduced system volume. Furthermore, overrated pipes (420 Bar for a 280 Bar system) also increase stiffness. Finally, the increase in fluid losses from the undersized pipes results in increased damping which removes some resonant effects which were observed during the modelling of the system.

A. Regenerative Hydraulic Pump-Motors

FASTBLADE is able to offer regenerative fatigue testing due to the unique digital displacement pumps developed by Artemis IP. The pump-motors consist of an array of radial pistons with individual electrically actuated high and low pressure valves, as shown in Fig 4, which can each be operated variably and independently. This allows the pump-motor to alter its output across its full range to respond to a control signal within milliseconds.

The regenerative loading cycle begins with the hydraulic pump-motors pumping fluid at pressure to the hydraulic actuators. As the hydraulic actuators extend, pressure builds, the test specimen deflects. In conventional hydraulic systems, once the peak load is reached, the high-pressure oil would be released from the cylinders and returned to a collection tank at low pressure where it is cooled, filtered, and reused. In doing so, a conventional hydraulic system would dissipate all the energy required to deflect the specimen. The unique technical innovation of FASTBLADE is to return that hydraulic oil to the tank via hydraulic motoring and recover 70 to 90% of the energy.

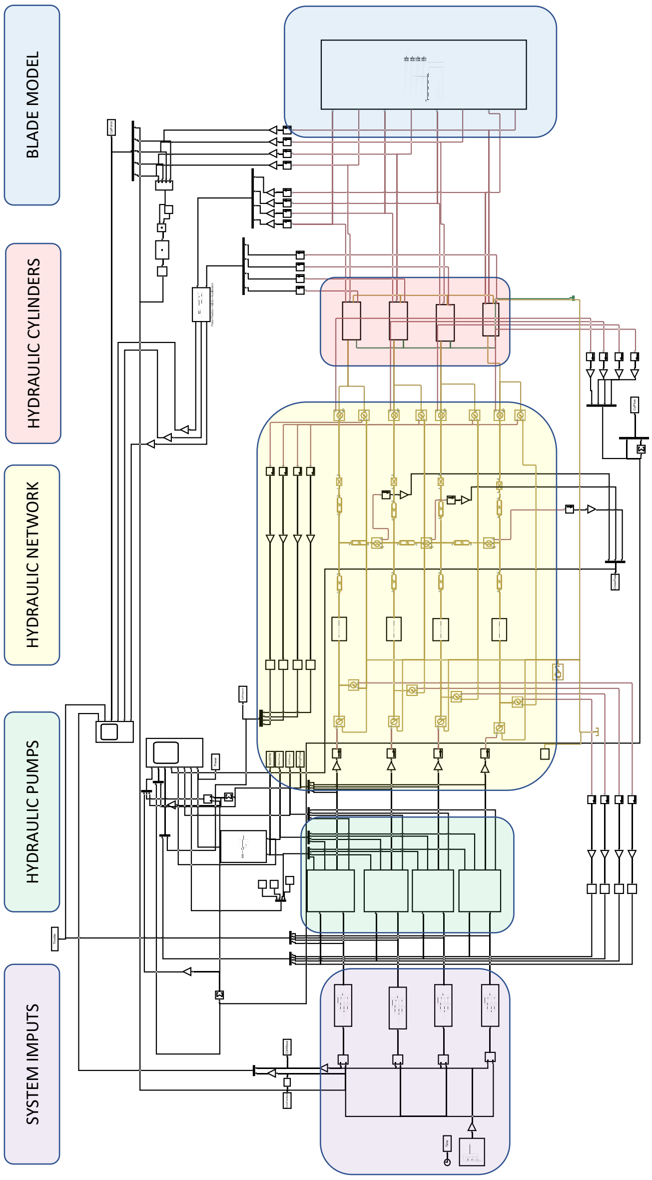

Fig. 2. Overview of the FASTBLADE Simulink digital twin.

The recovered energy is stored as kinetic energy in the spinning shaft as the hydraulic machine accelerates the drive train. The rotational kinetic energy is then transferred back to the hydraulic fluid in the following cycle as the hydraulic machine switches back to pumping mode to reapply the force to the test specimen. This has the added technological benefit of requiring a smaller inverter to operate the hydraulic pumps. The energy from the grid is only used to top up the energy losses due to inefficiencies in the system.

This simple energy transfer from potential energy to kinetic energy is the result of decades of hydraulic machine development. This unique application for testing tidal blades efficiently has required technical innovation at many subsystem levels. The novelty of the hydraulic machines has cascaded through each subsystem, requiring new applications or new designs, all of which were underpinned by a digital twin (shown in Fig 2) co-developed by Artemis IP and The University of Edinburgh. The model has been used to simulate the system throughout its design to verify design choices

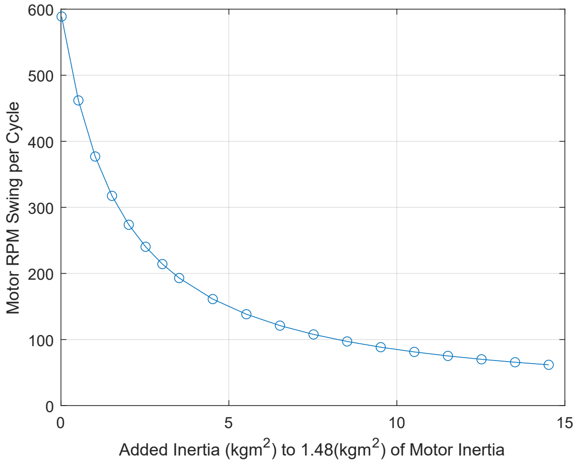

Fig. 3. RPM swing versus added inertia for standard 1Hz cycle at 440kN load and 400mm stroke.

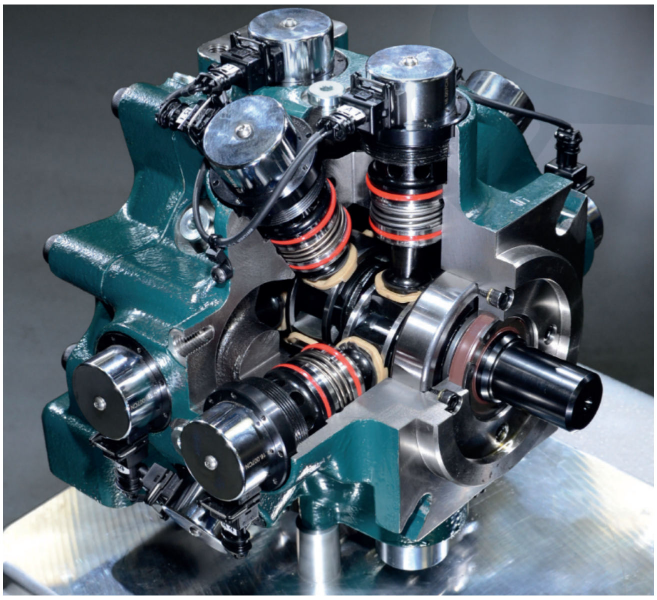

Fig. 4. Cutaway image of Artemis IP E96 hydraulic pump. [11]

and optimise configurations. For example, it was used to investigate the trade-off between RPM swing and system inertia as seen in Fig 3, justifying the selection of the 75 kW motors to maximise the energy storage potential within the rotating pumps, without the complexity of having to include additional flywheels within the system.

The modelling carried out of the FASTBLADE system showed that the regenerative hydraulic system would be capable of recovering at least 70% of the energy which would typically be wasted in a fatigue loading cycle. For a high cycle fatigue test, lasting 5 Million cycles, at 1 Hz, delivering a bending moment of 4.95 MNm to a specimen with a maximum displacement of 0.5 m, this would result in a saving of over £25,000 in electrical energy (assuming an electrical cost of 17.2 p/kWh).

B. Actuators

The initial actuators purchased from FOX-VPS have a 150 mm diameter bore, a 100 mm diameter rod and a 1000 mm stroke. At a nominal operating pressure of 280 Bar, the actuators can exert up to 495 kN in static push mode, 275 kN in static or fatigue pull mode and 220 kN in push fatigue mode.

Fig. 5. Rendered image of FASTBLADE Actuator.

By having all the complexity of the system contained within the hydraulic pump-motors, it is very cost-effective to purchase alternate size actuators to address any other specimen testing requirements. A rendered image of the actuators and bypass valving can be seen in Fig 5. The initial FASTBLADE system was designed for large blades (880 kN fatigue and 1.98 MN static loads). However, for each specimen load and deflection, the hydraulic actuator diameters should be carefully selected to maximise system response. The modelled response of these load capacities and tip deflections can be seen in Fig 6. The 800 lpm hydraulic pumping and motoring capacity allows FASTBLADE to oscillate loads at over 4 Hz fatigue rates at low displacements (0.1 m) and low loads (100 kN) or 0.5 Hz at high displacements (0.8 m) at 800 kN.

The oscillating flow within the hydraulic lines presents a technical challenge as there is no continual recirculation of oil back to the tank for cleaning and cooling. This challenge has been addressed by adding a variable flow return line within the actuator configuration which slowly recirculates oil back to the tank. This flow can be tuned to achieve adequate cooling, cleaning, or efficiency targets for the system (the higher the recirculation flow, the lower the system efficiency).

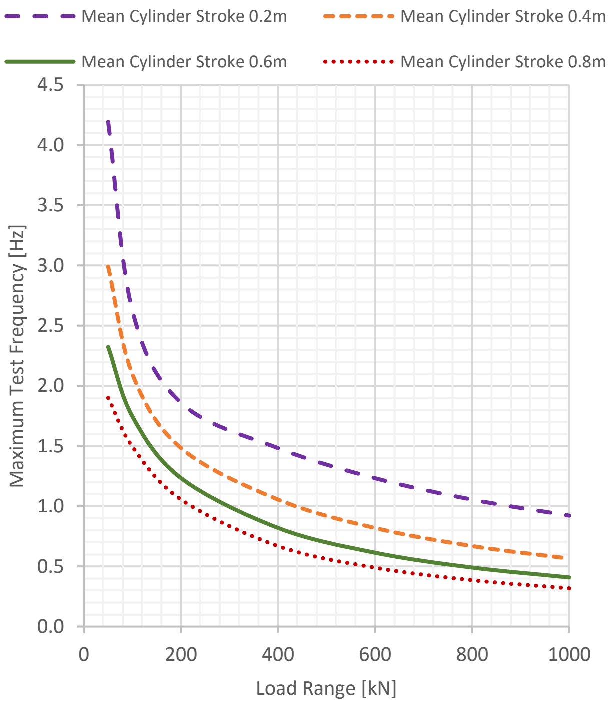

Fig. 6. Estimate of maximum fatigue test frequency and load range based on optimal actuator sizing for various hydraulic actuator strokes.

IV. Control System

The FASTBLADE control and instrumentation suite is designed to be flexible yet as robust as possible to enable FASTBLADE to adapt to clients needs. Due to the nature of full scale specimen and product testing, the test standards [12] [13] can only provide generic guidance on test setups and measurements. Due to the scale of the specimens being tested (up to 16 m in length), the distribution and synchronisation of all sensors, triggered systems, and data acquisition hardware needs careful consideration.

1) NI Hardware: In order to achieve the required synchronisation, distribution, integration of data acquisition, control, and calibration, an NI compact RIO system with Time Sensitive Networking (TSN) between the distributed DAQ modules has been selected. The main advantages of this system are that synchronisation of distributed systems is achieved and maintained automatically using the TSN protocol, with up to sub-microsecond timings. The system is expandable, allowing hundreds of sensors to be added as test requirements increase.

The daisy-chained and synchronised NI chassis can be populated with various input or output models for different types of signals such as voltage, current, temperature, digital triggers, and digital protocols such as serial and CAN bus. An example of this hardware can be seen in Fig 7. The majority of instruments use 4-20mA current outputs for reduced susceptibility to electrical interference and eliminates any voltage drop due to cable length, which can be an issue when using DC voltage outputs. The suite of strain gauge measurements will be most vulnerable to interference, as they are not amplified between the gauge and the DAQ. Therefore the DAQ system will be distributed over the test specimens in order to minimise cable runs between the gauges and the DAQ, as far as is practical.

Fig. 7. Image of NI cRIO Chassis populated with C-series DAQ modules. [14]

2) LabVIEW: The control and acquisition system is programmed in LabVIEW. The LabVIEW environment gives access to very low-level functionality of the acquisition hardware, enabling the code being developed to run more quickly, efficiently and reliably than by using higher-level Application Programming Interfaces (API's).

The control loops and data handling are performed in the same software, minimising any potential errors from either splitting signals or delays due to logging and controlling on separate hardware. In order to maintain deterministic real-time control, the primary control algorithms and data acquisition are run within the Linux Real Time environment. The user interface interacts with the real time control via deterministic network streams using a Queued Message Handler. This level of system division enables robust long term control and acquisitions, without being susceptible to delays from non-real-time operating systems, yet maintaining consistent access for a range of users. The development front panel user interface can be seen in Fig 8.

The system is specifically designed for long term fatigue testing in order to minimise testing time, while maximising pump energy recovery and efficiency. This is achieved by allowing the system to alter control strategies in real time to account for variations in component stiffness, and real-time tuning of the PID controller for the most optimal rpm swing from the pump. A key challenge with this system is dealing with the variation in pump flow throughout a fatigue cycle. In order for the energy recovery to work correctly, the pumps must be allowed to slow down as the specimen is deflected. This results in a reduction in hydraulic flow, which must be accounted for in order to ensure that the target load is correctly achieved. When operating near the hydraulic system's maximum capacity, this becomes very difficult, as there isn't the capacity to simply call for more flow. The system has therefore been designed to vary PID and set point gains throughout a cycle in order to achieve the optimum performance.

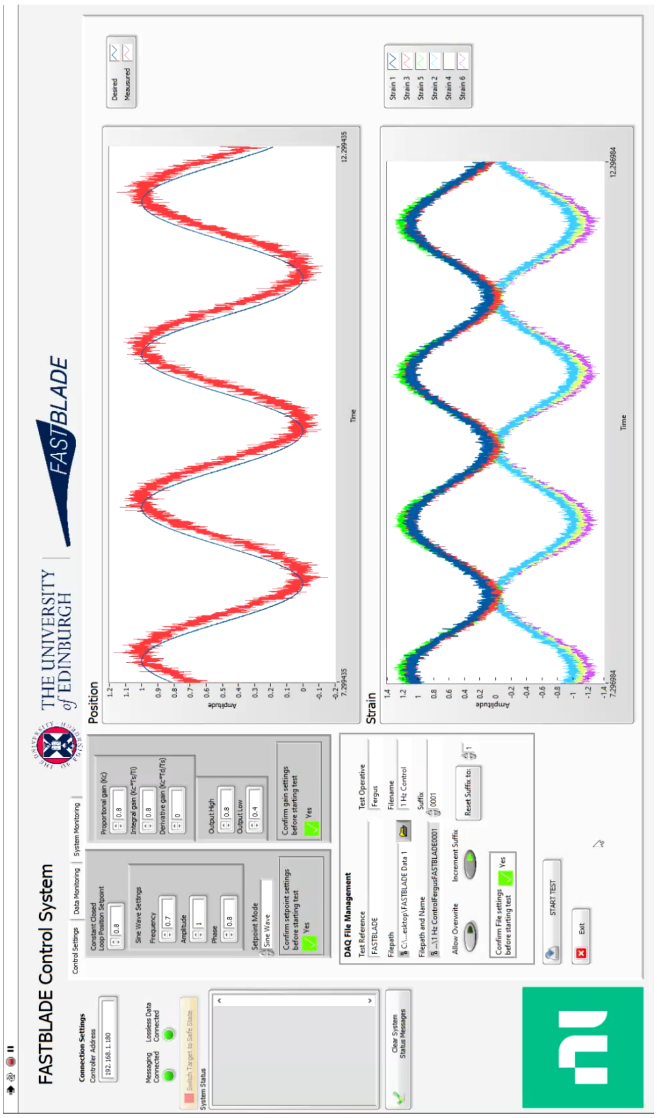

Fig. 8. Image of FASTBLADE LabVIEW control system.

V. INSTRUMENTATION

By implementing a custom data acquisition and control system, the facility can log any type of sensor input. The primary suite of instruments consists of load cells, 3-axis accelerometers, foil-type strain gauges, laser and Linear Variable Differential Transformer (LVDT) position measurement, thermocouples and pressure sensors. The system is also expandable to include additional sensing systems such as acoustic emission systems, Fibre Bragg Gratting (FBG) strain sensors and Integrated Electronics Piezo-Electric (IEPE) vibration sensors, by slotting the appropriate modules into the expandable chassis.

1) Calibration: In order to offer certified testing of tidal blades and other structures, the facility aims to achieve ISO-17025 [15] with traceable calibration of all data acquisition hardware and instrumentation. NI offers this calibration service for all of the data acquisition hardware they supply and calibration certification for all instruments can be provided to clients requiring certification.

2) Digital Image correlation (DIC): When working with large, complex components such as tidal blades, it is not economical or practical to place strain sensors (foil or other types) in all areas of potential interest. For this reason, FASTBLADE has partnered with Match ID to install a multi-camera 3D DIC system. A 2 camera DIC system is capable of measuring contours, displacements and surface strains of a specimen in 3 dimensions by tracking the deformation of a unique black and white pattern which is applied to the specimen. An introduction to the technique and the mathematics behind the correlation can be found online, provided by the International Digital Image Correlation Society [16].

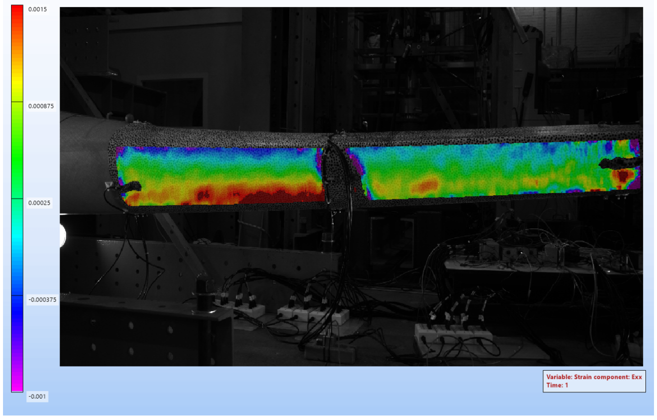

Fig. 9. Example result of 3D DIC using Match ID software in the EU H2020 Powderblade Project. [17]

The MatchID multi-cam DIC system goes beyond two camera stereo DIC setups to combine an array of 6 or more cameras to compute the strain in all directions over the full 360° of the blade surface, within a fully calibrated measurement volume. Correlation images may be captured throughout a fatigue cycle or at peaks and troughs throughout a test. Image acquisition is controlled by the NI & LabVIEW system so that the capture may be triggered to occur when the peak load is actually measured, rather than when it is predicted to occur from the input waveform.

The control system will also be continually monitoring for failures or anomalous vibrations and when detected, will trigger additional image capture which may be analysed to identify possible failure locations within the specimen. This functionality is only possible by using the multi-camera DIC system in combination with the real time DAQ and control system and should provide invaluable data to clients.

VI. REACTION FAME

To react the large forces and close the load path, Babcock has designed and is due to deliver a highly optimised and bespoke steel structure capable of reacting 400 million load cycles. The FASTBLADE Project Charter between Babcock and the University of Edinburgh outlined the project mission 'to apply innovative tools and techniques to deliver a unique structure to demanding criteria' which required in excess of 2500 person hours in design and simulation to ensure the stress levels of the reaction frame are low enough to

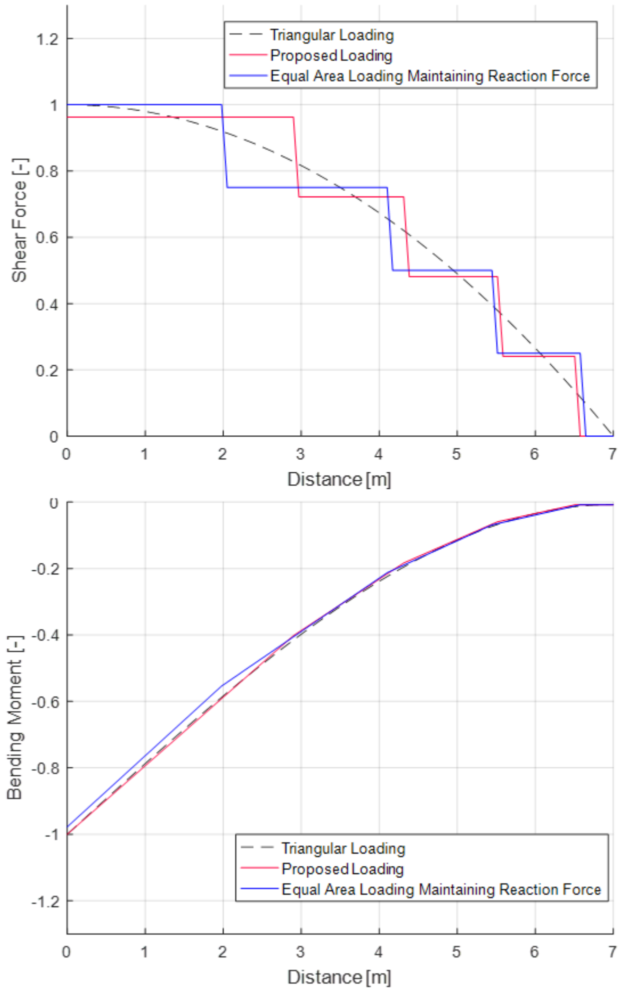

Fig. 10. Example actuator positioning optimisation, aiming to matching the bending moment resulting from a triangular load distribution. (Bending moment and shear force nondimensionalised)

accommodate the rapid oscillatory loads required to test all the potential specimens in its lifetime.

Before the structural design of the reaction frame could be started, the load requirements for tidal turbine blades and other potential test specimens required extensive research. Multiple tidal developers were approached to identify their current and future requirements in terms of load magnitude, profile and specimen dimensions. With this information, a series of representative load cases were developed which would form the basis for the design specification for the reaction frame. An example of the work done to investigate potential options for discretising a distributed load using a limited number of hydraulic actuators can be seen in Fig 10, which shows how four hydraulic actuators may be distributed to match the bending moment applied to a tidal blade by a triangular load distribution.

A. Frame requirements

The key design requirements focused on three main areas; static load capacity, fatigue load capacity, and overall dimensions (of both test specimens and surrounding building). The load capacities identified were 2 MN static shear and 11MNm static root bending moment and 1 MN shear and 5 MNm root bending moment in fatigue, with a point load capacity of a single actuator of 1 MN. As the facility is designed to provide lifetime testing for many different test specimens, the fatigue life of the reaction frame was specified to test 2 specimens a year at 10 million cycles with a predicted facility life of 20 years, giving 400 million full load fatigue cycles

The dimensional requirements primarily focused on actuator positioning, where it was identified that it should be possible to position actuators anywhere in a 2.5 m wide by 12 m long area below the test specimen, at angles of up to 45°. Other important dimensional constraints were that of the reaction frame itself. The building has a maximum crane hook height of 7 m. With specimen dimensions up to 3 m diameter, it was necessary to ensure sufficient space was available above a specimen for any lifting apparatus. Additionally, space had to be available below the specimen for all hydraulics with the appropriate stroke to achieve loads and displacements required.

B. Design Process

With the design constraints defined, an optioneering study was conducted to identify all potential design options. The results focused on either a concrete strong floor or a steel structure as the base of the frame and either a truss or a steel plate design for the support wall.

1) Strong Floor: A concrete strong floor is generally the gold standard for a modular, high capacity structural testing centre with a recent example being the Airbus wing integration centre in Bristol [18]. An extensive investigation was carried out on the feasibility of using a strong floor for tidal blade testing and it was determined that it would provide excellent capacity and adaptability to suit the tidal sectors need. The strict budgets and timescales of the project, however, ruled out a concrete strong floor as an option.

2) Truss Structure: Using a truss structure as a support wall was extensively investigated and a full concept design was developed, as shown in Fig 11. Once the design had progressed to a more detailed stage, a fatigue analysis was carried out, which identified multiple hotspots around the welded truss joints. This led to a full review of the design, where it was determined that addressing the fatigue hotspots would be uneconomical in terms of complexity of manufacture and materials cost, leading to the truss design being abandoned.

3) Box Beam: With the concrete strong floor ruled out for cost reasons, the design focused on a plate steel box girder construction. The large plates with extensive stiffeners work to avoid any stress hotspots, which would become an issue in fatigue. By using T-slot mounting plates on the base structure, it is possible to achieve infinite adjustability for actuator positioning.

The steel box girder design is the most cost effective design, however there are several major compromises which had to be made. The main points are that the width of the area where actuators may be connected

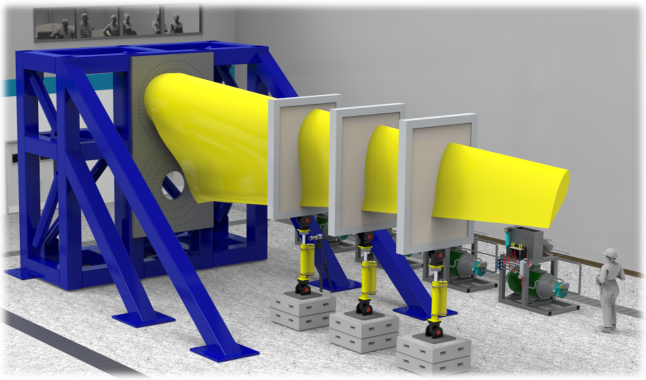

Fig. 11. Rendered Image of the FASTBLADE truss concept.

is 2.5 m wide. This compromise may be overcome by construction of custom actuator supports as required. Secondly, the frame is not able to achieve 400 million full fatigue load cycles when following Eurocode 3: Design of steel structures - Part 1-9: Fatigue [19].

This has been addressed by performing cycling tracking on the reaction frame to monitor the total cumulative fatigue stress applied to the frame. As not all tests will be at maximum fatigue capacity, it should be possible to achieve the 20 year life of the facility and it is possible to plan accordingly if it appears the fatigue life is being approached.

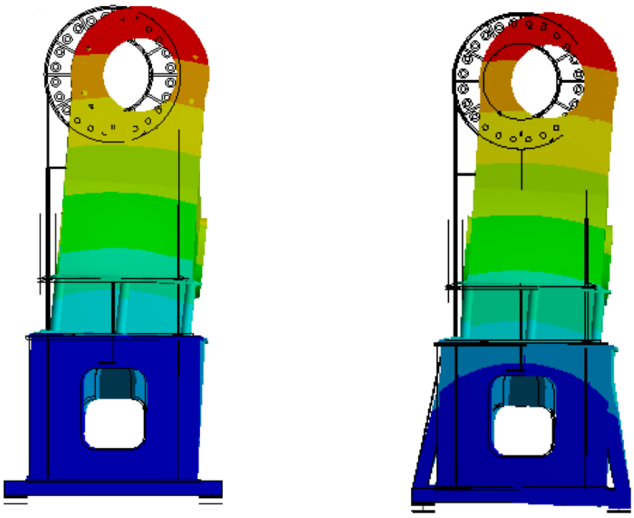

Fig. 12. Roll response comparison of FASTBLADE reaction frame support structure variations. [20]

4) Ground Supports: The combined mass of the steel structure with a blade and hydraulic system mounted is approximately 80 Tonnes, with a cyclic 1 Hz oscillation of a 5 Tonne blade up to 500 mm displacement resulting in the potential for damage to the building foundations.

To address this, the entire system is mounted on four bridge bearings which are able to account for any twisting and translational movements of the frame. The roll response of the reaction frame was optimised as far as was practical by adding additional supports to the bridge bearing connections, as shown in Fig 12.

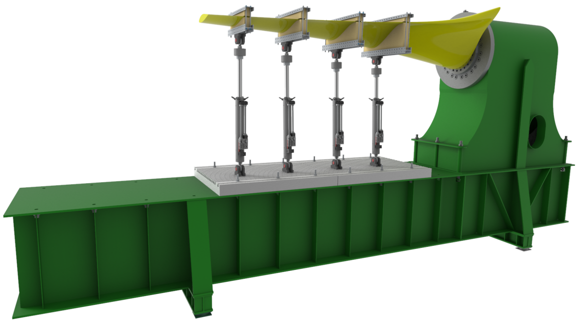

Fig. 13. Rendered Image of the FASTBLADE Reaction frame.

In addition, the foundations were dug 5 m down to bedrock, with a series of mass concrete trenches supporting a 400 mm concrete slab above, preventing any vibrations being transferred to any surrounding facilities. At the time of writing the reaction frame is under construction, a rendered image of the final design can be seen in Fig 13.

VII. IMPACT

Designed 'with industry, for industry', FASTBLADE will provide the missing capability in the technology development process for certain fatigue-critical composite structures. FASTBLADE's vision is to offer high-quality, low-cost fatigue testing of composites structures for research and product development. The research centre will provide the necessary expertise and equipment for full life testing of composite structures. The facility will enable the rapid evaluation of designs and manufacturing techniques for composite components.

The advancements made possible by FASTBLADE in tidal energy technology will enable the exploitation of this rich and predictable tidal stream energy source and help to mitigate the urgent threat of climate change. Validating current designs will enable the increasing length of tidal blades to increase energy capture and reduce the levelised cost of energy of tidal stream energy.

The initial facility was designed for 6 m structures, but it became apparent that tidal energy blades would eventually double in size. Whilst FASTBLADE's goal was to facilitate this development, it was important that FASTBLADE not become obsolete quickly. The collaboration with tidal developers made this long term impact possible.

The project team has researched demand and carried out market analysis to ensure that the facility is priced appropriately using the Transparent Approach to Costing (TRACS) [21].

The potential customer base has been identified and the first testing project has already been funded and scheduled for November 2021. To date we have identified 12 technology developers with a need for the testing facility.

FASTBLADE's initial focus is on fatigue testing of tidal blades. However, it will be of benefit to a variety of sectors, as it is multipurpose and can test stiff and slender components that are too costly to test with conventional hydraulics.

Without FASTBLADE, structural engineers and technology developers are left with unanswered questions on the suitability and reliability of their designs. FASTBLADE will answer these questions enabling technological advancement and verifying design uncertainty, allowing developers to break through barriers to design and manufacture.

VIII. CONCLUSION

FASTBLADE is the world's first test facility with ultra-efficient regenerative hydraulics, delivering a step change in structural fatigue testing. The collaboration has overcome technical challenges to design a system that can exert 20 years' worth of operational fatigue loads on a structure within less than 4 months. The development of the facility required a range of business and technical experts to collaborate on the ground-breaking application, to deliver a multitude of bespoke subsystems. FASTBLADE will offer accelerated structural testing to engineering sectors to de-risk designs and new materials, and build investor confidence prior to deployment, a critical part of tidal turbine blade development.

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