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Experimental modal analysis of British rock lighthouses

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ABSTRACT

Iconic lighthouses constructed on offshore reefs around the British Isles in the 19th century continue to play a crucial role in safe navigation, but the longevity of these historical structures is threatened by extreme weather. A program of experimental dynamic investigations has been carried out to support characterisation of extreme impulsive breaking wave loads on these structures, using monitored response data. This paper describes the procedures and outcomes of this program, which included modal tests of a collection of six of these lighthouses between June 2016 and October 2017.

Five of the six lighthouses tested (Les Hanois, Wolf Rock, Longships, Bishop Rock and Eddystone) feature a 20th century metal helideck atop a 19th century masonry tower, with a Scottish lighthouse (Dubh Artach) being the exception that provides baseline behaviour of a relatively simple tower. All the masonry towers are imperfectly axisymmetric to some degree and all present logistical challenges for experimental work as they can only be accessed by helicopter flights subject to severe weather and time constraints. Against such challenges it was possible to identify key modal parameters, and to highlight some interesting effects due to symmetry and helideck retrofit.

Notable findings were that most important modes have frequencies ranging between 4 Hz and 7 Hz and modal masses as low as ~200 t. The rarely investigated effect of imperfect axisymmetry on forced vibration testing is studied, along with the introduction of additional modes due to retrofitted helideck. The implications of these effects on experimental modal analysis from forced vibration test data is illustrated.

Finally, accelerations recorded on Wolf Rock Lighthouse during the 2017–2018 winter storm season show the modal test data can be used to infer breaking wave modal impulses up to 8 kNs.

1. Introduction

Victorian era rock lighthouses remain a vital aid to maritime navigation, yet the severe environmental loads they endure are not understood. Funded by the UK Engineering and Physical Sciences Research Council (EPSRC), Project STORMLAMP was initiated to develop a combination of physical and numerical simulation tools for both loading and structures needing to be validated by direct measurements of full-scale performance.

The direct measurements are described in this paper and feature lighthouses located on offshore rock outcrops or reefs which

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represent hazards to marine navigation in the English Channel and Western Approaches. The numerous shipwrecks in this area and around the British Isles led to the incorporation of Trinity House in 1514 b y royal charter from Henry VIII. Although Trinity House built its first lighthouse in Lowestoft in 1609, the first *rock* lighthouse was constructed on Eddystone Rocks south of Plymouth in 1698 and survived until the Great Storm of 1703 when it was destroyed along with its designer. The present Eddystone Lighthouse is in fact the fourth structure to be built on the site, the third having been rebuilt on Plymouth Hoe.

Likewise, the present structures at Wolf Rock, Longships and Bishop Rock (off the south west of tip of Cornwall) are successors learning from failures of previous designs, although the structures at Les Hanois (Guernsey) and Dubh Artach (Scotland) are the original structures, all of them constructed in the 19th century. With design evolution these British structures have, with the exception of Bishop Rock that was reinforced between 1882 and 1887, functioned with only minor structural repairs to their superstructures to the present day. Condition assessment has been mainly limited to visual checks on the masonry structure, with more detailed assessment of foundation, helideck and interior.

Information on condition assessments of lighthouses has been obtained with assistance from relevant lighthouse authorities. In the UK these are Trinity House, the Northern Lighthouse Board and Irish Lights, all operating under the umbrella of the General Lighthouse Authorities (GLAs). Blakeley and Warke [1] produced a Task Report for the UK GLAs on building condition monitoring, focusing on issues of humidity and condensation, and their effects on stonework. Their report built upon earlier work undertaken prior to solar photovoltaic installations [2] when the structures would have experienced different internal conditioning regimes. Warke et al. [3] present results of an associated monitoring study on the interior stonework of two Irish Lights towers, describing the different temporal and spatial characteristics of the deterioration. In 2009/2010 Trinity House commissioned full structural surveys of the rock lighthouses described in this paper, which comprised inspections of the interior and exterior including the helidecks and landing areas, generally noting that the structures were in reasonable condition. Raby et al. [4] describe a subsequent pilot project on the Eddystone Lighthouse that developed a monitoring system to relate the wave loading to the structural response of the tower. The structural response information, useful for assessing the tower's condition, led to the present STORMLAMP project to investigate a number of UK GLA rock lighthouses: Les Hanois, Longships, Wolf Rock, Bishop Rock and Eddystone which are managed by Trinity House, Fastnet which is managed by Irish Lights and Dubh Artach which is managed by Northern Lighthouse Board. Condition assessments through dynamic testing of all but Fastnet Lighthouse between June 2016 and October 2017 are described in this paper. Work on Fastnet is reported as part of a different study including detailed numerical and physical modelling [5].

This paper describes an experimental campaign to assess the condition of the lighthouses and provide information to support estimation of the severe loads they experience due to breaking and broken wave impacts. Structural characteristics have been identified as modal parameters via full-scale dynamic testing and linked modal analysis. The parameters, which are the modal frequencies, masses and shapes can support estimation of wave loads from measurements of their structural response through long-term monitoring.

The paper begins with structural descriptions of the lighthouses tested, with a focus on Wolf Rock, for which the most useful historic account is available and which (based on the modal test data) was chosen for long-term monitoring. Next, a relatively detailed description of the first vibration test, of Les Hanois Lighthouse, is presented. Modal test results from the set of lighthouses are summarised, pointing to effects on dynamics of imperfect symmetry and the retrofitted helidecks. These effects are then investigated using simple mathematical simulations related to the experimental data. Finally, a snapshot of monitoring data from Wolf Rock during Winter 2017/2018 is presented and interpreted, based on the modal test data, providing initial direct estimates of impulsive wave loads.

2. Description and structural details of the lighthouses

Details on location, construction and testing of the six lighthouses are given in Table 1. Five helideck-equipped lighthouses are studied along with one example with no helideck, Fig. 1.

There are various sources of information available on the construction of these lighthouses including numerous internet sites, drawings and other materials archived by the UK GLAs, and popular books e.g. Ref. [6]. Primary sources are relatively rare and include papers presented at the Institution of Civil Engineers [7–9] describing construction of Eddystone, Bishop Rock and Wolf Rock

Table 1
Lighthouse and modal test details.

Lighthouse	Location	Built	Designer	Tower height	Test date
Les Hanois	Guernsey west coast, 49°26′06.2″N 2°42′08.4″W	1860–1862	James Douglass	36 m	2 Jun. 2016
Wolf Rock	15 km west of Land's End, 49°56.72′N 05°48.50′W	1861–1869	James Walker	41 m	18 Jul. 2016
Longships	2 km west of Land's End, 50°4′00.69″N 5°44′48.39″W	1869–1875	James Douglass	35 m	23 Aug. 2016
Bishop Rock	South west of Scilly Isles, 49°52′22.52″N 06°26′44.49″W	1851–1858; 1881–1887	James Walker	49 m	26 Sep. 2016
Dubh Artach (no helideck)	West of Oban, 56°07′56.76″N 06°38′4.74″W	1868–1872	Thomas & David Stevenson	33 m	8–9 May 2017
Eddystone	21 km south west of Plymouth, 50°10′48″N 4°15′54″W	1879–1882	James Douglass	49 m	10–11 Oct. 2017