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FULL-SCALE IDENTIFICATION OF MODAL AND AEROELASTIC PARAMETERS OF THE CLIFTON SUSPENSION BRIDGE

Nikolaos Nikitas*, Jasna B. Jakobsen† and John H. G. Macdonald*

*Department of Civil Engineering
University of Bristol, University Walk, BS8 1TR, Bristol, UK
e-mails: N.Nikitas@bristol.ac.uk, John.Macdonald@bristol.ac.uk

†Department of Mechanical and Structural Engineering and Material Science
University of Stavanger, N-4036, Stavanger, Norway
e-mail: jasna.b.jakobsen@uis.no

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ABSTRACT: Large-scale engineering structures subjected to severe wind loadings, inherently suffer modelling assumptions and uncertainties that can ultimately be validated in a full-scale testing process. Consequently full-scale analysis methods are important especially for existing structures where revised designing trends are not taken into consideration. To this end we utilize a combination of conventional frequency based methods (for modal parameter extraction) together with a more elaborate stochastic identification technique (to retrieve flutter derivatives) for use with ambient vibration data collected in a testing series of the vibration response of the Clifton Suspension Bridge. The outcome of this analysis provides constructive insight on the bridge behaviour and proves the soundness of identification attempts with full-scale data, where randomness of wind excitation can raise validity issues.

1 INTRODUCTION

For full-scale structures such as bridges the most rational way to proceed with predictions on the reliability and operational safety include identification methods from response measurements only. For the current paper relating to the Clifton Suspension Bridge, shown in Fig.(1), we use the wind condition and bridge response recordings of a period of four months, from July 2003 to August 2003 (see [1]) and from December 2003 to March 2004. This included several periods of strong winds, and good ranges of wind speeds and directions. Nine servo-accelerometers and two ultrasonic anemometers were positioned along the bridge. The aims of this study were to determine i) the variation of modal characteristics with wind velocity ii) the effects of wind turbulence and vertical component of the wind iii) details of any large amplitude or other abnormal responses of the bridge. We herein use modal parameter estimates from a frequency based technique (for details on the procedure see [2]) together with a stochastic identification technique especially modified to extract flutter derivatives, as described in [3]. Results are comparatively assessed and practical information on the sensitivity of each method is given.

2 WIND CHARACTERISTICS

The stronger winds occurred along the gorge, presumably due to funnelling of the wind. The maximum 1hour average wind speed recorded, averaged between the two anemometers, was 15.3m/sec. There was a strong dependence of the wind turbulence intensity on wind direction and a weaker one of turbulence on wind speed. Wind spectra appeared as typical 1/f noise with a power exponent -5/3, a value consistent with any robust turbulence model.

Figure 1. Picture of Clifton Suspension bridge.

3 MODAL PARAMETERS

Modal parameters were calculated from the acceleration Power Spectral Densities (PSDs) using the Iterative Windowed Curve-fitting Method [4], specifically developed for the analysis of ambient vibration data since it allows for any specified loading spectrum. Measurements were only taken on the suspended bridge deck, but all modes inevitably involve vibrations of other parts of the structure, particularly the chains. Analysis was performed for frequencies up to 3Hz with twelve vertical, eleven torsional and four lateral modes being identified in this range.

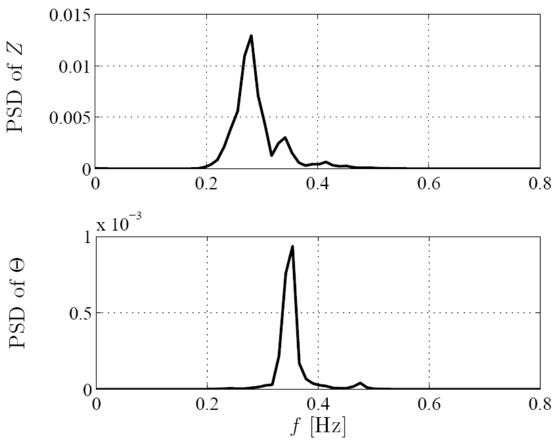

Figure 2: PSDs of filtered data for first vertical and torsional modes. The coupling action is evident in the vertical PSD for a wind speed of around 16m/sec.

The most interesting finding comprises of the close first pairs of vertical and torsional modes which seem to couple in a potentially incipient flutter motion. In Fig.2 response was filtered to only include motion of the first two modes and the peak in the vertical PSD just over the torsional frequency is a strong evidence of a coupling action. It is also worth noting that the next pair of modes showed an equal tendency for coupling action due to the close shape relevance and the close to unity frequency ratio.

4 FLUTTER DERIVATIVES

According to the semi-empirical Selberg [5] equation for flat panels:

$$\frac{U_{\mathrm{F}}}{f_{\theta 0}B} = C\sqrt{\frac{r_{\mathrm{g}}m}{\rho B^{3}}[1-(\frac{f_{z0}}{f_{\theta 0}})^{2}]} \quad ,^{1} \qquad (1)$$

the flutter onset speed is estimated around 15m/sec due to the close neighbourhood of coherent vertical and torsional modes. Such an estimation is threatening for the structural integrity of the historic bridge since it is within the operational range of wind speeds sustained in the area.

For evaluating the flutter behaviour we adopt the classical 2D formulation of Scanlan and Tomko [6] where aeroelastic forces are taken as a linear combination of the modal displacements and velocities appropriately multiplied with the flutter derivatives. Further we take on the preposition of small damping, thus setting the flutter derivatives to be only functions of the reduced velocity. Consequently we can assemble a state space formulation of the problem and use the Covariance Block Hankel Matrix Method initially applied by Hoen et al. [7] for modal identification of offshore platforms and later modified by Jakobsen [3] to be used in the estimation of flutter derivatives, to obtain approximations of the evolution of flutter attributes. The method is founded on the decomposition of a Hankel matrix built up by covariance estimates and assumes a white noise loading to recover the random loading process of wind excitation. Appropriate filtering can be used to reduce artefacts deduced by the colouring of the real wind spectra.

For the current treatise deviations of flutter derivatives from the expected zero values for no wind conditions (see Fig.(3)) should be attributed mainly to lack of precise estimates of structural damping and stiffness and to the distorting action of traffic on the response for low wind speeds. A sensitivity analysis on the measured wind characteristics, such as the turbulence and the mean wind direction, proved not to impose any considerable effect on the outcome. From the results there is clear evidence that the bridge is not susceptible to a so called “damping-driven flutter” (for definition of the term see Ref.[8]), which was the actual reason for the famous Tacoma Narrows Bridge collapse. In any case the wind speeds sustained during the testing period (maximum of 16m/sec) seems not to be critical for the bridge and for any additional quantitative considerations data inclusive of higher wind speeds should be considered.

5 CONCLUSIONS

Observed full-scale response of the Clifton Suspension Bridge was analyzed and flutter derivatives were extracted using an elaborate stochastic identification method. Results were key for further understanding the bridge behaviour but what should be even more decisive out of this analysis is the evidence that ambient vibration identification techniques can yield sensible results for real-scaled structures although such a task may seem formidable. The Covariance Block Hankel Matrix Method was tested for a range of different record and Hankel matrix lengths. Thus it allowed a valuable insight, which can be used in further assessments of monitoring potentially problematic large engineering structures.

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[1] U_{F}= flutter speed, B= deck width, r_{g}= radius of gyration, m= deck mass per unit length, C= constant depending on the mode shape similarity, ρ= air density, f_{z0} and $f_{\theta 0}$ =still air vertical and torsional frequencies.

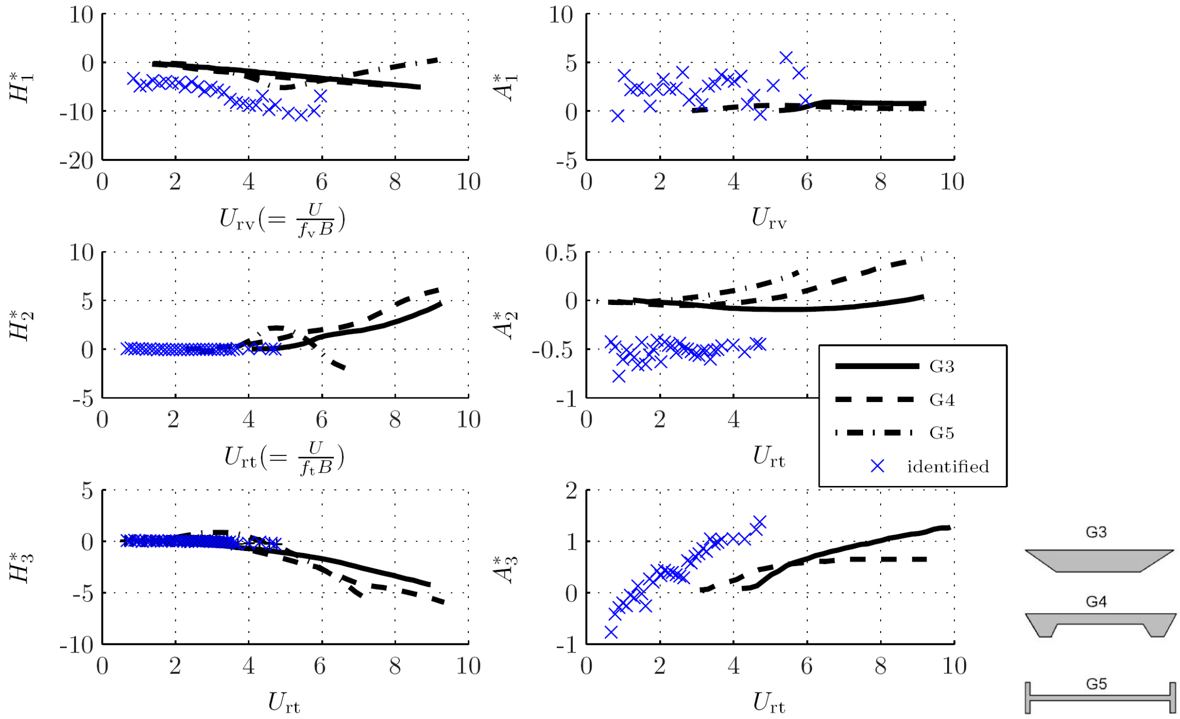

Figure 3: Flutter derivatives of Clifton Suspension Bridge from full scale data, compared with wind tunnel extracted flutter derivatives for various cross sections (after Scanlan and Tomko [6]). Where a line is not given the corresponding flutter derivative is negligible. Identified values correspond to averaged identified values.

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