Non-contact dynamic testing of a next-generation helical crossflow tidal turbine foil using a laser scanning vibrometer

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NON-CONTACT DYNAMIC TESTING OF A NEXT-GENERATION HELICAL CROSSFLOW TIDAL TURBINE FOIL USING A LASER SCANNING VIBROMETER

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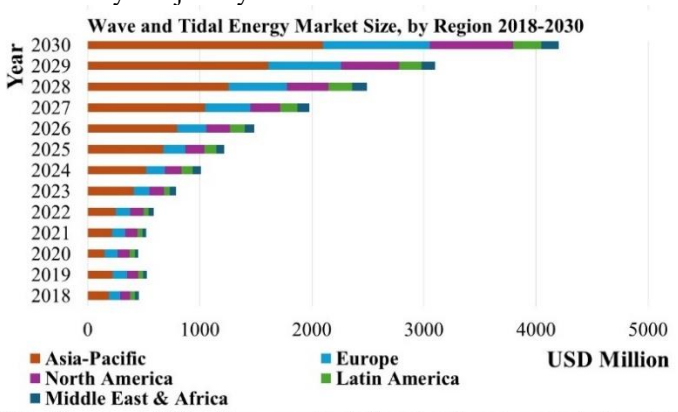
ABSTRACT

The renewable energy sector is strategically focused on mitigating risks associated with tidal energy converters to lower the cost of tidal energy to allow it to become a significant contributor to the renewable energy mix. In this study, dynamic testing was used to assess the structural performance of a next-generation helical crossflow tidal turbine foil made with carbon fibre prepreg composite material. Utilizing a Laser Scanning Vibrometer (LSV) expedites testing and data processing. A 5-metre foil prototype underwent dynamic testing in accordance with DNVGL-ST-0164 and IEC DTS 62600-3 standards. Two dynamic testing setups, with and without an unbalanced rotating mass system, were conducted before and after a series of static and fatigue tests. The research highlights the impact of altering tidal turbine system mass on dynamic response, offering crucial insights for designers. This study establishes the groundwork for a standardized LSV testing protocol for small to large scale tidal turbines, contributing to the optimization of next generation designs and performance. Ultimately, it paves the way for more efficient and sustainable marine energy solutions in the future.

Keywords: Dynamic response analysis, dynamics of structures, vibration analysis, structural integrity, renewable energy, marine renewable energy.

1. INTRODUCTION

Generation of green power has become a pivotal element in the modern world, with nations increasingly emphasizing sustainable energy production in alignment with their sustainable development goals. In this context, the tidal energy sector emerges as a promising frontier, harnessing considerable power using ocean tides and river currents [1–3]. Therefore, the industry is directing its efforts toward the development of next-generation tidal energy converters intended for deployment in shallow waters of oceans and rivers globally [1,4–6]. In this context, the tidal energy market is ready for substantial development in the coming years on a global scale, as illustrated in FIGURE 1. It reveals a noticeable upswing in the deployment of wave and tidal devices, marking a remarkable development in the industry's trajectory.



Note: The values in USD million were estimated based on the resource stacked bar chart

FIGURE 1: WAVE AND TIDAL ENERGY MARKET BY 2030, ADOPTED FROM [7]

The FIGURE 2 represents the global progress in developing next-generation tidal and river current energy generation devices based on specific site potentials. Therefore, some of these cutting-edge converters are strategically tailored for operation in rivers and areas characterized by low tidal potential, expanding the application of tidal energy to regions previously considered impractical. These innovative devices are engineered to tap into readily available energy resources economically, thereby

mitigating distribution losses and reducing initial investments [2,8].

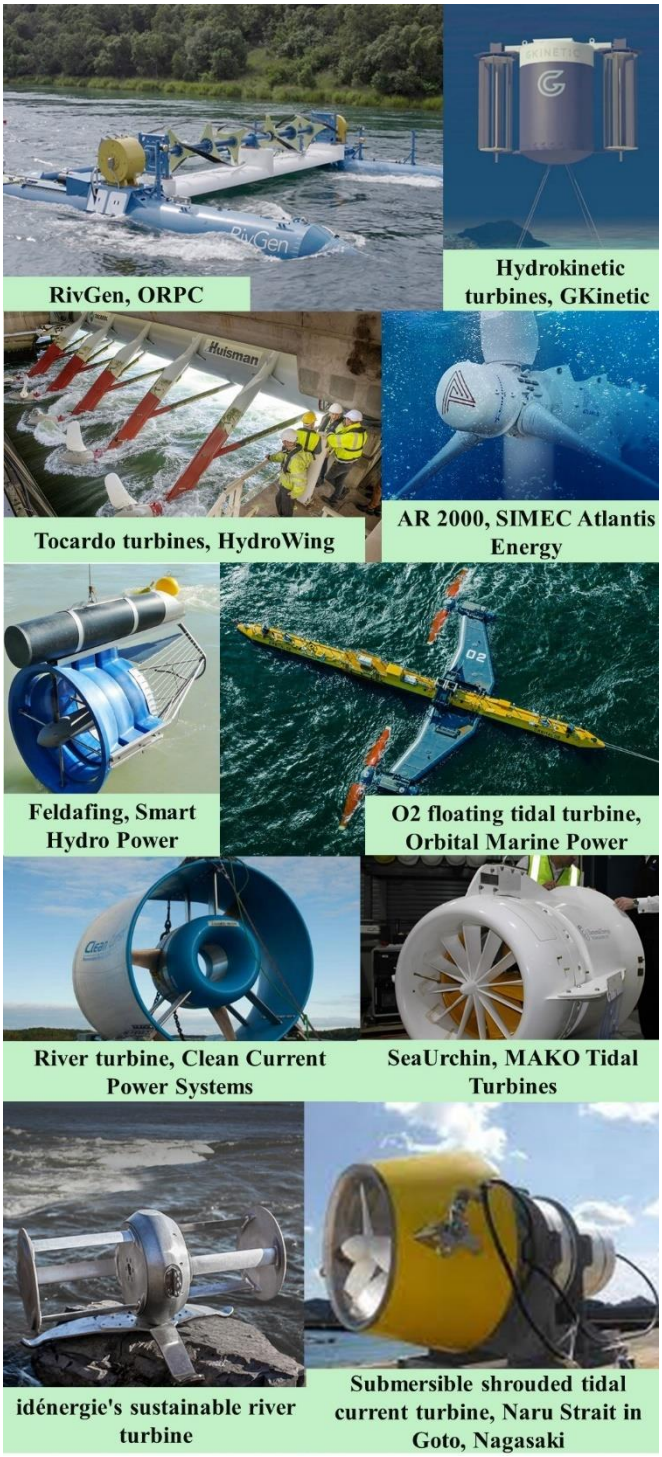


FIGURE 2: NEXT GENERATION TIDAL AND RIVER CURRENT ENERGY DEVICES [9–17]

However, to propel the tidal energy industry forward, a strategic focus on mitigating risks linked to next-generation tidal energy converters is important. This initiative aims to enhance their maturity, rendering them more appealing to investors on a global scale. The overarching objective is to expedite the deployment of highly efficient devices, positioning tidal energy as a significant contributor to the renewable energy landscape.

This targeted endeavor involves a comprehensive examination of the design, materials, and operational aspects of next-generation tidal energy converters. The implementation of rigorous testing procedures is integral to ensuring the reliability and efficacy of these converters, increasing confidence among both investors and stakeholders [18,19]. Through the systematic addressing of risks and the optimization of performance, this initiative strives to reduce the cost of tidal energy, positioning it as a competitive and sustainable alternative within the global energy portfolio [20,21]. The validation of the structural performance of tidal turbine blades is increasingly crucial in mitigating risks as it directly influences the lifespan of the turbine system [20]. This validation process encompasses dynamic, static, fatigue, and residual strength testing, accompanied by a comprehensive finite element analysis approach. Dynamic testing is a widely adopted method to identify damage during the structural testing process, significantly contributing to the evaluation of tidal blade structural performance [17,22,23]. It also plays a pivotal role in determining when to halt testing due to otherwise undetected blade failures [17,23].

In light of these considerations, this study primarily focuses on a comprehensive dynamic testing approach tailored to assess the structural performance of an innovative helical crossflow tidal turbine foil manufactured using carbon fiber prepreg composite material. The study employs a non-contact measuring technique and enhances testing efficiency and data processing accuracy by utilizing a Laser Scanning Vibrometer (LSV) equipped with a single scanning head, diverging from traditional methods that involve accelerometers. At the same time, the LSV facilitates the detection of any potential damage incurred during testing. Hence, this research makes a valuable contribution to establishing a novel knowledge base in non-contact dynamic analysis for tidal turbine blades, aiming to accelerate the structural testing processes for tidal turbine blades in the future [24].

2. MATERIALS AND METHODS

The main aim of this study is to assess the dynamic performance of the tidal turbine foil through a non-contact measuring technique and establish an efficient and user-friendly dynamic testing protocol for evaluating the performance of tidal turbine foils. To support this aim, this paper presents the following objectives:

I. Explore various testing arrangements and analyse how dynamic performances vary with different testing setups.
II. Contrast the dynamic performance using a non-contact measuring technique with the traditional method at various stages and observe changes in dynamic performance.

III. Study the impacts of foil excitation methods on dynamic responses of it.
IV. Examine the foil's natural frequencies at different stages of structural testing program and establish a clear method for identifying changes in dynamic responses.

The dynamic testing centers around a prototype, full-scale 5-meter tidal turbine foil designed by ORPC and manufactured by ÉireComposites teams. It was securely fixed to three composite struts linked to a robust steel frame, adhering to industry standards DNVGL-ST-0164 and IEC DTS 62600-3 [25,26]. The approach of conducting dynamic testing is represented in FIGURE 3. The steel frame was fixed to the strong concrete floor at the laboratory and linear variable differential transformers were attached to it for identifying small displacements of the frame during the testing. At the same time, strain gauges, fibre bragg grating sensors, string pots, and laser displacement sensors were incorporated to measure strain distribution and deflections of the foil. Moreover, the instrumentation remained consistent throughout dynamic testing, remaining connected to the tidal foil undergoing testing. These instruments, linked to the foil, had the potential to exert a notable influence on the dynamic performance of the foil. For dynamic testing, it was employed an LSV equipped with a single scanning head in combination with an accelerometer to validate the foil's dynamic response. Furthermore, the foil underwent free vibration induced by an impact hammer, shaker, and hand excitation methods at different stages of dynamic testing.

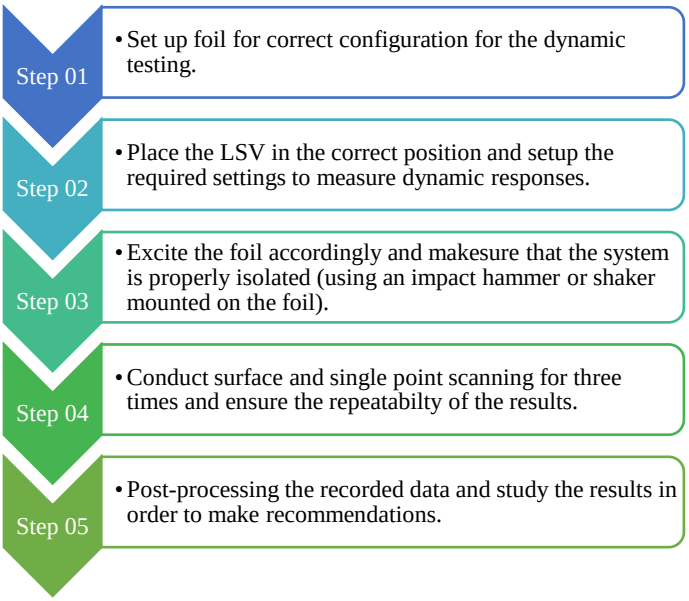


FIGURE 3: DYNAMIC TESTING APPROACH

2.1 Testing Arrangements

The Large Structures Testing Laboratory at the University of Galway was utilised to perform a diverse array of tests, encompassing dynamic, static, fatigue, and residual strength testing, where the testing procedure was developed in collaboration with ORPC team. According to the testing procedure, the static testing was performed using 500kN and 250kN servo-hydraulic actuators, applying forces to the cantilever end and the middle section of the foil, respectively. The loadings were introduced as percentages of idealised loading conditions based on the design calculations. At the same time, the fatigue testing program was designed into five fatigue cycle intervals and residual strength testing were conducted after each fatigue cycle intervals. In the residual strength test, a 30% of idealised loads were applied to the foil. In this context, the sign of fatigue degradation can be identified by the change in the foil deflection. Concerning all these aspects, the TABLE 1 highlights the dynamic tests conducted in this study while FIGURE 4 represents the Computer Aided Design (CAD) of the test setup used to perform structural testing, highlighting loading positions. Furthermore, FIGURE 4 depicts the exact orientations of the three struts connecting one foil within the full-scale tidal turbine system. At the same time, the actual model of this system incorporates three composite material foils around the rotor each connected with similar struts configuration.

TABLE 1: DYNAMIC TESTING PROGRAMME

Dynamic Test No	Remarks
Test 01	Prior to starting the testing.
Test 02	After completing the initial stage static testing.
Test 03	After completing first interval of 0-250,000 fatigue cycles.
Test 04	After conducting residual strength testing followed by first fatigue cycles interval.
Test 05	After completing second interval of 250,000-550,000 fatigue cycles.
Test 06	After conducting residual strength testing followed by second fatigue cycles interval.
Test 07	After completing third interval of 550,000-750,000 fatigue cycles.
Test 08	After conducting residual strength testing followed by third fatigue cycles interval.
Test 09	After completing fourth interval of 750,000-1,000,000 fatigue cycles.
Test 10	After conducting residual strength testing followed by fourth fatigue cycles interval.
Test 11	After completing fifth interval of 1,000,000 - 1,300,000 fatigue cycles.
Test 12	After conducting final static testing until failure of the foil followed by fifth fatigue cycles interval.

And also, the fatigue testing procedure involves the integration of an Unbalanced Rotating Mass (URM) system that impacts the dynamic response of the foil, resulting in two distinct sets of dynamic testing: one conducted without the URM system and another with it. Therefore, it was decided to measure the

performance with reference to two settings during each time of performing dynamic testing.

- Testing setup related to the static testing with no load introduction fixtures were attached to the foil. The foil was scanned at the tip end and exciting at tip end using an impact hammer (refer to FIGURE 5).
- Testing arrangement related to the fatigue testing with URM system was connected to the tip end of the foil. The foil was scanned at the tip end and excited using a shaker affixed to the tip end. (refer to FIGURE 6).

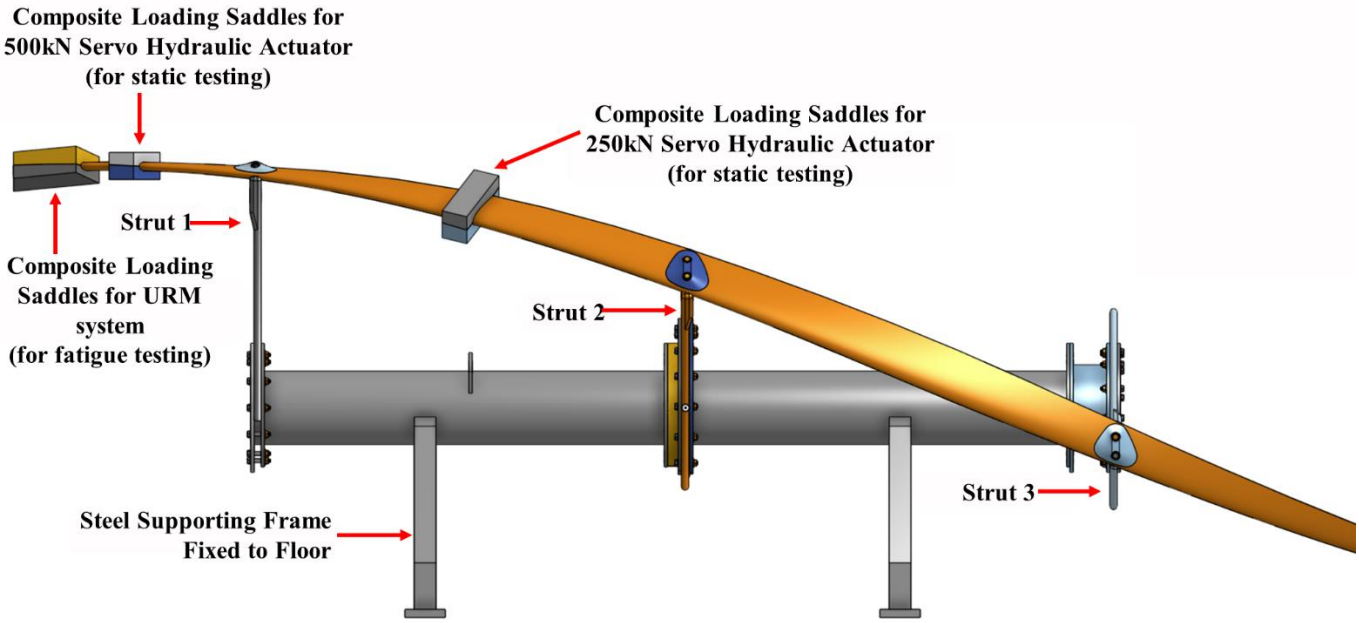


FIGURE 4: CAD MODEL OF THE TEST SETUP

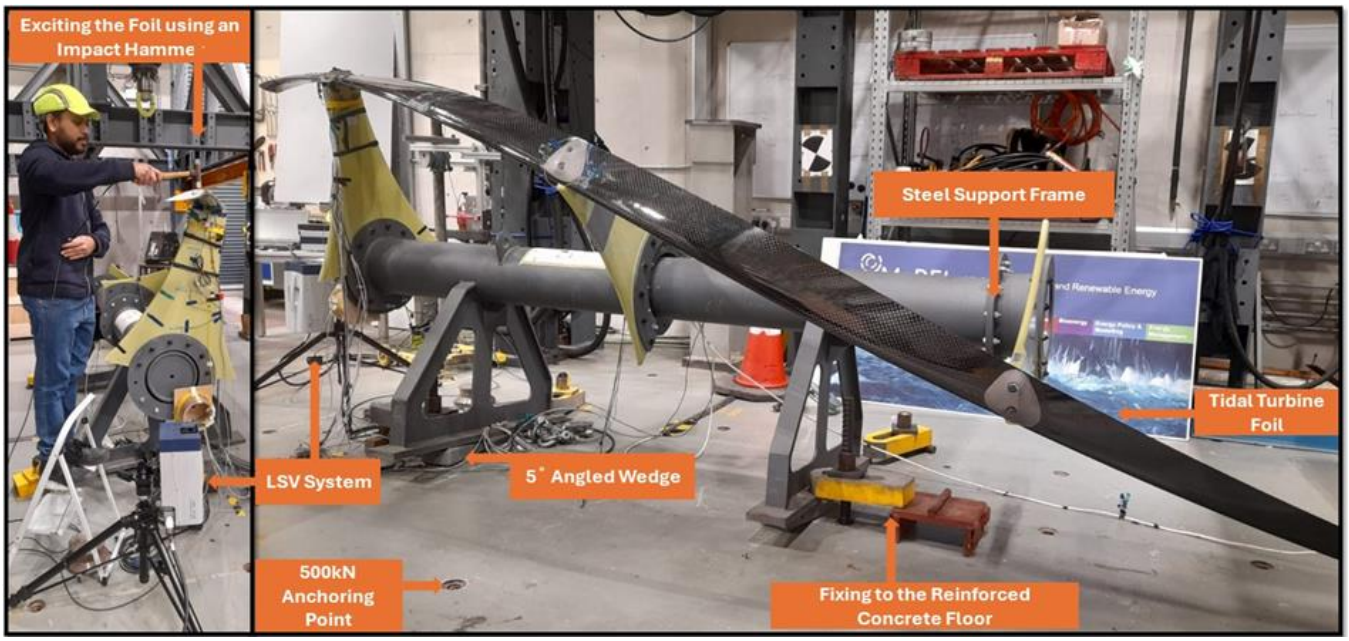


FIGURE 5: LSV SETUP FOR THE DYNAMIC TESTING WITHOUT URM SYSTEM

FIGURE 6: LSV SETUP FOR THE DYNAMIC TESTING WITH URM SYSTEM

During fatigue testing the URM is used to load the foil. As the speed of the URM increases, the excitation force synchronises with the foil's first natural frequency, resulting in higher amplitude oscillations at the tip end upon reaching resonance. Fatigue testing was carried out at this resonance, with the estimation of cycle numbers based on recorded data. Moreover, strain distribution of the top and bottom sides of the foil and cantilever tip end deflections were main parameters measured during the fatigue testing. Subsequently, dynamic testing with and without the URM system was scheduled to identify any potential foil damage before or after fatigue testing.

In order to ensure consistency across the two highlighted dynamic test setups mentioned earlier, specific scanning locations on the upper tip of the foil were separately marked, ensuring a uniform and consistent measurement environment. Concurrently, the positions of the LSV system for both dynamic test arrangements were clearly indicated on the floor, facilitating an easy comparison of results. With reference to these instrumentation schedules, all the parameters which decide the dynamic response of the foil were kept constant except the degradation of the foil due to the structural testing program.

Additionally, a series of dynamic tests were conducted on the foil to identify the sensitivity and limitations of the LSV system during the dynamic testing. This approach was implemented before starting the recommended structural testing program. Aligning with this objective, the LSV system was placed in various locations, and exposed to excitation forces using an impact hammer and a hand. Moreover, the light intensity level at the laboratory and its impact on results were analysed. The analysis employed the LSV system to transform time domain responses into frequency domain responses, utilising Fast Fourier Transform (FFT) to emphasise the natural frequencies vs displacement of the foil. These tests showed that repeatability of the test was typically within +/- 0.75 Hz accuracy. Simultaneously, a thorough investigation was carried out on the dynamic responses of each test associated with and without the URM system, carefully studying the mode shapes generated by the LSV system to distinguish between noise and system responses.

3. RESULTS AND DISCUSSION

The results of the dynamic testing related to the with and without the URM system can be represented as two separate sections for clear understanding as following.

3.1 Dynamic testing without the URM system

The assessment of the foil's dynamic performance involved evaluations both before and after static testing, aimed at identifying any damage incurred during the testing. The initial stage static testing involved four distinct load cases, ranging from 10% to 30% of the estimated full load conditions. In this context, FIGURE 7 presents the results of dynamic test conducted prior to these initial stage static testing.

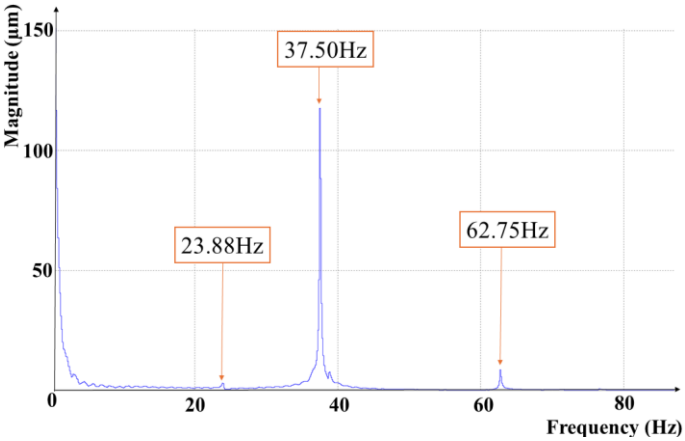


FIGURE 7: DYNAMIC PERFORMANCE OF THE FOIL BEFORE THE PHASE 01 STATIC TESTING

The recorded natural frequencies in this case were 23.88Hz, 37.50Hz, and 62.75Hz, respectively. After completing the initial static testing phase, a series of dynamic testing were conducted without the URM system, as illustrated in TABLE 1. However, there were no significant alterations in dynamic responses until the foil endured damage during the final static testing. In this context, it was reasonable to assume that there was no substantial fatigue degradation observed during the fatigue testing program. This inference could lead to potential overdesign of the tidal foil or indicate that the estimated loading conditions during fatigue testing were characterised by low-stress fatigue cycles. Moreover, the damage was observed in the foil's leading edge, trailing edge, and cantilever fixed end. This damage was recognized as a combination of shear fractures in the matrix materials, bond failures at the matrix-fibre interface, and fibre breakage from both edges of the foil, involving skin-stiffener debonding, material strength failure, and buckling. The results after the damage under final stage static loading have been represented in FIGURE 8.

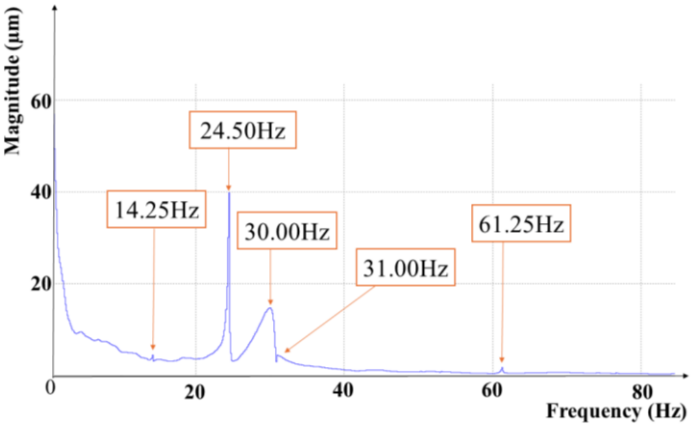


FIGURE 8: DYNAMIC PERFORMANCE OF THE FOIL AFTER IT WAS DAMAGED

In this context, a noticeable variation in natural frequencies was evident, with identified natural frequencies at 24.50Hz, 30.00Hz, and 31.00Hz. The decrease in natural frequencies indicates a shift in the structural behaviour of the tidal foil. Remarkably, the frequency of 24.50Hz is conspicuous in these findings, having been observed during dynamic testing without URM system prior to the foil failure. Upon investigating natural frequencies in different regions of the foil, it was found to align with the natural frequencies of struts, primarily recorded as 14.25Hz and 24.00Hz for the struts. From this analysis, it can be assumed that 24.50Hz represents a natural frequency of the struts, particularly in the transverse direction, and becomes dominant after the foil's failure.

The reduction in observed natural frequencies signifies alterations in the stiffness or mass distribution of the structure, predominantly arising from structural damage that modifies the overall configuration of the foil. Consequently, conducting a thorough analysis of these frequency shifts becomes imperative to comprehend the dynamic response and ensure the structural integrity of the system. This analytical approach provides valuable insights into the effects of external forces and material degradation, thereby contributing to a holistic understanding of the dynamic characteristics inherent in the tidal foil system.

Furthermore, FIGURE 9 offers a comprehensive comparison of the variations in the first mode shape during both initial and concluding phases of static testing. In this instance, the LSV system generated mode shapes for a rectangular area situated on the bottom side of the cantilever section of the foil. The specified area measures 750mm in length and 80mm in width, positioned 50mm from the central point of the cantilever tip on the foil, excluding the URM system. The illustrated area highlights micrometer-scale displacements resulting from the impact hammer-induced free vibrations. This meticulous examination of first mode shape variations at distinct testing stages provides valuable insights into the foil's structural behavior and performance under diverse conditions, facilitating a comprehensive evaluation of its dynamic responses.

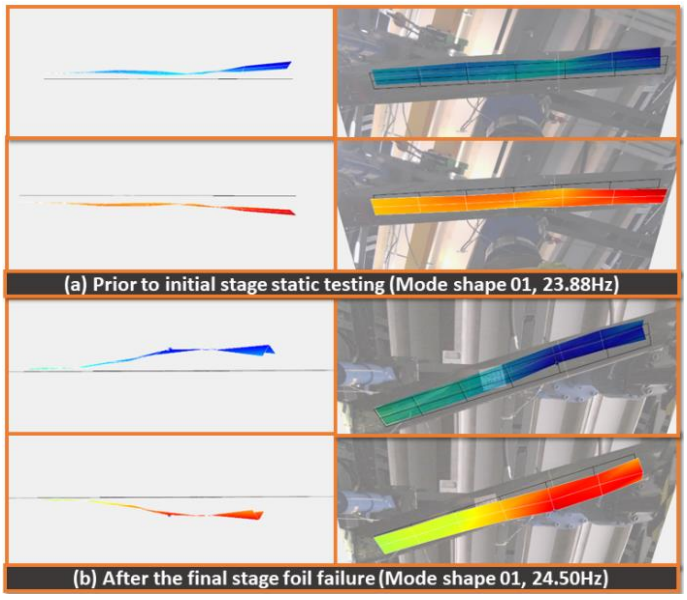


FIGURE 9: FIRST MODE SHAPE AT INITIAL AND FINAL STAGE OF STATIC TESTING

3.2 Dynamic testing with the URM system

Dynamic performance associated with the URM system was planned due to the utilisation of a URM system in the fatigue testing procedure. It aimed to expedite the fatigue testing process and enhance testing efficiency. The URM system, with a substantial weight of 60.43kg compared to the foil's 26.7kg, was expected to introduce significant variations in dynamic properties, as depicted in FIGURE 10.

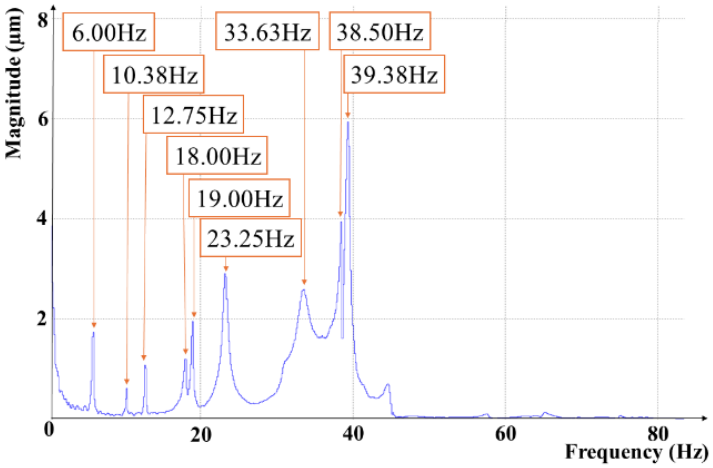


FIGURE 10: DYNAMIC PERFORMANCE OF THE FOIL PRIOR TO TESTING

In this context, the initial five natural frequencies were identified as 6.00Hz, 10.38Hz, 12.75Hz, 18.00Hz, 19.00Hz, 23.25Hz, and 33.63Hz, respectively, before initiating static or fatigue testing for the foil. Notably, there was a noticeable shift in natural frequencies upon attaching the URM system and shaker (28.5kg with the attachments) to the foil, as illustrated in FIGURE 10. Subsequent to the initial stage static testing, a series of dynamic testing were performed aligned with URM system as outlined in TABLE 1. However, there was no discernible alteration in the dynamic response of the foil until it reached 1,300,000 fatigue cycles. Consequently, the fatigue testing program concluded without significant fatigue degradation to the foil.

3.3 Summary of the dynamic testing with and without the URM system

The dynamic testing relevant to with and without the URM system highlights how minor and major structural failures, as well as testing arrangements, influence the dynamic responses of the foil. It also showcases the sensitivity of the LSV system to slight variations in the testing setup, emphasising the advantages of advanced non-contact measuring systems for dynamic testing. In addition, the results of the LSV system demonstrated precision and consistency, confirming its suitability for carrying out dynamic testing on more extensive structures with complex structural testing programs. For maximising the efficient utilization of the LSV system, it is crucial to strictly adhere to established guidelines. Therefore, this study highlights the necessity of creating a set of guidelines explicitly tailored for the implementation of the LSV system in the future dynamic testing related to the larger structures.

The TABLE 2 highlights some of the important aspects related to the dynamic testing with and without the URM system. The results indicate the significant impact of the structure's mass, revealing a reduction in overall system dynamic responses as mass increases. This emphasizes the importance of minimising the mass of structures while simultaneously increasing structural stiffness. Consequently, the study highlights the critical role of utilising materials with a higher stress-to-weight ratio in manufacturing structures for tidal energy systems to improve structural integrity.

TABLE 2: SUMMARY OF THE DYNAMIC TESTING

Phase of the dynamic testing	Frequency response **without URM system** (Hz)	Frequency response **with URM system** (Hz)	**Remarks**
Prior to testing	23.88, 37.50, and 62.75	6.00, 10.38, 12.75, 18.00, 19.00, 23.25, 33.63	
After the initial stage static testing	23.63, 36.75, and 62.38	5.88, 10.13, 12.38, 19.13, 23.75, 29.25	Suspect that the core material (non-structural) damage during calibration.
After completing 550,000 fatigue cycles	24.75, 36.88, and 62.75	5.88, 10.38, 12.63, 18.75, 19.50, 24.00	Tightening the strut bolts after completing 250,000 fatigue cycles.
After completing 1,300,000 fatigue cycles	24.38, 36.75, and 62.50	5.88, 10.38, 12.75, 18.75, 19.50, 24.25	No significant fatigue degradation.
After the final stage static testing	24.50, 30.00, 31.00, and 61.25	Not conducted.	Foil damaging during the final static testing.

3.4 Recommendations when using the LSV system

Based on the results and observations from dynamic testing using the LSV system, the following recommendations are proposed to improve the accuracy and effectiveness of dynamic testing with this system. These suggestions are relevant not only for tidal turbine foils but also for a range of structures.

- **Consistent Testing Arrangement**

Ensure a consistent testing arrangement when using the LSV system. The study underscores the system's sensitivity to

changes in testing setups, making it crucial to maintain a standardised configuration for accurate and reliable results. Simultaneously, it is necessary to consistently position the LSV system in the same location and orientation, ensuring the measurement of the identical surface region with the same number of scanning points for accurate surface mapping. This approach allows to compare the dynamic responses at different stages of the structural testing protocol.

- **Select most Suitable Section to Scan**

Conducting dynamic testing for large structures may not require scanning all sections of the structure. Based on observations, natural frequencies appear independent of the scanning location, whereas the vibration magnitude varies. Consequently, it is recommended to focus scanning on surfaces subjected to loading during static and fatigue testing.

- **Optimal Lighting Conditions**

Control lighting conditions during dynamic testing become very important. The research highlights that variations in light intensity can impact LSV system results. Maintaining low light intensity is recommended to reduce noise levels and achieve clearer responses during testing. However, the impact of the light intensity depends on the surface conditions of the structure therefore, it is advisable to check the influence before commencing the main testing program.

- **Shaker Excitation Method**

Consider using a shaker as an excitation method. The research reveals that the shaker demonstrated a consistent excitation pattern throughout testing, in contrast to variations introduced by hand and impact hammer excitations. Careful attachment of the shaker is advised for obtaining reliable vibration amplitudes. However, it is feasible to employ an impact hammer in conjunction with the trigger effect of the LSV system, evaluating the results in connection to the impact force applied to the structure by the impact hammer.

4. CONCLUSION

In conclusion, the research paper provides a thorough examination of dynamic testing scenarios for a tidal turbine foil system, offering valuable insights into the system's behaviour under different conditions. Moreover, no damage was indicated due to static or fatigue testing but there was a significant change when the destructive testing was carried out. At the same time, the study emphasises the importance of analysing frequency shifts, and testing conditions for understanding dynamic responses and ensuring structural integrity. For optimal utilisation of the LSV system, it is recommended to maintain a consistent testing arrangement, control lighting conditions, select the most suitable section to scan, and ensure precise attachment to the structure. Additionally, considering the shaker as a reliable excitation method can contribute to obtaining consistent and accurate results during dynamic testing. The findings of this research have significant implications for the design, testing, and evaluation of tidal foil systems in real-world applications. The recommendations provided offer practical guidance for researchers and engineers engaged in similar dynamic testing endeavors, contributing to the advancement of knowledge in the field. In addition, the dynamic testing procedure developed in this paper offers a non-destructive test to examine composite components, which may be incorporated into a quality process or for examining structural damage during operation.

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