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Footbridge system identification using wireless inertial measurement units for force and response measurements

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ABSTRACT

With the main focus on safety, design of structures for vibration serviceability is often overlooked or mismanaged, resulting in some high profile structures failing publicly to perform adequately under human dynamic loading due to walking, running or jumping. A standard tool to inform better design, prove fitness for purpose before entering service and design retrofits is modal testing, a procedure that typically involves acceleration measurements using an array of wired sensors and force generation using a mechanical shaker. A critical but often overlooked aspect is using input (force) to output (response) relationships to enable estimation of modal mass, which is a key parameter directly controlling vibration levels in service.

This paper describes the use of wireless inertial measurement units (IMUs), designed for biomechanics motion capture applications, for the modal testing of a 109 m footbridge. IMUs were first used for an output-only vibration survey to identify mode frequencies, shapes and damping ratios, then for simultaneous measurement of body accelerations of a human subject jumping to excite specific vibrations modes and build up bridge deck accelerations at the jumping location. Using the mode shapes and the vertical acceleration data from a suitable body landmark scaled by body mass, thus providing jumping force data, it was possible to create frequency response functions and estimate modal masses.

The modal mass estimates for this bridge were checked against estimates obtained using an instrumented hammer and known mass distributions, showing consistency among the experimental estimates. Finally, the method was used in an applied research application on a short span footbridge where the benefits of logistical and operational simplicity afforded by the highly portable and easy to use IMUs proved extremely useful for an efficient evaluation of vibration serviceability, including estimation of modal masses.

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1. Introduction and objectives

With the main focus on safety, design of structures for vibration serviceability is often overlooked or mismanaged, resulting in some classic and public failures [1,2] to perform adequately under human dynamic loads due to walking, running or jumping.

Designing for, assessing and improving vibration serviceability of footbridges for human dynamic loading requires reliable estimates of modal parameters, which may be obtained from numerical simulation (finite element modelling) or from full-scale testing (modal testing and system identification). In either case the ensuing performance simulations will assume bridge behaviour in the linear range so that modal responses can be treated individually and then summed directly in either time or frequency domain.

The numerical modelling route is the only option for a footbridge yet to be built, but for a structure being retrofitted (e.g. with a tuned mass damper) or that has been completed but not yet opened to the public, the most reliable values of modal parameters are recovered by in-situ testing. This approach was adopted for vibration serviceability assessment of Singapore's Helix Bridge [3] where modal parameters from a full-scale test using a pair of shakers and an array of wired accelerometers were used to create a modal model. In-house simulation software was then used to simulate and assess response in line with relevant guidance.

The Helix Bridge modal test was a major exercise involving costly air-freighting of 125 kg of sensors and cabling and loan of two heavy shakers from 1st author's local contacts. Considering the logistical complexity of the testing exercise and the comprehensive level of performance data provided begs the question: what is the logistically simplest testing programme that can be used to provide just enough information for required performance assessment?

Hence the objective of the research described here was to evaluate:

1) The capability of lightweight portable wireless MEMS accelerometers for synchronous acceleration measurements at multiple locations on a footbridge of sufficient quality for reliable operational modal analysis;
2) The capability of the same sensors to allow indirect estimation of ground reaction forces (GRFs) during jumping, as a means of exciting response in specific footbridge vibration modes;
3) The feasibility of using the GRF (input) and footbridge acceleration (output) as a low cost method to generate frequency response functions of sufficient quality to recover all modal parameters including modal mass.

The study considers only vertical vibration modes and does not directly address human-structure interaction. Two footbridges are chosen for the study, but as the objectives are purely to demonstrate capability for full modal parameter identification, neither their serviceability nor features of their dynamic behaviour or any human-structure interaction are discussed. However, it is believed the methodology opens up new possibilities for such studies through in-situ field testing.

1.1. Modal testing of footbridges

A variety of modal testing methods are available for footbridges and there is extensive literature [4–7] on case studies primarily relating to vibration serviceability for both vertical and lateral vibrations.

Footbridges, particularly those requiring investigation are often lightweight, their natural frequencies tend to be below 5 Hz and damping ratios can be below 1 percent. As such, they can be very lively under the exact type of loading for which they are designed.

For a ‘well behaved’ footbridge acting as a simply supported beam and having well separated modes with shapes resembling sine waves, identification of natural frequencies and damping ratios can be very simple: a single accelerometer and a time domain system identification procedures such as the logarithmic decrement method. For more complex structures with closely spaced vibration modes and irregular mode shapes more elaborate instrumentation involving large numbers of measurement points and sensors along with sophisticated system identification procedures including operational modal analysis are needed [7,8].

1.2. Estimating modal mass

The requirement for a measurable and controllable mechanical excitation and difficulties with accurate estimation mean that modal mass is seldom reported from footbridge modal tests. However, if the modal test data are to be used via a modal model to simulate in-service performance and develop vibration mitigation strategies including retrofit, a reliable modal mass estimate is vital. Direct experimental estimation of modal mass requires in-situ measurement of excitation forces, applied via an instrumented hammer [7], drop-weight [7] or shaker [3]. These devices have practical limitations; instrumented hammers are highly portable and need only battery power, but testing requires careful adjustment of signal to noise ratios to avoid overloading (nearby) sensors while sharing enough energy among all the modes engaged by a single impulse. A well-designed drop-weight with deceleration pulse shaped to focus force in the low frequency range should perform better than a hammer but is far less portable. Shaker testing is the ideal solution but shakers are expensive, heavy, and require powerful electrical supplies and synchronised signal generation.