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DYNAMIC PERFORMANCE OF ROCK LIGHTHOUSES DUE TO EXTREME BREAKING WAVE LOADS

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Abstract: *Lighthouses are critical infrastructure for safety of seafarers and protection of trade. They are also important heritage of Victorian engineering, remarkable structures built to high standards in extreme environments, and for both reasons their preservation is a priority for their operators. In order to check their condition and viability as they age and climate conditions change a research programme including field investigations of seven remote rock mounted lighthouses, numerical simulations and physical modelling was undertaken. This paper describes some of the challenges of the dynamic field tests and some of the surprising results.*

Introduction

Victorian era rock lighthouses are still vital for maritime navigation around the UK, but very little is known about the severe environmental loads they endure. EPSRC-funded project STORMLAMP aimed to combine physical and numerical simulation tools that would be validated by direct measurements of full-scale performance in the form of modal testing and long-term monitoring.

Modal tests were carried out on seven lighthouses to learn about their behavior and to identify one or two candidates for long-term monitoring of wave-induced response. Five modal tests were carried out in 2016, on Bishop Rock, Wolf Rock and Longships Lighthouses (accessed by helicopter from Land's End, Cornwall), Les Hanois Lighthouse (from Guernsey) and Fastnet Lighthouse (from Castletown-Bearhaven, Ireland). In 2017, Dubh Artach Lighthouse (from Oban, Scotland) and Eddystone Lighthouse (from Liskeard) were tested. Finally, Wolf Rock was revisited in 2019 to fill in some gaps in the 2016 test data. Out of the set of seven, Fastnet and Wolf Rock were chosen for long-term monitoring, and these are the focus of the paper.

Wolf Rock and Fastnet lighthouses

Wolf Rock lies in 37 m deep water 15km off the southwest tip of the English mainland. After failed attempts to erect beacons on the site, work on the present granite tower (designed by James Walker) began in 1862 (Douglass, 1870). Due to the extreme challenges working on the site, the first course of granite blocks was not complete until 1864, in a shallow pit chiselled and blasted in the rock, and the lighthouse was completed in 1869. The tower was constructed as 70 courses of pre-shaped granite blocks, with block masses in the range 2-4t. The first course has only two blocks and the second is a complete circular disk of blocks each secured to the rock below by metal bolts. Stones in the external ring of blocks are dovetailed vertically and horizontally to fit neighbours, and each stone in the third to twentieth courses is secured to the course below by steel bolts. For anchoring and water-tightness Medina Roman cement was used between the blocks up to the level of high-water spring tides, and Portland cement was used above high water. Maximum outside diameter is 12.23m at the complete second course, reducing to 5.18m just below lantern level, at course 68. Internal diameter increases from 2.74m for the entrance room to 3.81m for living room, bedroom and service room. Total volume of granite is 1260m^3 having mass 3350t, and the lighthouse cost £62,726. Now operated by Trinity House, the General Lighthouse Authority (GLA) for England and Wales, Wolf Rock was the world's first lighthouse to be equipped with a helideck, 6.35m tall structure of prefabricated steel frames supporting a steel grillage with aluminium infill panels. These panels distribute helicopter weight and payload and

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are designed to separate from the grillage (and sometimes land in the sea) under extreme vertical breaking wave impact loads.

Fastnet Lighthouse (Morrissey, 2005) sits at the end of Fastnet Rock, 13km from south west Ireland. Its construction was a demanding challenge that began in 1897 and took seven years to complete, with first operation on 16th June 1904. The (new) granite lighthouse was designed by William Douglass and replaced an existing and inadequate cast iron lighthouse dating from 1854. Fastnet is operated by Irish Lights, the GLA for Ireland and consists of a 36.7m high masonry tower body topped by an 8.3m high lantern. The diameter reduces from 12.10m at the base to 6.25m near the top and first 12 courses, up to the height of 6.62m, is solid masonry. A substructure of 13 incomplete courses lies below these first complete courses as its base is built into the rock. The masonry structure comprises 8 different levels divided by vaulted floors, plus the lantern structure on the top. The wall thickness varies between 2.44m at the entrance level and 0.76m at the upper level. Each block is connected to the next with elaborate dovetailed joggles. A total of 2074 granite blocks, with a weight of 4300t were required for the construction.

Modal testing

Modal testing is a standard tool for structural condition assessment and comes in two varieties. Forced vibration testing (FVT) requires use of a mechanical shaker so that input-output relationships in the form of frequency response functions (FRFs) can be identified. Ambient vibration testing (AVT) measures response to ambient loads, requiring more sophisticated system identification procedures. Accelerometers, cables and data acquisition equipment are required for both, while FVT requires a heavy shaker and some form of power supply (hydraulic pump or amplifier). Transport of vibration test equipment to an offshore lighthouse requires meticulous planning considering limited helicopter payload against weight of crew, passengers and equipment, safe lifting of equipment from helicopter to helideck and then below to lantern-level lighthouse entrance and restrictions on materials (such as magnets). The need to carry an electro-dynamic shaker for FVT was very carefully considered given that the total weight of shaker and amplifier exceeds 100kg, while the number of accelerometers (with conditioners and cabling) was limited to keep weight low and test layout simple in unknown and (most likely) cramped and cluttered conditions.

The real benefit of FVT is the direct estimation of modal mass, which enables forward and backward analysis of the load-response relationship, an essential component of the larger scale study of lighthouse endurance under severe wave loading. Modal mass can be estimated to a degree if mode shapes are well characterized and mass distribution is known. Usually mass distribution is poorly defined and mode shapes well characterized but it turned out that thanks to an extensive archive of original drawings preserved by Trinity House the mass distribution was very well known, whereas mode shape identification from AVT was surprisingly difficult. On top of this the expected signal to noise ratio (SNR) with environmental loading was not known and taking a shaker was a calculated risk regarding obtaining adequate SNR for modal identification. Assuming a simple linear mode shape, a 500t estimate of modal mass from the drawings -of Eddystone -one of the two largest lighthouses- suggested that resonant up to 1milli-g could be achieved assuming 2% damping, probably adequate against ambient response. The FVT itself eventually showed major differences in measured and guessed mode shape having significant effects on modal mass.

All modal test activity needed to be programmed within one of the 6-monthly maintenance periods when GLA staff and contractors would be visiting a lighthouse, and capacity could be found within the helicopter flight schedule (which only operates in good visibility). This meant that for the (first) single-day Wolf Rock visit, extreme constraints of time on station including unpacking, setting up, running the test and repacking meant that only a few hours were available in a totally unfamiliar, cramped and disorienting environment. For Fastnet an overnight stay was planned, taking some pressure off, although due to bad visibility the overnight stay extended to a week on station. For both structures, an APS113HF shaker was used, with a set of Honeywell QA750 servo-accelerometers and Data Physics Signalcalc spectrum analyser. For both Fastnet and Wolf Rock, problems with shaker operation (believed to be due to extreme vibration in the helicopter hold) compromised the FVT data quality.

Wolf Rock

The modal test sequence for Wolf Rock (Figure 1) is given in Table 1. Level 1 (L1) is entrance, L6 is bedroom, L7 is battery room, L8 is service room and L9 is the helideck.

Figure 1: Wolf Rock Lighthouse (Courtesy Trinity House and James Bassitt)

Table 1: Wolf Rock FVT and AVT details

Run/ swipe	Levels	Shaker direction	Excitation	Duration (s)
5/1	1,2,5,6,8,9	x	Swept sine 3-10 Hz	600
6/1	1,2,5,6,8,9	x	Swept sine 3-7 Hz	900
9/1	1,2,5,6,8,9	x	Ambient	350
12/1	1,2,5,6,8,9	y	Swept sine 3.4-8 Hz	400
14/1	1,2,5,6,8,9	N/A	Ambient	900
16/2	3,4,7,8,9	N/A	Ambient	80
17/2	3,4,7,8,9	y	Swept sine 3.4-8 Hz	900
18/2	3,4,7,8,9	x	Swept sine 3.4-8 Hz	630

Data acquisition was set up, with the shaker, in the service room and twelve accelerometers were laid out in biaxial pairs in two sets (‘swipes’) of measurement runs (Table 1) for different types of measurement, such as ambient or forced vibration and direction and bandwidth of the shaker. Both swipes shared measurements at levels 8 and 9 so that mode shapes could be normalised to a common scale. Between runs the accelerometers were moved to remaining levels. This plan was based on previous success with other structures but it turned out to be logistically expensive compared with the approach subsequently used at Fastnet. It also meant that frequency domain normalisation via common cross-powers needed to be applied prior to operational modal analysis (OMA). While this technique normally works, due to poor signal coherence it delivered poor results for Wolf Rock, compounded by the very short duration of ambient data resulting form the extreme time constraints.

Figure 2 shows excitation (lower) and response (upper) signals for shaker test swipe1/run2. This was intended to be a forced vibration measurement but the shaker failed leaving 80s of ambient response providing the only recording of ambient response for this swipe.

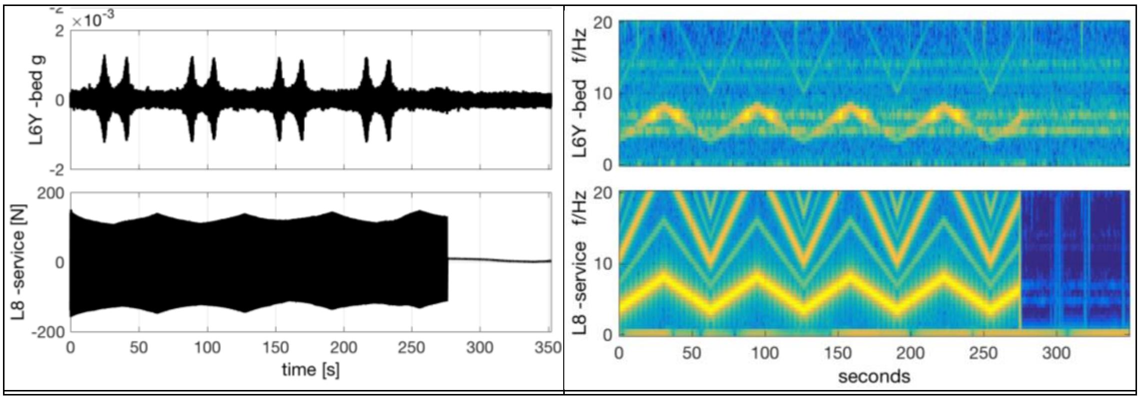

Figure 2: Time history and spectrogram of forcing and response for FVT of Wolf Rock.

Different forms of modal analysis (experimental and operational) were applied to the data. Experimental modal analysis (EMA) of the FVT data was used circle fit (Ewins, 2000) and global rational fraction polynomial (Richardson and Formenti, 1985), while OMA of AVT data used stochastic subspace identification or SSI (Peeters, 1999)), NExT/ERA (James III, Carne and Lauffer, 1995) and Bayesian operational modal analysis or BAYOMA, (Au, 2017).

Figure 3 presents information from ambient and forced vibration measurements in frequency domain. The AVT data in the form of auto-power spectral density (PSD) plot reveals more modes than identified in the FVT, many of them apparently due to the helideck, while the FVT, via the frequency response function (FRF) reveals that the second mode, around 6.8Hz responds more strongly and has a lower modal mass of 314t compared to 3000t for the 4.7Hz mode. Modal masses are for mode shapes unity-scaled to service room (top of masonry tower).

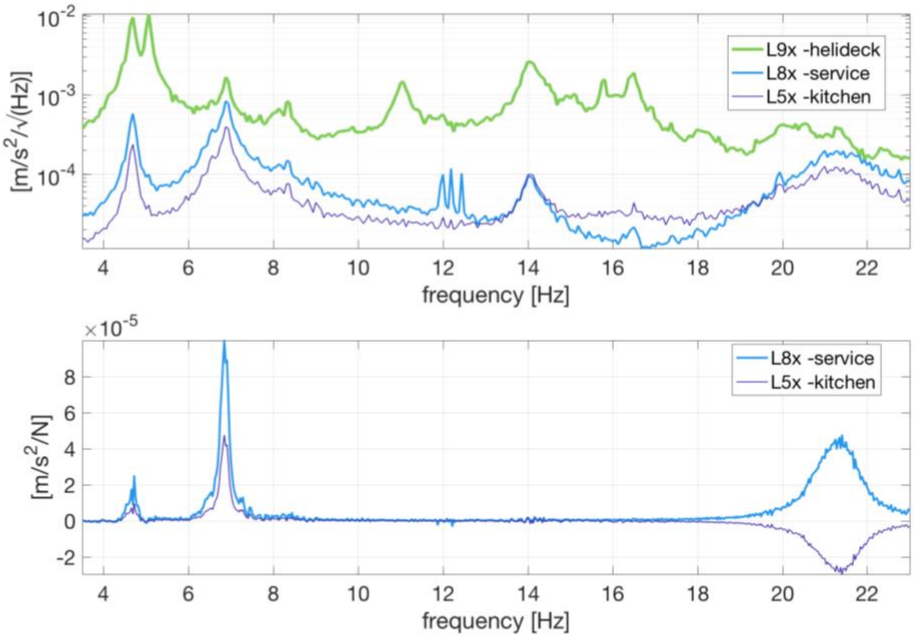

Figure 3: Ambient response PSD (upper) and FRF (lower) for Wolf Rock.

Figure 4 presents two mode shapes obtained from GRFP for the two lowest frequency vibration modes. This provides the explanation for the very different modal masses: the lower frequency mode engages very large response of the helideck which therefore contributes strongly to the modal mass. This type of behaviour is seen with all other helideck-equipped lighthouses to different degrees i.e. two modes with cantilever node shapes in the tower and alternate phase angles in the helideck modal ordinate. GRFP was applied to identify both modes in for two orthogonal directions that were arbitrarily chosen for logistical simplicity and alignment with common features at all lighthouse levels. They identified the same modal properties for both directions, within identification error.

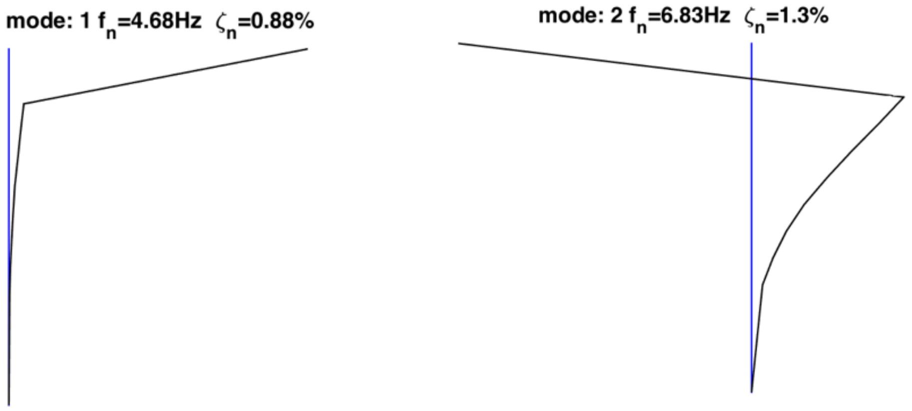

Figure 4: Wolf Rock mode 1 and 2 shapes from shaker testing

Fastnet

Fastnet is one of the two lighthouses tested that have a separate helipad at foundation level, with no retrofitted structure around the lantern. It also has clear asymmetry with respect to the lower masonry courses, whereas Wolf Rock is practically axisymmetric, hence the almost identical properties in orthogonal directions -which presents an identification challenge.

For all five modal tests after Wolf Rock a different procedure was followed for greater efficiency. Accelerometers were aligned simultaneously at all nine levels in one direction, except for one level where a biaxial (x,y) pair was located, together with the shaker.

Figure 5: Fastnet Lighthouse (J Bassitt)

For Fastnet, the biaxial/shaker location was the kitchen, with the other seven accelerometers (and shaker) aligned in x direction, running swept sine in the range 3-7Hz (guided by preliminary ambient measurements) then rotating shaker and accelerometers to y direction. The shaker continued to cause problems, and the time series were corrupted, compromising on-site quality assurance of the data. In fact, the noise was out of band and post-processing showed the data to be adequate for experimental modal analysis.

FVT for Wolf Rock appeared to show very clear single mode Nyquist circles for the upper and lower modes (with helideck in and out of phase). For Fastnet there were two distinct modes at close frequencies, being the same mode with the same shape in different directions. The different frequencies are due to the non-symmetric foundation of the lighthouse.

For best identification, GRFP was used, simultaneously fitting to two modes from shaker and response data in one direction (either x or y) as shown in Figure 6.

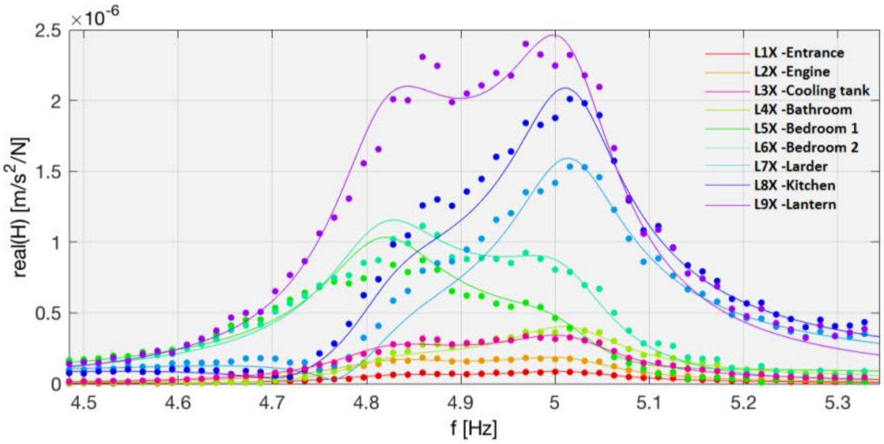

Figure 6: GRFP identification from Fastnet FRFs

The two modes have the same cantilever shape with frequencies 4.8Hz and 5.0Hz, with damping ratios 1.44% and 1%. The difference (as suggested) is almost certainly due to the depth of masonry courses on one face of the lighthouse, and the fact that both modes are observed in the shaker FRFs means that the arbitrarily chosen x and y directions did not coincide with the 'principal axes' or mode shape directions of the lighthouse.

Wolf Rock extended ambient vibration measurements

In January 2019 extended (overnight) ambient vibration measurements were made at Wolf Rock using an array that excluded the helideck. This represented a considerable improvement on the 80s of data previously obtained. The auto power spectral densities are shown in Figure 7 which now indicate a third vibration mode (or mode pair) just above 8Hz. Singular value decomposition of the cross spectral density matrix shows that there are three pairs of modes, all three having a simple (zero-noded) cantilever shape. As the helideck was not measured, the helideck phase angle with respect to the tower for the third mode(pair) is unknown.

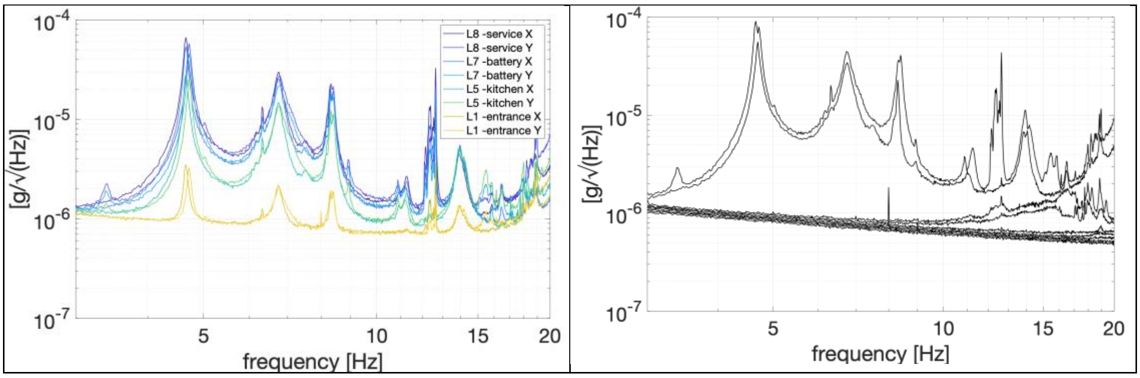

Figure 7: Auto spectra (left) and singular value spectra (right) from eight hours of recording at Wolf Rock.

Fastnet extended vibration measurements

Almost nine hours of overnight ambient vibration measurements were made with the accelerometer array during the overnight stay on Fastnet and auto power spectra and singular value spectra are shown in Figure 8. The singular value spectra clearly show there to be two modes with separate frequencies around 5Hz, with possible single modes around 9Hz. The first two modes involve no lantern response while the auto specrtra show the higher modes to be almost entirely response of the tall lantern structure.

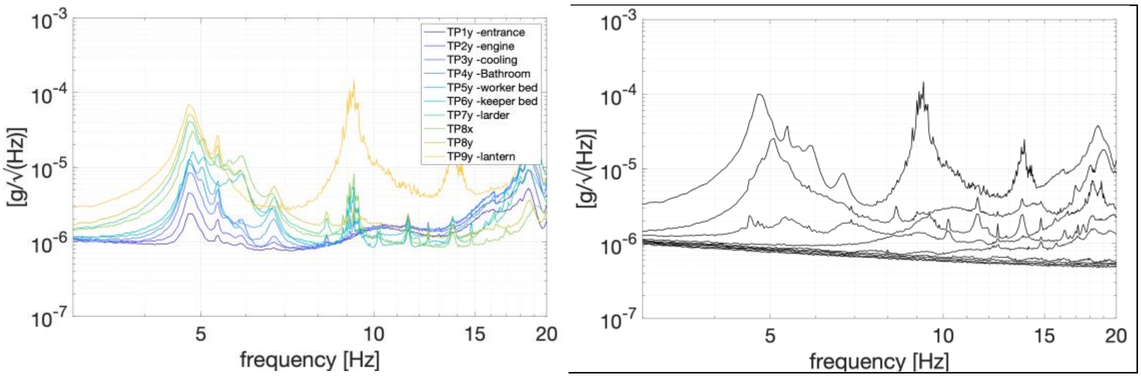

Figure 8: Auto spectra (left) and singular value spectra (right) from eight hours of recording at Fastnet.

RESPONSE MONITORING

Seven lighthouses studied in the STORMLAMP project were potential candidates for monitoring to capture statistics of extreme response, and hence loading. Eddystone Lighthouse is in the English Channel and was previously monitored (Raby *et al.*, 2016) while Les Hanois and Longships are close to land rather than being in open sea. Bishop Rock is in the Atlantic approaches to the Scilly Isles and lighthouse keepers have reported strong vibrations. However, Wolf Rock is a better candidate as it is a smaller, lighter and potentially more vulnerable structure, being in a very exposed position on a pinnacle that rises sharply out of the sea. Lighthouse keepers have reported very strong rocking movements.

Of the two lighthouses without helidecks, Fastnet has the more exposed location, and benefits from extensive numerical studies. Hence Wolf Rock and Fastnet were chosen for monitoring.

The aim of long-term monitoring is to capture dynamic response that can be used for inverse estimation of wave impact loads. Given the modal test data including full development of mode shapes there is no need to locate accelerometers at more than one location, so in both cases the most convenient location near the top of the tower and with access to power supply was chosen.

Fastnet Monitoring

The first installation was at Fastnet, with a single JA70 MEMS triaxial accelerometer in the lantern room. The equipment (during installation) is shown in Figure 9, along with the main components.

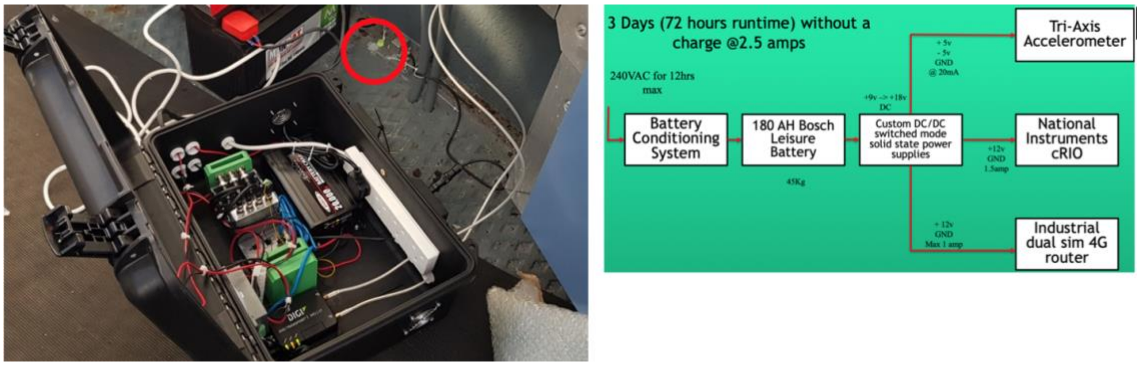

Figure 9: Fastnet monitoring equipment. JA70 accelerometer is circled.

The accelerometer has micro-g resolution and data are acquired at 128Hz along with battery Voltage via NI-9234 4-channel 24-bit data acquisition card in National Instruments CompactRIO chassis. The cRIO system operates automatically when powered and saves to a USB drive. The system, including 4G router is powered form a high capacity battery which also drives the 4G router.

Power is a major constraint, since the battery bank, charged by solar cells, primarily serves to maintain full function of the lighthouse and a limited power budget is available for the monitoring system. Fastnet has no solar cells and all functions are powered by diesel generators and a large battery bank. To save power all life support (heating, cooking, lighting) for visiting crew shuts down when they leave and it took three visits (by helicopter, for the far southwest tip or Ireland, subject to weather constraints) to organise a permanent power connection, which has operated reliably since February 2019. 4G connection is intermittent and low capacity so that only live data can be retrieved, whereas historic data covering periods of poor signal (and bad weather that is usually good for monitoring) requires physical retrieval.

Figure 10 shows the spectrum of Fastnet acceleration response during Storm Freya in March 2019. Channel 1 (left) picks up response in three apparent modes, channel 2 responds in only one mode.

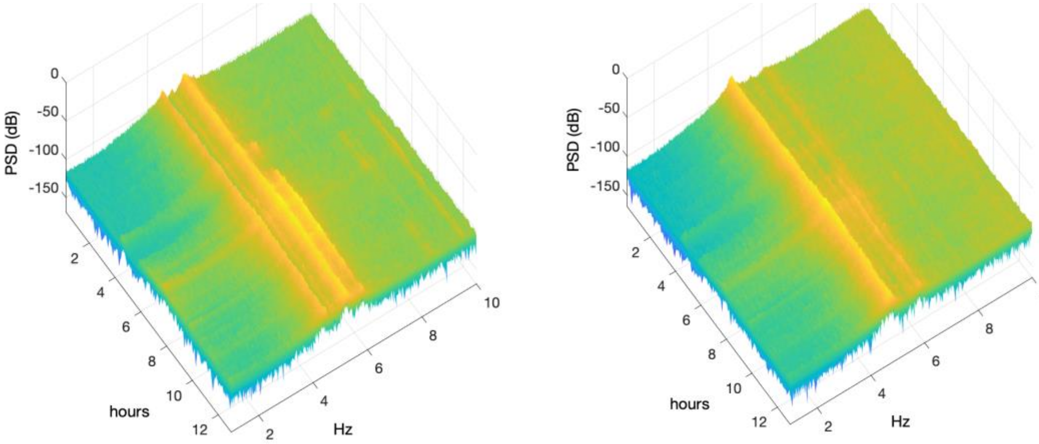

Figure 10: Fastnet response during Storm Freya, 2019 as spectrograms.

Shown as time series in Figure 11 the response is typical of wind-induced response of a building, but with a few transients, likely to to impacting wave loads.

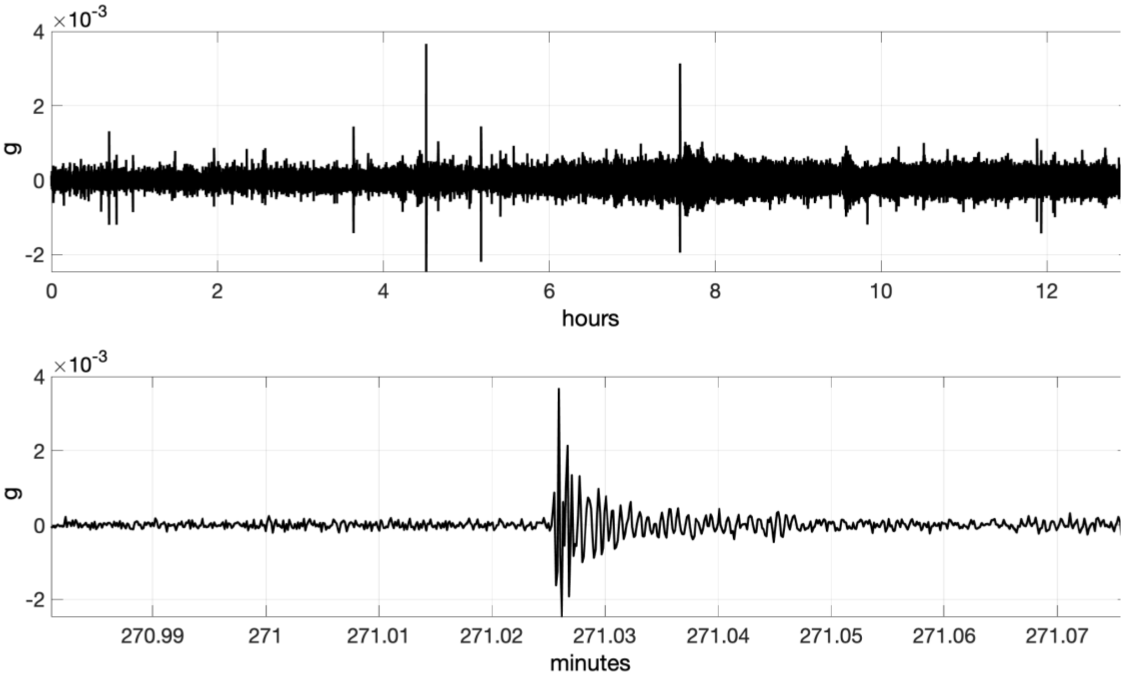

Figure 11: Fastnet response during Storm Freya, 2019 as time series

Wolf Rock Monitoring

A similar system was installed at Wolf Rock (Figure 12); the accelerometer was installed in the battery room (L7) rather than the service level (L8) which is at the top of the masonry tower. Hence recorded response is rescaled according to the mode shape(s) for (inverse) estimation of response.

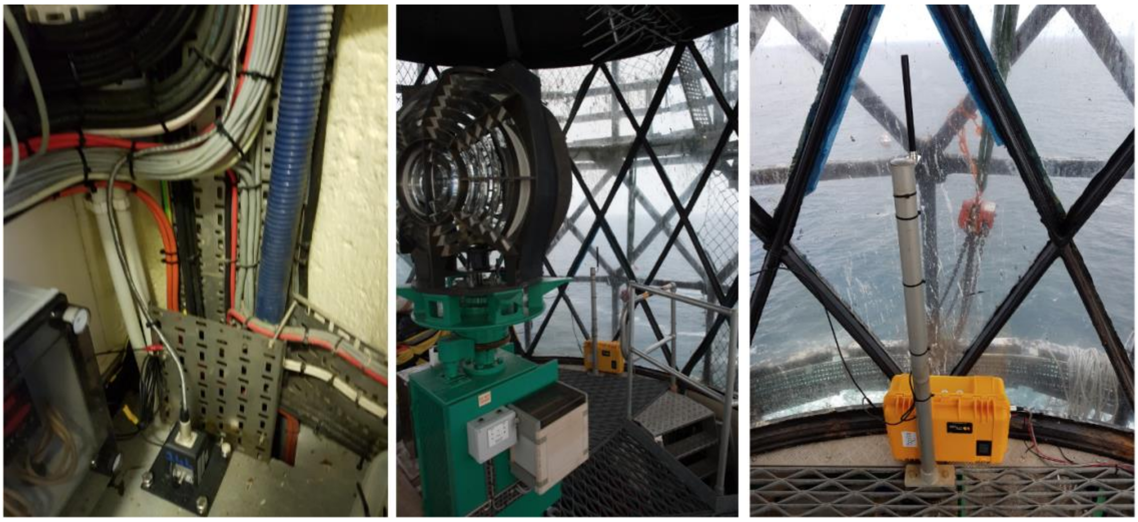

Figure 12: Wolf rock monitoring: JA70 in battery room, logger package and 4G aerial in lantern room.

The system has been operating successfully since it was installed in September 2018 and has recorded response to a large number of storms. Figure 13 Shows an example of response during Storm Brian, on 11th March 2018.

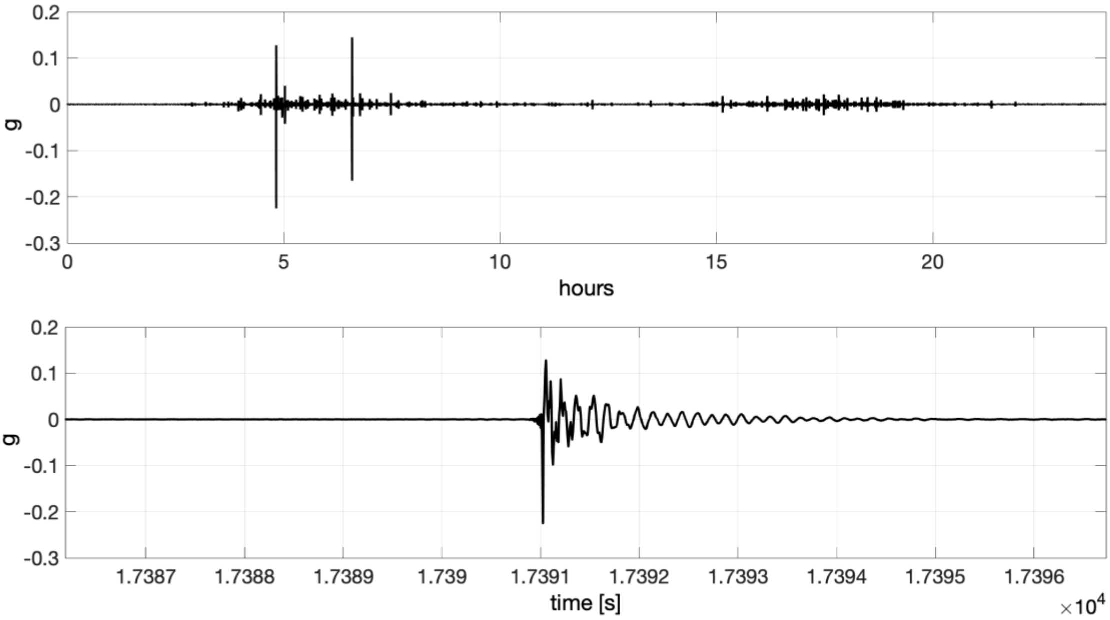

Figure 13: Wolf Rock response during Storm Brian, 2018.

Storm Brian has generated the largest accelerations so far observed. The 24-hour record shows two periods of higher response, which reflects the tidal variation, a pattern that recurs during all stormy weather, and which is very different from Fastnet response. Knowing the modal mass and modal ordinate at the monitoring accelerometer allows the corresponding impulsive force to be estimated, assuming the response to be in a single mode, which turns out to be the 6.8Hz mode with modal mass of 300t. Hydrodynamic studies show that breaking wave impact is at approximately 1/3rd height of the tower, with largest force over the first 0.025s, effectively an impulse. This information allows the scale of the force to be estimated and compared with extreme value predictions.

Conclusions

The paper provides a sample of the experimental campaign on a set of lighthouses around the British Isles as part of the STORMLAMP project and which has provided some useful insights, most usefully that the simple impulsive response of Wolf Rock allows it to be used as a kind of of load cell for tracking extreme breaking wave loads.

Acknowledgements

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