Sensor Measurement Strategies for Monitoring Offshore Wind and Wave Energy Devices

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Abstract. While the potential of offshore wind and wave energy devices is well established and accepted, operations and maintenance issues are still not very well researched or understood. In this regard, scaled model testing has gained popularity over time for such devices at various technological readiness levels. The dynamic response of these devices are typically measured by different instruments during such scaled tests but agreed sensor choice, measurement and placement guidelines are still not in place. This paper compared the dynamic responses of some of these sensors from a scaled ocean wave testing to highlight the importance of sensor measurement strategies. The possibility of using multiple, cheaper sensors of seemingly inferior performance as opposed to the deployment of a small number of expensive and accurate sensors are also explored. An energy aware adaptive sampling theory is applied to highlight the possibility of more efficient computing when large volumes of data are available from the tested structures. Efficient sensor measurement strategies are expected to have a positive impact on the development of an device at different technological readiness levels while it is expected to be helpful in reducing operation and maintenance costs if such an approach is considered for the devices when they are in operation.

1. Introduction

Offshore wind and wave energy technologies have seen major advances in recent years. Wave energy in particular is growing in popularity [1,2]. Operations and maintenance (O&M) costs are a highly relevant factor in the overall financial assessment of such projects, all the more so in offshore projects due to lower availability of the device [3]. This has pushed the need for reliable structural monitoring systems for accurate and reliable information about the health of these energy conversion devices. With a move in recent times towards offshore energy solutions, loss in ease of accessibility may lead to damage going undetected, and the increased risk of catastrophic failure [4].

There is clear financial benefit to optimizing time between inspections and scheduled maintenance work, which affects the uptime of systems while also coming with their own costs- an unscheduled maintenance event is five times more costly than one that is scheduled [5]. However, high costs related to some sensing systems outweigh the benefits to O&M cost savings so the value of expensive sensing systems must be evaluated, usually at the scaled testing stage. There are many forms of sensing systems, based on various technologies. Accelerometers have been successfully applied to identifying
and locating the presence of structural damage in offshore structures [6], as well as motion cameras and load cells [7,8] and Fiber Bragg Grating (FBG) to measure strain. Cameras can even be employed in underwater situations to detect damage [9] where marine growth exasperates fatigue damage. However, little is known of the relative merits of these technologies.

Wireless sensor networks (WSN) are a promising technology which have in recent years gained much attention from academia and industry alike. The application of WSN technology to structural health monitoring (SHM) has the potential to provide a substantial and quantifiable improvement to existing monitoring solutions for civil infrastructure [10]. While wired SHM systems would require more maintenance and more frequent site visits as wires can be damaged over time, wireless SHM systems offer flexibility, even on difficult to access structures, and significantly reduced costs of installation and maintenance. However, some of the existing wireless systems for SHM still have high power consumption. The high power consumption and the limited power budget make these systems unsuitable for long-term installation on a structure and require frequent site visits for system maintenance. WSN nodes are battery powered and because of their limited energy source they are not suitable for long-term structural health monitoring applications. With the focus on enhancing the life time of a wireless sensor node, a popular is by complementing an energy harvesting technique with an efficient energy management algorithm [11]. This approach has the potential to achieve self-sustainability of the node with harvesting energy from the environment and effectively managing the node activity (i.e. the sampling rate of the sensors) according to the energy levels and the dynamics of the phenomenon observed.

While possibilities related to the deployment of sensors remain relevant and topical, there is little experimental information present from wave basin testing that compares the measured data from different sensors and highlights different issues related to the choice, positioning and sampling aspects of such sensors. This paper attempts to address this gap by reporting a wave basin testing for a Tension Leg Platform (TLP) where a number of different sensors where deployed to measure and monitor the dynamic responses of these structures.

2. Experimental Model

2.1. Scaled model

A scaled Tension Leg Platform (TLP), a truss like structure with a hexagonal base, was tested in this study. This device consists of a gravity base connected by six mooring tethers to the Buoyancy Ring and the Upper Structure and the Tower and Nacelle. The mooring lines are designed to reduce heave motion and increase horizontal stability, but the lines become a weak point against surge motions. A photograph of the tested device is presented as Figure 1.

2.2. Instrumentation and testing

The model was instrumented with 6 Tedea-Huntleigh stainless steel single ended bending beam load cells which were attached to the six mooring line cables and bolted to the gravity base. These measured the cable tension in Newtons (N). The instantaneous positions of 3 reflective markers, which were attached to the six corners of the hexagonal base, were monitored by 4 Qualisys 3-Series Oqus Marker Tracking Cameras with a sampling frequency of 32Hz. A Laser Doppler Vibrometer (LDV) was also employed during testing to record the velocity of the TLP. This high resolution technology samples at a rate of 480 Hz. Displacements and velocities were recorded in the wave direction, as this was considered the most critical plane. The model was tested at the Hydraulics and Maritime Research Centre (HMRC), University College Cork (UCC), Ireland in its Ocean Wave Basin. A variety of periods and wave amplitudes were used and the Bretschneider wave spectrum was chosen, to represent a more realistic sea state.
3. Results

3.1. Dynamic Displacement Response

The camera recorded the position of the TLP at 3 different locations; the Inner Ring, the Outer Ring and the Middle Mast. The dynamic response was recorded in 3 perpendicular directions but only the surge motion of the device has been used in this paper since this was the motion that was most relevant. The velocity of the structure as recorded by the LDV was used to find displacement values and consequently, the displacement obtained by the LDV is a derived quantity, while that measured by the camera is not. Figure 2(a) shows the peak displacements recorded by the camera at the 3 tracked positions. Due to the far larger amplitude of displacement at the mid mast position, due to the flexible nature of the mast and its sensitivity, these readings were omitted from the average value shown in Figure 2 (c), as they were viewed to be skewing the data (see Figure 2 (b)).

The observations indicate that there is an uncertainty and mismatch in the measurement from camera and from LDV. These mismatches or variability in results are dependent on the wave periods apart from the wave heights, which in turn guide the levels of displacement. Consequently, more than one source of measurement can be appropriate for such measurements to ensure that there is an agreement of the results. However, it also leads to the debate on the necessity of a very highly sophisticated or calibrated instrument, when a large number of relatively lower quality instruments are measuring data in a higher number of locations. When no benchmark is available, at least some part of data matching with a high quality instrument is recommended, though based on current observations and the investigations carried out next, deploying a large number of inexpensive sensors can then be very beneficial.
3.2 Variation of Peak Frequency in Measured Responses

The displacement time series for the LDV and the motion camera were converted into the frequency domain using the Fast Fourier Transform (FFT) and the dominant peaks were picked.

In Figure 3, the response of frequency of the output for the two different instruments is compared to the known frequency of the wave input to the system. The peak frequency of the velocity output of the LDV is, on average, 18.7% lower than the wave frequency of each particular test. However, the peak frequency of the camera’s displacement is an average of 31.9% higher than the same inputs. The same comparison, but for the frequency of the LDV’s velocity output yielding a difference of only 7%, on average, from the wave input.
3.4 Variation in Load Cell Data

Load cells were attached to tendons at Bow Port, Bow Starboard, Mid Starboard, Stern Starboard, Stern Port, Mid Port and were labelled White, Red, Yellow, Green, Brown and Blue respectively. The average peak and RMS load values of tension in the tendons for each load cell for 20 different tests are represented in Figure 4.

The values were recorded in the direction of the wave, at the bow and at the stern of the structure. As expected, the tendons at the front and back of the structure, as the structure moves in the wave condition, are under the most tension. Analysis of the effect of removing different load cells to the overall data was carried out, a sample of which is shown in Figure 5. Data obtained from the white cell at Bow Port was removed from the global analysis, and the estimate shown from remaining data shows a loss in accuracy of the loading on the structure.
Such an accuracy loss may relate to one of the sensors becoming defunct during its operational regime of monitoring and how such events affect the estimated averages of loading on the structures tendons. The four load cells attached to the bow tendons and the stern tendons are shown to record the highest tension values, so should be the focus of analysis.

4 Energy Aware Adaptive Sampling Algorithm for Energy Harvesting WSNs

The development of WSN technology is hindered by their limited energy supply. In the case of monitoring applications, sensors can be expensive with respect to energy requirements. It is desirable to develop protocols that effectively manage the sensor power consumption while still meeting the requirements of the application. Adaptive sampling algorithms (ASA) are often used as a tool to minimize the communication between the sensor nodes within the network and at the same time to minimize the power consumed by the sensors by reducing the sampling rate according to the needs of the phenomenon observed. An ASA presented in [12] was implemented and evaluated using data collected with sensor for displacement response recorded by the motion cameras.

The algorithm used evaluates the maximum frequency of the signal using FFT and then decides the sampling frequency by multiplying the maximum frequency with a constant which is ≥2 satisfying the Nyquist criterion. A detailed description of the implemented algorithm with all relevant parameters explained can be found in [12].

In Figure 6, the sampling frequency according to the ASA and the maximum frequency of the signal are presented. The following values were chosen for the relevant parameters: \( c = 2.1, h = 5, W = 50, \delta = 0.1\% \). Details for each of these parameters are explicitly given in [12]. The time between successive frames was 0.3125, thus the starting sampling frequency was 32Hz. ASA reduces the number of acquired samples with respect to the traditional fixed sampling rate approach. The approach highlights the effectiveness of using efficient algorithms to handle large volumes of monitoring data.

![ASA Implementation of Camera Displacement Data](image-url)
5 Conclusions

This paper highlights the importance of considering sensor choice, placement and measurement for monitoring offshore renewable energy devices at a scaled testing stage. A comparison was made between high quality LDV data and lower quality motion camera data which recorded 3 different locations on the structure. Additionally, load cells were used to assess the wave load that was generated for each test. It can be observed from the test that there should be an awareness of the variation of measured or estimated values of dynamic responses in the time and the frequency domain based on what instrument is being used, its location and whether the response is directly measured or derived. Additionally, there seems to value in addressing the issue of whether a large number of relatively inexpensive sensors can provide similar or better information regarding the dynamic response as opposed to a single or a small number of expensive sensors. Malfunctioning of sensors appear to have a significant effect on the estimated average dynamic responses and this leads to the importance of investigating and quantifying the sensor redundancy that is required to offset such issues, including strategies related to their placement to minimize such redundancy. More studies quantifying these issues are expected to improve wave basin testing at different technological readiness levels [13] and possible intervention schemes [14] for controlling dynamic responses. Efficient and optimized sampling of measured data is observed to be beneficial in terms of energy demand of the sensors network. In applications where a battery powered system is used to interface a power hungry sensor, reducing the sampling rate when possible will extend the life of the battery while still maintaining the application data requirements. Dynamically changing the sampling frequency according to the needs of the phenomenon under observation can also improve the data quality.

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