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Procedia Engineering 00 (2017) 000–000

Procedia Engineering

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X International Conference on Structural Dynamics, EURODYN 2017

Modal testing of offshore rock lighthouses around the British Isles

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Abstract

Given that 95 per cent of the UK's international trade is transported by sea, and as a vital complement to fallible virtual navigational aids such as GPS, rock-mounted lighthouses constructed in the 19th century have a crucial role to play in safe navigation. However the longevity of these historical structures is threatened by extreme weather so in the UK, the General Lighthouse Authorities comprising Trinity House, the Northern Lighthouse Board and the Commissioners of Irish Lights are supporting three British universities in a program of linked experimental and analytical investigations of full-scale performance under extreme wave loading. The aim is to use structural models calibrated by modal testing to deduce wave loading from response recorded by long-term monitoring.

The paper describes the procedures for modal testing, taking into account the constraints on access, logistics, unfamiliar layout and time. The test program sequentially covered Les Hanois, Wolf Rock, Longships and Bishops Rock lighthouses over summer 2016 followed by Fastnet Rock in December 2016.

Some conventional techniques of forced and ambient vibration testing were used along with some unusual excitation methods. Results from the measurements and observations on the particular challenges associated with testing two of these iconic structures are presented.

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Peer-review under responsibility of the organizing committee of EURODYN 2017.

Keywords: Lighthouse modal test ambient shaker

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1. Introduction

Victorian era rock lighthouses remain a vital aid to maritime navigation, yet the severe environmental loads they endure are not understood. EPSRC-funded project STORMLAMP was initiated to develop a combination of physical and numerical simulation tools for both loading and structure that will be validated by direct measurements of full-scale performance. This paper describes part of the experimental campaign, the structural identification of two lighthouses chosen for physical and numerical modeling with possible long-term monitoring.

2. Lighthouses selected

Six lighthouses were selected for modal testing and possible monitoring, with five modal tests carried out in 2016. Bishop Rock, Wolf Rock and Longships Lighthouses were accessed by helicopter from Land's End Cornwall, Les Hanois Lighthouse from Guernsey and Fastnet Lighthouse from Castletown-Bearhaven, Ireland. The sixth structure is expected to be Dubh Artach Lighthouse, near Colonsay, Scotland. The paper focuses on two extreme examples, Bishop Rock (Fig. 1 left), Wolf Rock (Fig. 1 middle), whose locations are shown in Fig. 1 (right).

Fig. 1. Left to right: Bishop Rock, approach to Wolf Rock, locations off South West England.

Wolf Rock, 8 miles off Land's End, was tested on 7th July 2016. Completed in 1869, its 43 m height is topped by the first helideck installed on a lighthouse. Bishop Rock Lighthouse is situated on the world's smallest island 4 miles of the west of the Scilly Isles. Completed in 1857, it was strengthened in 1887 and so is a much larger structure than Wolf Rock, at 48 m tall. For both lighthouses the masonry structure comprises concentric courses of masonry blocks keyed together vertically and circumferentially with lower courses set into recesses hacked out of the rock foundation. Both are exposed to extreme weather of the Atlantic Ocean resulting is large impulsive wave loading and would need reliable system identification to estimate wave forced from monitored response.

3. Lighthouse testing logistics and procedures

Carrying equipment to an offshore lighthouse requires meticulous planning considering the lifting capacity of the helicopter for crew, passengers and equipment, the safe weights to be handled while moving equipment between helicopter, helipad and lighthouse lower levels and restrictions on materials that can be carried on aircraft. Passenger (test crew) baggage must also include provision for overnight stays i.e. bedding and food as well as warm weather gear and immersion suits. In particular the need for a mechanical (i.e. electro-dynamic) shaker was very carefully considered given that the total weight of shaker and amplifier exceeds 66 kg. Due to weight (and space) limits the number of accelerometers that could be used was limited, preventing the ideal solution of monitoring all lighthouse levels in both directions simultaneously.

For the modal testing one person set up and ran the data acquisition and modal analysis while other crew laid out cables and positioned and moved accelerometers to cover all measurement points (two orthogonal horizontal

directions per level) sequentially rather than simultaneously. In each case extensive photographic records were made, including continuous video recording principally to resolve uncertainties with sensor location and cabling. Time for unpacking, setting up, running the test and repacking was extremely tight and there was no opportunity either for reconnaissance or follow up. The intention of the modal testing was to identify the fundamental horizontal vibration mode or modes expected to occur around 5 Hz, as well as a few higher modes, sufficient to allow validation of numerical models. Test (measurement) points (TPs) were located at each level.

4. Wolf Rock modal test

A test team of Bassitt, Hudson and Antonini, also technician Ian Moon flew from St Just on 18/8/2016 in two flights each way with the first pair on board Wolf rock at 09.30 and the last leaving at 17:00. Data acquisition setup started at 11.50 concurrent with laying out accelerometers for the first of two sets of measurements or 'swipes'.

For swipe 1, accelerometers were located at six levels: level 1 (entrance), level 2 (freezer), level 5 (kitchen), level 6 (bedroom), level 8 (service room) and level 9 (helideck).

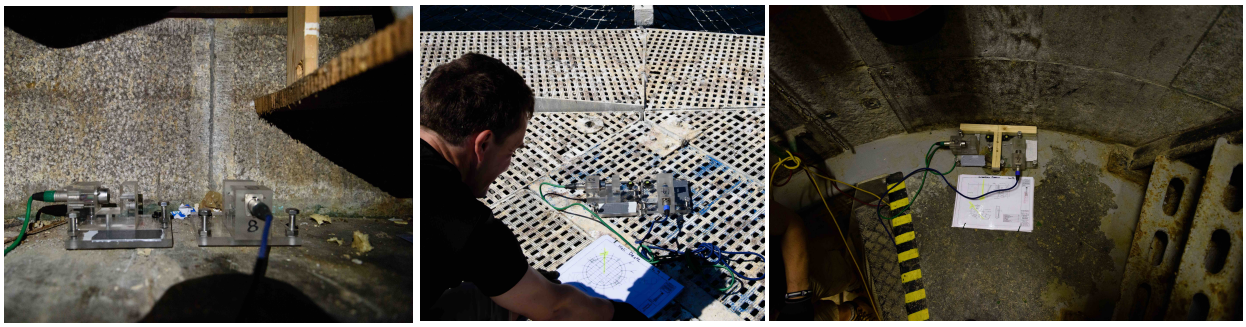

Fig. 2. Wolf Rock: Accelerometers on bedroom floor, on helideck and in service room, with alignment jig.

For swipe 2, accelerometers were located at six levels: level 3 (engine room), level 4 (bathroom), level 6 (bedroom), level 7 (battery room), level 8 (service room) and level 9 (helideck), so the two upper levels were used as common references points.

For each level, accelerometers were positioned in nominal x and y directions using an alignment jig (Fig. 2), at the same circumferential reference point, based on Trinity House drawings showing internal layouts and reference points at each level. Accelerometers locations were at north-east point against the masonry wall at every level, with x-direction to south-west and y-direction to south-east. Data acquisition was set up in level 7 with the shaker at level 8 and for each swipe at least three measurements were made: one ambient, one with shaker in x-direction and one with shaker in y-direction. Table. 1 summarises the sequence of measurements, excluding test runs.

Table 1. Wolf Rock: Vibration measurement summary

Run	Swipe	levels	Shaker direction	Excitation	Start time	Duration (s)	comment
5	1	1,2,5,6,8,9	x	Random 3-30 Hz	12:55	600	Shaker response drowned in ambient
6	1	1,2,5,6,8,9	x	Swept sine 3-30 Hz	13:10	900	Poor signal to noise ratio
9	1	1,2,5,6,8,9	x	Swept sine 3.4-8 Hz	13:45	350	Shaker failed at 300 s
12	1	1,2,5,6,8,9	y	Swept sine 3.4-8 Hz	14:30	400	Shaker failed at 380 s
14	1	1,2,5,6,8,9	N/A	Ambient	15:10	900	Strong structural transient observed.
16	2	3,4,7,8,9	N/A	Swept sine +Ambient	15:25	350	80 s of ambient after shaker failed
17	2	3,4,7,8,9	y	Swept sine 3.4-8 Hz	15:50	900	Good quality data
18	2	3,4,7,8,9	x	Swept sine 3.4-8 Hz	16:10	630	Shaker failed at 580 s: prepare to leave

Auto spectra for selected levels from Run 14 are shown in Fig. 3. System identification on ambient data (eigen-system realization algorithm, ERA) reveals modes at 4.7 Hz and 6.8 Hz as well as at 4.85 Hz and 5.1 Hz. The 4.7 Hz mode involves proportionally very large motion of the helideck while the 4.85 Hz mode seems only to be the helideck moving in x-directions. The 6.8 Hz mode has strong helideck motion, but proportionally less strong than for the 4.7 Hz mode. For the 4.7 Hz and 6.8 Hz modes there are components in the nominal x and y directions; the mode shapes are (later) identified using classical modal analysis using the forced vibration data.

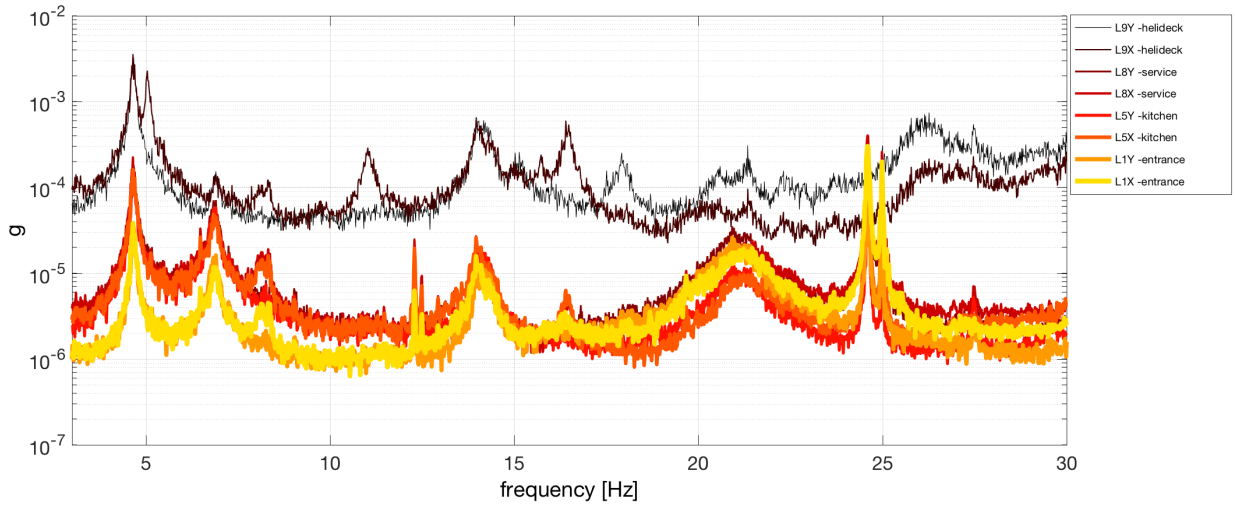

Fig. 3. Wolf Rock: Auto-spectrum for ambient response –all available channels in swipe 1, Run 12.

Spectrograms for Run 16 are shown in Fig. 4 that begin with swept sine shaking and end in ambient response after the shaker cuts out. The strong response clear in the masonry structure corresponds to the 6.8 Hz mode, while the helideck channel shows more complex response with both 4.7 Hz and 6.8 Hz modes driven by both wind and shaker. The 4.7 Hz mode responds strongly due to the wind after the shaker stopped. The modal behavior is clear in the spectrogram. The shaker characteristic indicates non-sinusoidal response and a mode around 14 Hz that is driven by wind.

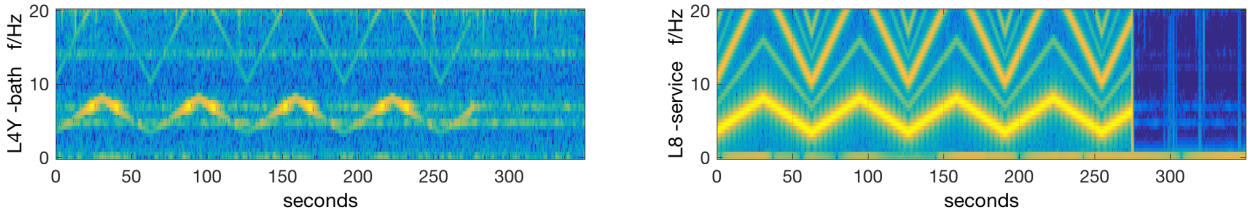

Fig. 4. Wolf Rock: Spectrogram for response and forcing function.

The best quality modal identification was obtained by single input single output (SISO) circle fitting and by single input multiple output (SIMO) global rational polynomial curve fitting using frequency response functions of acceleration with respect to the shaker force.

Fig. 5 left is a circle fit of the 6.8 Hz mode using x-direction point mobility in the service room at the top of the masonry tower; the modal mass estimate is 330 tonnes (after correction of accelerations to SI units). This is the lowest modal mass measured of any of the lighthouses tested, consistent with the relative small size. The 4.7 Hz mode does not provide a clear circle fit whereas SIMO is more successful and reveals a clean pair of mode shapes for y-direction (Fig. 5, right). Mode shapes were not so clearly identified from ambient data using ERA.

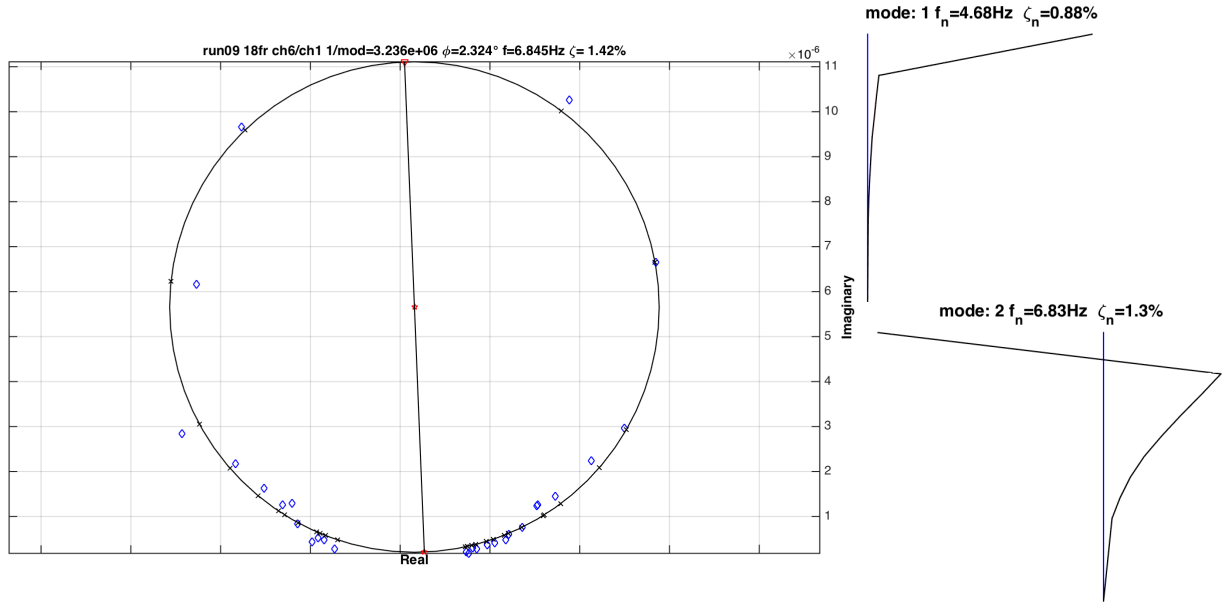

Fig. 5. Wolf Rock: Left: SISO circle fit for x-direction. Right: SIMO mode shapes for y-direction.

Outwardly the almost perfect axi-symmetric is upset only by the small openings for windows and cutouts for spiral staircase access in the circular floor slabs. In fact both the 4.7 Hz and 6.8 Hz modes appear to be omni-directional in the sense that applying a coordinate transformation to rotate time series data does not indicate any one direction in which either mode tends to disappear, while the 5.1 Hz peak in the Fig. 6 auto-spectra definitely aligns with the chosen x-axis so appears to be an isolated mode of the helideck only. What is more remarkable and very clear is the effect of the helideck, which splits one mode into two in the manner of a tuned mass damper, suggesting the low lateral stiffness and mass have a similar ratio to those for the masonry structure.

5. Bishop Rock modal test

A test team of Bassitt, Antonini and Moon flew from St Just on 26/9/2016 arriving at 10.30. All measurements were completed by 16:00 and equipment packed ready for the return flight. However weather had deteriorated and the lighthouse was fogbound until ‘visual flight rules’ allowed helicopter operations to resume the following morning. Fig. 6 shows modal testing in progress and the eerie night view from the lantern room.

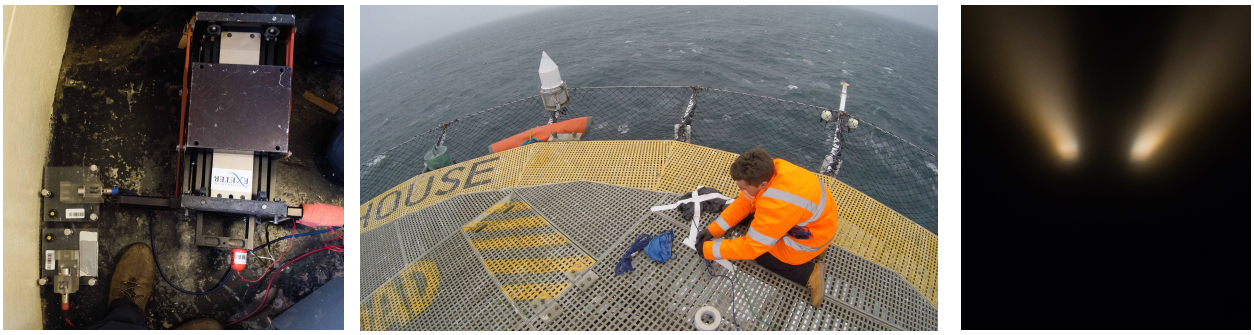

Fig. 6. Bishop Rock: Setting up shaker and accelerometers in battery room; weather protection for helideck sensors; twin beams in foggy night.

Ambient modal identification (using ERA) for the two-swipe gluing of mode shapes used at Wolf Rock was challenging, and the process of moving accelerometer cables halfway through the exercise caused delay. Hence for Bishop Rock the measurements were done keeping accelerometers at all ten levels but with (first) y- and (then) x-alignments of non-reference accelerometers and shaker. Helideck (level 10) and battery room (level 8) used x-y accelerometer pairs, with the shaker at level 8 (battery room). Since the Victorian strengthening of Bishop Rock led to a much more massive structure and a lower power shaker had to be used there was a concern about achieving a signal to ratio adequate for modal identification even using the H1 frequency response function (FRF) estimator.

FRFs are shown in Fig. 7 based on 34 averages of 32-second frames with frequency sweeping (alternately up and down) between 3 and 8 Hz. H1 estimator is used due to the imperfect coherence.

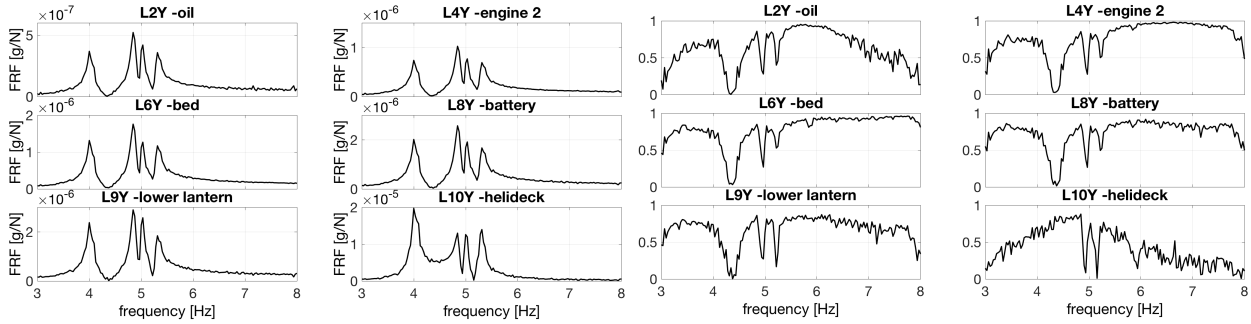

Fig. 7. Bishop Rock: y direction frequency response functions (FRFs) for sweep 1 run 8. H1 FRF (left) and coherence (right).

Mode shapes for three of the peaks in Fig. 7 are given in Fig. 8. Modal mass estimates are 1650 tonnes and 2800 tonnes for the 4.02 Hz and 4.85 Hz modes, considerably larger then for Wolf Rock.

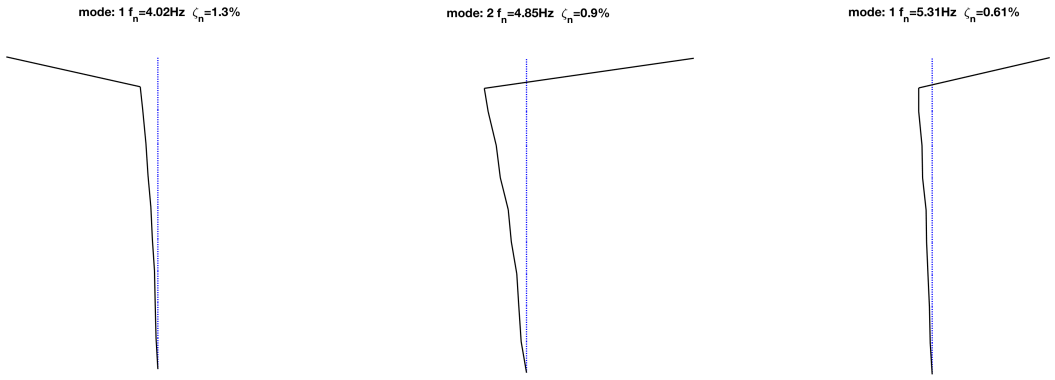

Fig. 8. Bishop Rock: mode shapes.

6. Conclusions

Offshore lighthouses represent an extreme challenge for modal testing due to logistics and issues with capability of the shaker to generate good signal to noise (s/n) ratio was uncertain. Imperfect axi-symmetry and helidecks provided the most interesting effects, providing some challenges to structural identification as they obscure the behaviour of the rigid masonry structure.

Acknowledgements

Thanks to Trinity House, and to Ian Moon. The research was funded by EPSRC grant EP/N022955/1.