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Bayesian operational modal analysis of offshore rock lighthouses for SHM

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Abstract

During 2016 and 2017 a program of field vibration measurements was made on a set of Victorian era granite lighthouse towers around the British Isles. The field tests were designed for structural identification to enable condition assessment and identification of extreme wave loads through long term monitoring. The primary test method was forced vibration, and ambient vibration measurements was used as a backup. The best operational modal analysis (OMA) results were obtained using Bayesian OMA, which provide a clear picture of the directionality of the mode shapes which appeared at very close frequencies due to the symmetry of the towers. The paper describes measurements and sample analysis illustrating difficulties and achievements.

1. Introduction

Despite widespread use of virtual navigational aids such as GPS, visual navigational aids such as lighthouses are still needed to protect mariners and preserve trade. These are the same motives for lighthouse construction for the last two or three millennia, but it is apparently only in the 17th century that lighthouses were first constructed on the dangerous offshore rock outcrops causing multiple shipwrecks. Apparently the first example was the lighthouse constructed on Eddystone Reef in 1698, in the south west approach to Plymouth by Henry Winstanley. He had the right to collect all dues from ships passing the light for the next 5 years, then half dues for 50 years before all dues were to Trinity House. The same business model is still operated by Trinity House and the two other General Lighthouse Authorities operating around the British Isles i.e. The Northern Lighthouse Board and Commissioner of Irish Lights. The present-day Eddystone Lighthouse designed by James Douglass was completed in 1882 (1). Douglass also designed the Les Hanois (1862) lighthouse off Guernsey and Longships Lighthouse (1875), close to Land's End, while Wolf Rock (1869) and Bishop Rock (1858 and 1887) lighthouses further southwest were designed by James Walker.

The five lighthouses (Eddystone, Les Hanois, Longships, Wolf Rock and Bishop Rock) are all concave elliptic frustums constructed from dovetailed granite blocks and were all retrofitted with steel frame helidecks between 1973 and 1981.

2. STORMLAMP project definition

Project STORMLAMP: *STructural behavior Of Rock Mounted Lighthouses At the Mercy of impulsive waves, funded by EPSRC,* was initiated in 2016 with the aims to

- Identify experimentally modal parameters of a set of at least six rock lighthouses
- Monitor dynamic performance of at least one lighthouse over an extended period
- Develop structural models based on construction data and dynamic testing
- Investigate worst case hydrodynamic loading due to breaking waves and
- Formulate guidance for structural condition assessment and management

2.1 Helideck-equipped lighthouses: Logistical challenges.

Five of the lighthouses studied for STORMLAMP are the five previously mentioned that are located in the English Channel and Atlantic approaches and which are the subject of this paper. Lighthouses at Fastnet Rock (Ireland), Dubh Artach (Scotland) and Skerryvore (Scotland) are being studied, but these lack the retrofitted helidecks and as such are technically less challenging, from the point of view of operational modal analysis (OMA). Logistical challenges of the helideck-equipped lighthouses are also significant due to operational limits of the aircraft used to access them. Total weight of passengers and freight is limited and they operate according to visual flight rules which prevent them flying in foggy weather which often envelopes lighthouses. Experimental field campaigns require a return trip in one day or an overnight stay and are synchronised with visits of GLA maintenance teams that take priority so flights can be re-timed or cancelled at short notice with consequences on the experimental work.

2.2 Modal test planning: Signal to noise ratio challenges

The only prior information to inform test planning was response monitoring of Eddystone Lighthouse (2) using geophones, which had indicated a fundamental frequency around 4.4 Hz. Electrodynamic shakers such as APS 113 and APS 400 operate optimally at this frequency but Douglass' paper (1) gives total mass of granite as 4.8 10^6 kg which represents a structure usually regarded as being too massive to 'get going' with a shaker. The modal mass with mode shapes unity scaled at the top of the tower (where the shaker would operate) could be much less and a reasonable signal to noise ratio might be obtained using the larger shaker. H

3. Les Hanois Lighthouse modal test

A three-person test crew left Guernsey Airport at 1PM (2 June 2016) and returned by 6PM. Allowing for a 5 minute helicopter flight, unloading, setting out equipment and packing up this left 2-3 hours of for modal testing on a structure unlike any the test team had experienced. The ten levels for measurement are shown in Figure 1 and include two levels resulting from the helideck retrofit. Data acquisition equipment comprising a 24 channel 24-bit Data Physics spectrum analyser running at 204.8 Hz and accelerometer power supplies was set up in level 8 (battery room). At level 9 (lantern room, gallery level) the shaker was set up on the external gallery, which also provides access inside the lighthouse from the helideck above, with a pair of accelerometers arranged as references in orthogonal directions inside the lantern room.

Figure 1: Les Hanois Lighthouse layout (Trinity House) and view from land (1 km away).

(upper engine room/battery room). The aim of using two swipes with orthogonal accelerometers was that the two reference pairs at levels 9 and 10 would enable assembling or ‘gluing’ of mode shape pieces in the modal analysis process.

Measurements are summarised in Table 2. These exclude system checks and unsuccessful measurements and account for 70.5 minutes of good quality measurements. In each swipe a series of individual measurements (runs) were made, varying shaker conditions or recording ambient response.

Table 2: Les Hanois Lighthouse measurement sequence

Run	Swipe	levels	Shaker direction	Excitation	Duration/ s
5	1	1,2,5,6,9,10	-	ambient	940
6					

3.2 Bayesian OMA

Bayesian operational modal analysis (BAYOMA) (4) yields the probability density function of modal properties (MP) using the FFT of ambient

For Les Hanois, there are two additional modes with the 0   phase of the helideck ordinate, which do not make sense structurally; while many of the peaks in the ambient response PSD appear only in the helideck this pair has clear response in the masonry tower. Figure 3 also indicates the uncertainty in the MP estimates in terms of coefficient of variation (standard deviation/mean). As usual, frequency estimates have low uncertainty while damping (given as ratio, not percentage) is significantly larger, although in the case of lighthouses damping ratio is not a parameter having major influence on response.

4. Wolf Rock lighthouse

Wolf Rock Lighthouse lies 15 km southwest of Land's End, and is built on a rock outcrop rising sharply 37 m from the sea bed. It is exposed to extreme wave loading mainly from the Atlantic Ocean in the southwest direction. In addition, anecdotal evidence from lighthouse keepers suggests that it experiences lively dynamic response (rocking) during storms. The modal test procedure for Wolf Rock was very similar to that at Les Hanois, with similar high-pressure timescales, and Figure 4 shows the ambient response PSD for one measurement. This PSD is shown for X-direction, which was chosen for logistical convenience when planning the measurements (based on Trinity House drawings), there being no prior knowledge of principal directions of major and minor stiffness.

Figure 4: Wolf Rock Lighthouse (Trinity House) and ambient response PSD.

As with Les Hanois, the helideck response is much stronger than the masonry structure *except for the second mode* and there are at least two X-modes in the low frequency range (0-10 Hz) plus an extra peak of helideck-only response. Mechanical problems with the shaker meant that 15 minutes of ambient response were obtained for swipe 1, but only 64 s of data were available for swipe 2. The shorter swipe 2 duration resulted in greater uncertainty and

connection was lost until repaired on a visit in February 2018, when the winter data were retrieved. The period featured several major storms including Storms Aileen, Ophelia (formerly a hurricane), Brian and Eleanor. Figure 9 shows response for two horizontal (orthogonal) directions during one day of significant (but not extreme).25 a.3(n)29.0(bum5(.25)-20(ni)7(fi) though the relatively high natural frequencies benefit MP identification from OMA, there are challenges due to the axi-symmetry, which lead to imprecise and difficult to identify plan alignment of mode shapes and to very close mode frequencies. In fact realistically, only OMA can identify the alignment directly and this has been done successfully in this study.

BAYOMA provides extra confidence in MP estimation via the uncertainty quantification, and this exercise demonstrates the need to quantifying uncertainty in the alignment, which is the aim of further research.

Bayesian OMA (as for other techniques such as stochastic subspace identification and eigensystem realisation algorithm) suggests modes that forced vibration testing cannot find, but the challenge is to find if those modes are significant in terms of operational response in the case of extreme wave loading. The modal test data obtained for Wolf Rock is now being used to interpret response data from a pair of accelerometers permanently installed in the masonry tower

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