This is a repository copy of *Monitoring energy recovery in a full-scale fatigue test*.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/221321/

Version: Accepted Version

Proceedings Paper:

Munko, M.J., Dubon, S.L., Cuthill, F. et al. (2 more authors) (2024) Monitoring energy recovery in a full-scale fatigue test. In: Proceedings of the International Conference on Condition Monitoring and Asset Management (CM 2024). 20th International Conference on Condition Monitoring and Asset Management (CM 2024), 18-20 Jun 2024, Oxford, UK. British Institute of Non-Destructive Testing (BINDT) , pp. 12-23.

https://doi.org/10.1784/cm2024.6a3

© 2024 The British Institute of Non-Destructive Testing. Except as otherwise noted, this author-accepted version of a paper published in Proceedings of the International Conference on Condition Monitoring and Asset Management (CM 2024) is made available under the terms of the Creative Commons Attribution 4.0 International License (CC-BY 4.0), which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/

Reuse
This article is distributed under the terms of the Creative Commons Attribution (CC BY) licence. This licence allows you to distribute, remix, tweak, and build upon the work, even commercially, as long as you credit the authors for the original work. More information and the full terms of the licence here: https://creativecommons.org/licenses/

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Monitoring Energy Recovery in a Full-Scale Fatigue Test

Marek J Munko, Sergio Lopez Dubon, Fergus Cuthill and Win Rampen
School of Engineering, The University of Edinburgh
The King's Buildings, Mayfield Road
Edinburgh, UK
EH9 3JL
M.Munko@ed.ac.uk

Conchúr M Ó Brádaigh
Faculty of Engineering, The University of Sheffield
Sir Frederick Mappin Building, Mappin Street
Sheffield, UK
S1 3JD

Abstract

A fatigue test aims to subject a specimen to a multitude of loading cycles to stimulate damage. This way objects such as beams, columns, or blades can be tested at an accelerated pace, and their degradation patterns can be examined before they are commissioned for mass production/service. Fatigue tests are energy-expensive processes due to the vast number of cycles required. Some tests benefit from energy savings when the specimen, such as a wind turbine blade, can be actuated at its natural frequency and resonance occurs. However, stiffer objects, such as polymer composite tidal turbine blades or aircraft wings, have a much higher resonant frequency and the specimen would suffer degradation due to overheating, rather than cyclic loading. FastBlade, a test facility at the University of Edinburgh, incorporates a novel energy recovery system for fatigue tests, opening the door to efficient testing of stiffer specimens. In this work, we introduce the principle of operation of the proprietary energy recovery system and describe the associated condition monitoring hardware. We then discuss various ways of quantifying hydraulic system efficiency. Running an offline test, it was found that more than 60% of the mechanical energy stored in the system was transferred into producing useful actuation work by the hydraulic system, while the electric motors driving the pumps were unpowered. We subsequently suggest system upgrades that can be integrated for more accurate energy savings estimation in real-time.

1. Introduction

The mechanical properties of structures, such as beams, columns or wind turbine blades, must be verified before they can be safely deployed in their operational environment. An effective way of evaluating the long-term performance of structures is through fatigue tests, which stimulate the degradation of an object when cyclic stresses are applied. This way, a long real-life fatigue cycle (e.g., spanning more than twenty or thirty years of expected service) can be simulated at an accelerated pace based on applying equivalent damage(1).

Among many areas where fatigue tests are applied, such as in testing of aircraft wings(2), rail components(3) and bridge members(4,5), they play a crucial role in reducing the risk of deployment of renewable energy plants, including wind turbines(6). The increase in demand for electricity generation from renewable energy sources has stimulated the growth of the wind turbine industry. Increased rotor size and advancements in materials used to build wind turbine blades have contributed to developing relevant testing facilities and introducing new standards. A widely applied solution for examining the mechanical properties of full-scale wind turbine blades is by conducting fatigue tests. In such set-ups a blade is attached to a strong wall, and a driving force actuates the specimen under test at its resonant frequency(6–8). The actuation of a blade at a frequency close to its resonant frequency results in energy savings, which makes the tests feasible despite the significant number of fatigue cycles applied to a specimen. An example of such a test rig is presented in Figure 1. The specimen is mounted on a strong wall, and a series of actuators pull on the blade at clamping locations, causing it to deflect. The loading-relaxation cycles introduce fatigue into the blade.

Figure 1. Wind turbine blade test rig(9).

One of the main problems in the wind energy sector is the lack of reliability of the resource caused by naturally occurring wind variations. This issue can be addressed by considering alternative renewable energy sources, such as tidal energy. Tides are highly predictable, and given significant availability of this resource in many areas around the world, tidal energy constitutes an attractive alternative to wind. In the UK, the tidal energy potential is estimated at 50 TWh per year, constituting about half of the European resource(10) and 30.2 MW of tidal generation capacity was installed in Europe alone between 2010 and 2021(11). However, one of the factors impeding the development of associated technology is the fact that, due to their high natural frequencies, tidal turbine blades cannot be tested as efficiently as their wind counterparts. Operating in a much denser medium (seawater), tidal turbine blades are shorter and stiffer than equivalent wind turbine blades, and actuating them at their resonant frequency would make the polymer composite blades suffer damage due to overheating(12).

Among a variety of tests which have been developed to overcome the aforementioned challenges, FastBlade, a research facility at the University of Edinburgh, stands out as a purpose-built site for fatigue testing tidal turbine blades(12,13). FastBlade, pictured in Figure 2, is fitted with a proprietary energy recovery system, which allows the facility to carry out efficient tests of slender structures such as beams, columns or tidal turbine blades. This paper aims to focus on challenges associated with monitoring the proprietary energy recovery system, describe the hardware necessary for evaluating its performance and discuss potential system upgrades.

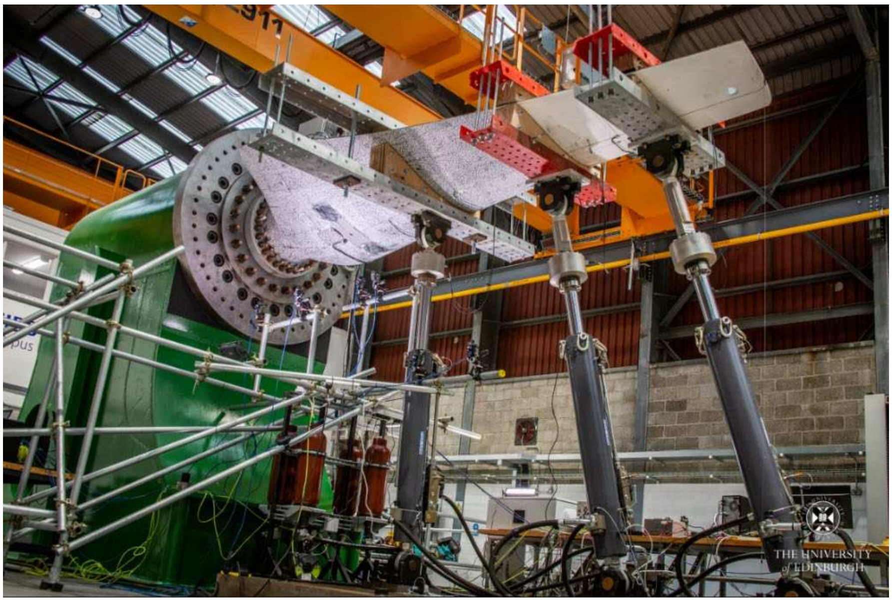

Figure 2. The main test set-up at FastBlade. The tidal turbine blade under test is mounted on a strong wall and three hydraulic actuators are used to deflect the specimen. The machinery room, which comprises electric motors, pumps and an oil supply system, is in the pit beneath the main test rig.

2. FastBlade hardware and operation

2.1. The relevance of monitoring energy recovery to condition monitoring

The hardware detailed in this section plays a critical role in the operational functionality of FastBlade, particularly in facilitating energy recovery during fatigue testing. The sensors outlined are essential for system control, enabling direct measurement of various physical parameters, including actuator displacement, specimen load, and oil pressure. This capability not only supports precise control of the testing process but also lays the groundwork for effective condition monitoring (CM) of individual components, such as electric motors and hydraulic actuators. However, while the fitted sensors provide valuable insights into specific parameters, they do not directly measure overarching indicators of the energy recovery system's health, such as energy recovery rate or system efficiency. Consequently, establishing a viable method for estimating energy recovery ratio is crucial for the effective CM of the system. In addition to monitoring the adherence of measured parameters to desired values, such as load characteristics, the efficiency estimate serves as a crucial system-wide CM metric.

A declining energy recovery rate or efficiency would signify potential issues, prompting further investigation at both the system control and hardware levels. By leveraging these CM indicators, proactive measures can be implemented to address emerging issues and uphold the optimal performance of the energy recovery system within FastBlade.

2.2. Operation of the proprietary energy recovery system

The principle of operation of the proprietary energy recovery system used at FastBlade is described in the patent document assigned to Artemis Intelligent Power Limited (later acquired by the Danfoss Group)(14). The company supplied the Digital Displacement® Pump/Motors (DDPMs), which are indispensable for the implementation of the system. This subsection aims to introduce the necessary hardware and the basic operational principle of the system, allowing discussion of the condition monitoring considerations.

2.2.1 General principle of operation

The energy recovery in the system relies on the transfer of energy between the hydraulic actuation system and the specimen under test, which is mounted on the reaction frame. During deflection, the specimen stores elastic potential energy (like a compressed spring), which, instead of dissipating as heat when the blade returns to its original position, is transferred back to the hydraulic system. The energy in the hydraulic system is stored predominantly in the form of rotational kinetic energy of the motors which drive the DDPMs. To this end, the dimensions of the motors are larger than required to solely actuate the specimen at a required load, providing additional energy storage resources in the form of a flywheel. Similarly, the pumps (coupled with electric motors) used in the system are not chosen solely based on their ability to provide enough pressure to actuate the blade at a desired load, but the technological advantage of DDPMs is a crucial enabler for the energy recovery to work.

Therefore, the operation of the system during a fatigue test is clearly divided into two phases during each cycle. In the pumping phase, the pressurised fluid extends the actuator to provide the desired load on the blade, while in the motoring phase, energy is recovered by the fluid pushing back on the spinning camshaft, increasing the kinetic energy of the electric motor connected to the DDPM. The control system is configured to match the desired load characteristics, varying the pressure by setting appropriate DDPM control signals. The speed oscillation between the pumping and motoring half-cycles is made possible by a non-aggressive tuning of the speed control loop. Electric energy, which is the main operational cost of running the facility, is provided to the motors by Danfoss frequency converters, known under their tradename VLT. Due to the nature of high-frequency fatigue tests, additional hardware requirements involve the installation of LP accumulator tanks, where oil can be transferred during the motoring half-cycle, which mitigates flow inefficiencies relative to using an open tank.

2.2.2 The operation of Digital Displacement® Pump/Motors

The DDPMs are built around a radial format, with banks of cylinders along a common crankshaft. What makes the DDPM significantly different from legacy machines is that commutation of flow into and out of the cylinders is managed by electro-magnetically

actuated poppet valves. The valves control the flow of the fluid in relation to the position of the camshaft. The instance when the camshaft is the closest to a valve is referred to as the top dead centre (TDC) and when it is on the opposite side – the bottom dead centre (BDC). By sequencing the opening and closing of the low-pressure (LP) and high-pressure (HP) valves, pumping, motoring and idle cycles can be achieved.
A *pumping cycle* can be created by opening the LP valves during the expansion phase of the cylinder. The subsequent contraction phase of the cylinder is used to automatically open the HP valve and expel the HP liquid into the HP manifold, from where it can do useful work to an actuator. The HP valve will then naturally close, allowing the LP valve to reopen and continue the cycle.

The *motoring cycle* is achieved in the DDPM by having both the LP and HP valves electromagnetically actuated. The key feature of this cycle is the opening of the HP valve, which allows the inflow of the HP fluid into the DDPM. The opening of the HP valve is timed to take place shortly after the TDC and continue towards the BDC. The pressure exerted by the fluid on the camshaft during that time raises the rotational speed of the DDPM. Since the DDPM is coupled with the electric motor which drives it, the increase in the rotational speed of the shaft results in the increase of the kinetic energy of the electric motor. Therefore, the energy of the HP fluid is not dissipated as heat, but is converted back to useful energy.

2.3. Monitoring the proprietary energy recovery system

This section aims to introduce the hardware installed across the energy recovery system to monitor critical system parameters and the state of the assets. The sensors used are categorised based on the components to which they are attached, namely the actuators, the DDPMs, and the electric motors.

2.3.1 Hydraulic actuators

The hydraulic actuators are fitted with load cells and mounted between two parts of the movable actuator rod. The compression of the load cell is equivalent to the load exerted by an actuator on the specimen. Since the load is the independent variable in each test, the load cell measurements provide a crucial feedback signal for controlling the rest of the system parameters. The load cells used at FastBlade, supplied by Applied Measurements Ltd., provide an analogue output and can measure load values between 0 kN and 500 kN(15). Another crucial sensor installed in each actuator arm is a position sensor, measuring the linear displacement of the actuator with a non-contact ring-shaped position magnet(16). The transducers have a maximum stroke length of 1 m and provide an analogue measurement output. For a fixed load test, the displacement measured by the sensor will depend on the stiffness of the specimen. As it will be later presented, the displacement and load data can be used to measure work done on the specimen in each fatigue cycle. The actuators are also fitted with integrated pressure transducers, which measure the pressure variation of the fluid in the actuators during each cycle. The sensors, supplied by WIKA, have a range of 0 bar to 400 bar and also provide an analogue current output(17). Lastly, the actuators are fitted with contact-free, inductive end-of-stroke sensors, which provide a binary output, indicating when the hydraulic cylinder has returned to the initial position, increasing the reliability of the actuator(18).

2.3.2 Digital Displacement® Pump/Motors

Although the sensors integrated into the DDPMs offer an insight into their operation, the control of pump valves is not controlled by the main control system at FastBlade but rather by the proprietary software package provided by the DDPM suppliers. The LP transducers measure the pressure at the DDPM inputs, which is set by a separate, conventional pump, to ensure correct DDPM operation. Danfoss provides the pressure sensors to ensure high accuracy and insensitivity against temperature variations even in environments characterised by pressure pulsations and vibrations(19). Danfoss also supplies the HP transducers, which have a measurement range between 0 bar and 600 bar(20). The pressure measured by the sensor at the DDPM outlet is characterised by higher-pressure spikes relative to the pressure measured by the sensors mounted in the actuators, which measure the pressure of oil once it has dissipated across the hydraulic system. The rotational speed encoders measure the frequency of rotation of the shaft coupling each DDPM/motor pair. The resolution of the sensor is 1 RPM, which results in an accuracy of 0.05%, operating at the nominal rotational speed of 2000 RPM. The coupling is presented in Figure 3, and the chosen system elements are highlighted.

Figure 3. Left: A side view of the machinery in the FastBlade pit. Right: DDPM close-up. 1) Electric motors; 2) DDPMs; 3) LP accumulators; 4) LP accumulator hose; 5) LP oil inlet; 6) HP oil outlet; 7) Sensor outputs wires.

2.3.3 Electric motors

The key parameters to monitor in the operation of the electric motors driving the DDPMs are their rotational speed and the electric energy they consume. Since a shaft provides a mechanical coupling between each motor and pump, the motor speed is measured by the rotational encoders integrated into the DDPMs. Power supplied to spin the motors is monitored by the sensors integrated into the VLT units(21) (pictured in Figure 4), which provide an analogue signal output corresponding to the instantaneous power provided. Therefore, the electric energy consumption of the motor is calculated as the integral of the power trace over a desired time interval.

Figure 4. The VLT units controlling the power supplied to the electric motors. The four bigger units supply power to the motors driving the DDPMs, while the smaller VLT to the right controls the motor driving the pump feeding LP oil.

3. Evaluating the energy recovery of the system

This section aims to determine how the hardware mentioned above can be used to evaluate the energy recovery of the system. The considerations presented touch upon the differences between assessing how much energy is recovered by the system retrospectively and the ability to determine the amount of energy recovered in real-time.

3.1. Overall efficiency of the system

Primarily, the overall efficiency of the hydraulic actuation system in a fatigue test can be determined using the ratio between the useful work done and the energy input into the system, namely:

$$\eta = \frac{W_{out}}{E_{in}} \qquad (1)$$

where η is the test efficiency, W_{out} is the work output and E_{in} is the energy input into the system. For the test considered, W_{out} is the work done by the system on the specimen, and E_{in} is the electric energy consumed by the electric motors (in relation to which the energy required to pressurise the fluid intake of the DDPMs and operate the DDPM valves is considered negligible). The electric energy input per cycle can be evaluated as the area under the power input trace over the cycle duration, namely:

$$E_{in} = \int_{t_0}^{t_1} P(t)\, dt \qquad (2)$$

where t_0 and t_1 denote the time when a cycle begins and ends respectively, and $P(t)$ is the input power variation. On the other hand, the work done on the specimen can be evaluated as:

$$W_{out} = \int_{s_0}^{s_1} F(s)\, ds \qquad (3)$$

Where s_0 and s_1 are the minimum and maximum actuator displacement in a cycle, and F is the load exerted. Therefore, when the load is plotted against the corresponding actuator displacement, the work done by the actuator on the specimen is the area under the graph. The parameters described in equations (2) and (3) are presented in Figure 5.

The clear division into cycles is visible in all traces in Figure 5. The information presented can be used to calculate overall process efficiency. However, calculating the system's overall efficiency does not provide information on how efficient the energy recovery system is. The way that the system is controlled makes it impossible to run the same setup with a disabled energy recovery to allow a side-by-side comparison.

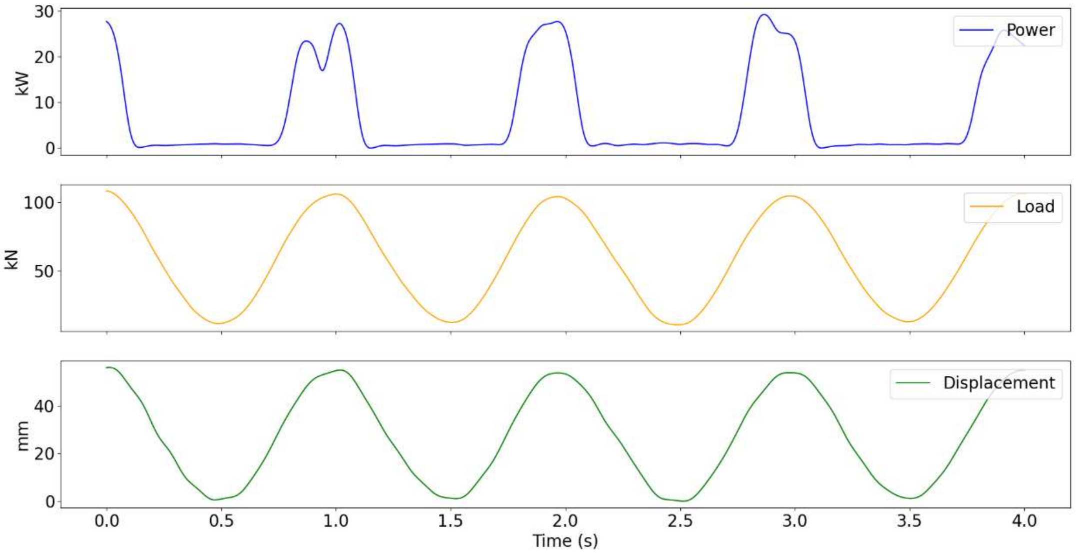

Figure 5. Filtered power, load and displacement recorded for one motor pump actuator system.

3.1.1 Comparison with a servo–actuator–driven system

Servo-actuators are alternative actuators which can be used at FastBlade, where the spool, which switches the output between the pressure valves, is servo-controlled and allows more flexibility than a poppet valve or a solenoid spool valve. However, such a mechanism prohibits the bidirectional HP oil flow between the actuator and the DPP, meaning that hydraulic energy cannot be recovered. Therefore, running the system in such a configuration would allow a direct efficiency comparison of a test running at the same frequency and desired load. As a result, W_{out} would be similar to the one performed by the other set of actuators, while E_{in} would be expected to increase. However, although such an approach would quantify the energy savings achieved by the proprietary energy recovery system, it is not suitable for quantifying the efficiency of different energy transition stages in the system or real-time monitoring.

3.2. Efficiency of the hydraulic system

The above approaches do not offer a direct way to determine how efficient the transition of mechanical energy between the spinning electric motor, the pressurised fluid and the specimen under test is. One way to extract this information is by cutting off the electric power supply to the motors while still demanding the system to apply cyclic loads to the specimen. As a result, the system still performs useful work on the specimen while no extra electric energy is consumed. Ignoring the electric energy required to actuate the DDPM pistons, the energy in the system is stored as the deflected specimen's elastic energy and the motor's kinetic energy. Therefore, by examining the variation of the motor's kinetic energy within a single cycle and the respective work done by the actuator, it is possible to quantify how efficient mechanical energy transmission is within the hydraulic system.

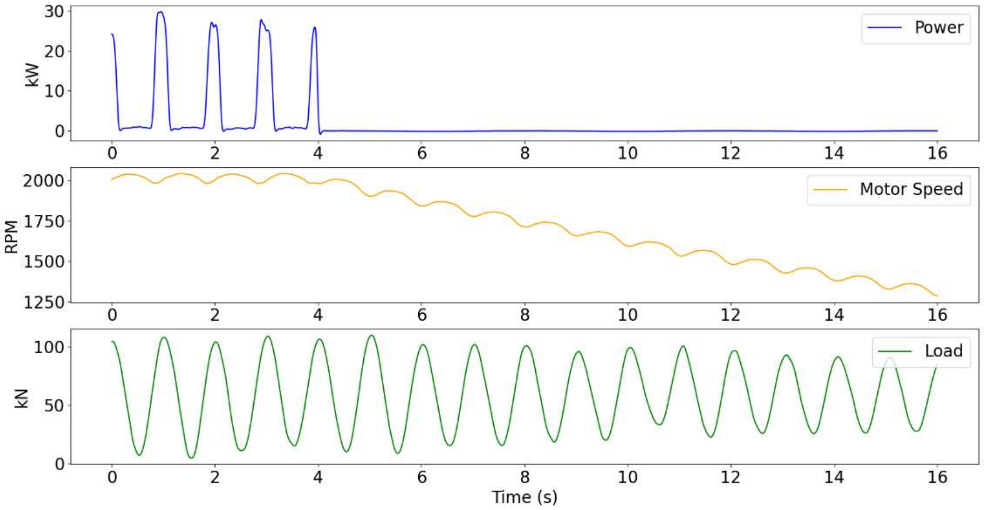

Figure 6. Filtered power, motor speed and load traces, before and after the cut-off of electric power to the motors.

The power cut-off takes place at time equal to four seconds, as presented in Figure 6. The cyclic variation in the motor speed, evident in the figure, corresponds to the energy transfer to and from the specimen. The motor speed increase, after the power is cut off, suggests that mechanical energy is recovered when the specimen relaxes, thanks to which the system's potential to carry on performing actuation work increases.

3.2.1 Quantifying the energy savings

Referring to equation (3), the work done by the system can be evaluated as the integral of force applied with respect to the resulting displacement. Therefore, the traces of actuator load and position can be used to quantify the amount of work done by the hydraulic system on the specimen. Since the useful work considered is the actuation of the blade, the displacement and force variations solely from the positive loading half-cycle are considered. Moreover, once the supply of electric power to the motors is withdrawn, almost the entirety of energy in the system is stored in the form of the kinetic energy of the motors. Using the moment of inertia of the motor-pump coupling, the value of kinetic energy stored in the system is estimated to be 97.0 kJ before electric power ceases to be delivered the motors. Twnety-six loading cycles were recorded after the power cut-off, at which point the kinetic energy of the motors was equal to 10.5 kJ. The sum of the total work done in this period is equal to 53.2 kJ. Considering the drop in the kinetic energy of the motor and the amount of work done by the hydraulic system actuating the blade, it is found that approximately 61.5% of the mechanical energy stored in the system was transformed into actuation work.

3.2.2 Real-time evaluation of the hydraulic system efficiency

The real-time assessment of the efficiency of the hydraulic system would be possible if the energy of the fluid could be quantified during the pumping and motoring stages. This would allow the quantification of the efficiency of converting the kinetic energy of the motor into the energy of the fluid, the calculation of losses in the specimen compression stage and determining the amount of fluid energy transferred to the spinning motor in the motoring stage. Therefore, integrating necessary hardware and methodology to achieve this is suggested as further work. This step would not only allow close efficiency monitoring at different stages, but through the anaylisis of historic and real-time data, it should be possible to optimise system parameters, such as test frequency and the motors' nominal speed, to enhance the efficiency of the energy recovery system.

4. Conclusions

Full-scale fatigue tests provide a reliable platform for determining the mechanical endurance of structures before they can be commissioned. Given the energy potential that tidal energy has, it is desirable for tidal turbine blades to be tested efficiently, reliably and at a feasible pace. However, the relative stiffness of the blades makes conventional testing methods, which are common in the wind industry, unsuitable for the tidal sector. FastBlade is a research facility featuring a proprietary energy recovery system which aims to mitigate the problem of test inefficiency, and in turn contribute to the increase in tidal energy turbine deployment.

Monitoring the system's energy recovery is crucial not only to validate and quantify the energy savings it achieves, but also for CM purposes. To this end, a variety of sensors are installed across the site, including HP and LP transducers, contactless displacement sensors and speed encoders. Quantification of electric energy used per cycle and the work done by the hydraulic system on the specimen allows the calculation of the overall system efficiency. Moreover, to determine the energy efficiency of the hydraulic system alone, a test with an intermitted electric power supply was run, and according to the experimental data recorded, the system was able to recover energy and continue the actuation of the blade by converting the remaining mechanical energy.

However, the above approaches do not allow real-time energy consumption monitoring. Therefore, integrating necessary hardware and methodology to monitor fluid energy in the pumping and motoring stages is suggested as a future improvement. This should be an enabling step not only for the real-time quantification of energy recovery in the system, but should also serve as a tool for optimising system parameters to maximise efficiency, potentially through a digital twinning process.

Acknowledgements

Marek Jan Munko: The doctoral research project has been funded by Babcock International and The Data Lab.
Sergio Lopez Dubon: This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 801215 and the University of Edinburgh Data-Driven Innovation programme, part of the Edinburgh and South East Scotland City Region Deal.
All authors: The authors also wish to thank the Supergen ORE Hub for funding received through the Flexible Fund Award FF2020-1063.

References and footnotes

1. Kou H, An Z, Ma Q, Guo X. Lifetime Prediction of Wind Turbine Blade Based on Full-Scale Fatigue Testing. J Shanghai Jiaotong Univ Sci. 2020 Dec 31;25(6):755–61.
2. Wanhill RJH. Fatigue Requirements for Aircraft Structures. In: Aircraft Sustainment and Repair. Elsevier; 2018. p. 17–40.
3. Tarifa M, Zhang X, Ruiz G, Poveda E. Full-scale fatigue tests of precast reinforced concrete slabs for railway tracks. Eng Struct. 2015 Oct;100:610–21.
4. Bertolesi E, Buitrago M, Adam JM, Calderón PA. Fatigue assessment of steel riveted railway bridges: Full-scale tests and analytical approach. J Constr Steel Res. 2021 Jul;182:106664.
5. Tsakopoulos PA, Fisher JW. Full-Scale Fatigue Tests of Steel Orthotropic Decks for the Williamsburg Bridge. Journal of Bridge Engineering. 2003 Sep;8(5):323–33.
6. Melcher D, Bätge M, Neßlinger S. A novel rotor blade fatigue test setup with elliptical biaxial resonant excitation. Wind Energy Science. 2020 May 28;5(2):675–84.
7. Eder MA, Belloni F, Tesauro A, Hanis T. A multi-frequency fatigue testing method for wind turbine rotor blades. J Sound Vib. 2017 Feb;388:123–40.
8. Greaves PR, Dominy RG, Ingram GL, Long H, Court R. Evaluation of dual-axis fatigue testing of large wind turbine blades. Proc Inst Mech Eng C J Mech Eng Sci. 2012 Jul 10;226(7):1693–704.
9. Buchholz M. Fraunhofer Institute for Wind Energy Systems. 2024. Full scale blade testing.
10. Yates N, Walkington I, Burrows R, Wolf J. Appraising the extractable tidal energy resource of the UK's western coastal waters. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2013 Feb 28;371(1985):20120181.
11. Collombet R, Parsons A, Gruet R. Key trends and statistics 2021. Ocean Energy. 2022 Mar;
12. Lopez Dubon S, Cuthill F, Vogel C, Ó Brádaigh C, McCarthy ED. A full-scale composite tidal blade fatigue test using single and multiple actuators. Compos Part A Appl Sci Manuf. 2024 Jun;181:108140.
13. Munaweera Thanthirige TR, Goggins J, Flanagan M, Finnegan W. A State-of-the-Art Review of Structural Testing of Tidal Turbine Blades. Energies (Basel). 2023 May 12;16(10):4061.

14. Rampen WHS, Caldwell N, McCurry P. Displacement of an object with hydraulic actuators. US20190226959A1, 2021.
15. APPLIED MEASUREMENTS LTD. Pancake Load Cell, Low Profile Force Sensor, DSCC. 2024.
16. MTS SYSTEMS CORPORATION. Temposonics®, Absolute, Non-Contact Position Sensors. OPERATION MANUAL. E-Series Embedded Analog. 2016.
17. WIKA. Pressure transmitter Model A-10; 0...400 bar gauge; 4...20 mA, 2-W @ 8...30 V DC. 2024.
18. CONTRINEX. Inductive sensors; DW-LX-703-P12G . 2017.
19. Danfoss. Pressure transmitters for heavy duty applications; MBS 8200 and MBS 8250. 2018.
20. Danfoss. OEM Pressure Transmitters for heavy-duty applications; MBS 1200 and MBS 1250. 2019.
21. Danfoss. VLT® AutomationDrive FC 301/302 Design Guide, 0.25-75 kW. 2013.