Engineering Structures 156 (2018) 284–293

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Flutter derivatives from free decay tests of a rectangular B/D = 10 section estimated by optimized system identification methods

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ARTICLE INFO

Keywords:
Torsional flutter
Coupled flutter
Flutter derivatives
Free vibration
System identification
Aeroelasticity

ABSTRACT

The present paper suggests a hybrid system identification method to estimate the flutter derivatives from coupled free vibration tests. An optimized covariance-based method is used as the initial guess in the modified unifying least squares method. This combination optimizes the accuracy described by the coefficients of determinations between measured and synthesized signals. Flutter derivatives are identified at high wind speeds, close to and even above the critical flutter wind speed. Results for a sharp-edged rectangular section with a width-to-depth ratio $B/D = 10$ are presented for two different torsional-to-vertical frequency ratios. In one case the torsional frequency are lower than the vertical, due to a high mass moment of inertia, which makes it possible to estimate the flutter derivatives at very high reduced wind speeds. This reveals that the torsional aerodynamic damping derivative A_2^* reaches a positive maximum followed by a continuous decreasing tendency and eventually negative A_2^* values are identified. This implies that torsional flutter for the $B/D = 10$ section can be avoided if the structural damping is designed to balance the negative torsional aerodynamic damping expressed by the positive peak value for A_2^*.

1. Introduction

The objective of the present work is to describe the self-excited forces, also known as the motion induced or unsteady aerodynamic forces, of a sharp-edged rectangular section with a width-to-depth ratio, $B/D = 10$. The self-excited forces are usually expressed by a parametric representation of the flutter derivatives (FD's), A_i^* and H_i^* ($i = 1,2,3,4$). These are defined as functions of the reduced wind speed, $U/(\omega B)$, where B is the bridge deck width, U is the mean wind speed and $\omega = 2\pi f$ is the circular frequency of motion. It is the aim of the present work to estimate, evaluate and enhance the accuracy and precision of the flutter derivatives estimated from coupled free vibration tests.

The $B/D = 10$ section is known to be prone to single degree of freedom torsional flutter [20] because of positive A_2^* values, which indicate negative aerodynamic damping for the torsional degree of freedom. However, negative A_2^* values have been estimated for the same section by free vibration tests with low amplitudes [21] and recent results for coupled free vibration tests with larger amplitudes [2] showed that both torsional and coupled flutter were avoided when the torsional natural frequency in still air, $\omega_\alpha = 2\pi f_\alpha$, was lower than the vertical, $\omega_h = 2\pi f_h$. The latter indicates that A_2^* is close to zero or even negative at higher reduced wind speeds.

The FD's estimated by system identification methods of wind tunnel tests, which can be either forced motion or free vibration tests, express the damping and stiffness in the fluid-structure system. Since the motion of a real bridge is complex and may have a broadbanded response spectrum, both forced motion tests and coupled free decay tests relies on the principle of superposition of aeroelastic forces. If the principle of superposition holds, the flutter derivatives should be independent of the motion. This implies that the FD's estimated by forced motion and free decay tests should be identical.

It is often assumed that the FD's depends mainly on the geometry of the bridge cross section, see e.g. [11,25,33]. Amplitude of motion and wind turbulence can however possibly influence the FD's [23,29]. Even small discrepancies in the estimated FD's may cause large differences in the calculated critical flutter wind speed [18,26]. The accuracy of the experimental models and the flutter derivatives estimated by system identification methods are therefore of crucial importance.

1.1. Free vibration system identification methods

Scanlan and Tomko estimated the flutter derivatives, by free

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https://doi.org/10.1016/j.engstruct.2017.11.059
Received 21 March 2017; Received in revised form 20 November 2017; Accepted 22 November 2017
0141-0296/

vibration tests in [28]. First, two single degree of freedom (SDOF) free decays were used to estimate the 'direct' derivatives (H_1^*,A_2^*,A_3^*) and then a coupled two degree of freedom (2DOF) free decay was used to estimate A_1^*,H_2^* and H_3^*. Their pioneering work relied on the principle of superposition of the aeroelastic forces and that $H_4^* = A_4^* = 0$. Ibrahim and Mikulcik [12] introduced a MDOF time-domain method known as the Ibrahim time-domain method (ITD) where a multi degree of freedom state space representation of a structure was estimated by using only a single free decay test where the response of several degrees of freedom were measured simultaneously. Sarkar and Scanlan [27] developed a modified Ibrahim time-domain method (MITD) where the original ITD was used as the starting point in an iteration procedure aiming to improve the damping estimate given by ITD. This method allowed the simultaneously estimation of 8 FD's, H_i^* and A_i^* (i = 1–4), by a single free decay test.

Poulsen et al. [25] estimated the flutter derivatives for the Great Belt Bridge by minimizing the residual sum of squares between the measured coupled free vibrations and the response predicted by the estimated model parameters based on Newton-Raphson iterations. Different torsional-to-vertical frequency ratios ranging from $\gamma_\omega = 1.4$ to $\gamma_\omega = 3.4$ were tested for this section and no frequency ratio dependency was observed. Each test was repeated 10 times in order to minimize the statistical uncertainty. Gu et al. minimized the residual sum of squares in the unifying least squares (ULS) method where an unified error function for the vertical and torsional degree of freedom was introduced. The initial estimate was given by the MITD [27] method [10]. The ULS method was used to show that the still air mechanical properties had *almost* no effect on the estimated FD's in a parametric study of the streamlined Jiangyn Bridge in [11].

Li et al. introduced weighting factors to the ULS method aiming to scale the vertical and torsional signals to have the same root mean square value [17]. The iterative procedure used in the ULS method was enhanced in the modified unifying least squares (MULS) method by Bartoli et al. [3]. A variation of the MULS method is the improved stochastic search algorithm by Xu et al. [34] which uses random variation of the modal parameter in the iterative scheme.

Juang and Pappa [16] developed the Eigensystem Realization Algorithm (ERA), where the measured time-domain free responses are organized in a general block-Hankel matrix and a time-shifted block-Hankel matrix. The singular values and singular vectors of the general block-Hankel matrix are used to estimate the model parameters. Since the theoretical auto-covariance functions of the response of a white noise excited linear structure are identical to a theoretical free decay of the same structure, the covariance functions of random response measurements can be used within the classic ERA algorithm. This is utilized in the covariance block-Hankel matrix (CBHM) method [4,13,14] and in the covariance driven stochastic subspace identification (COV-SSI) method [9].

It was shown by Jakobsen [13] that the theoretical auto covariance function of a SDOF free decay is identical to the free decay itself. Thus, it is also possible to use the covariance driven methods to estimate the FD's from coupled free decay tests, which will be used as the initial estimate for the MULS method in the present work. However, it is well known that the covariance driven methods are sensitive to the number of points (i.e. discrete time lag values) used from the estimated covariance functions [4,9]. Therefore, in the present work, the model parameters are estimated using several different number of time lags, where the accuracy is evaluated for each.

In addition to the wind tunnel techniques discussed in the present paper, it is also possible to use computational fluid dynamics to estimate bridge deck flutter derivatives. Numerical simulation of the free vibration method are conducted in [32].

1.2. Torsional flutter

The rectangular section with a width-to-depth ratio, $B/D = 10$, is known to have hybrid flutter properties [21] because both coupled flutter and torsional flutter can be observed. In [21] it was shown by free vibration tests, that A_2^* was negative for small angular vibration amplitudes and positive for larger. These results have not received much attention in the literature [5,6,20,22,26] where several references instead are given to later works [20,22]. In [20,22], the estimated FD's for the $B/D = 10$ section are obtained by SDOF harmonic forced motion tests and simultaneous pressure measurements. Based hereon it is suggested, generally, that torsional flutter instability occurs for rectangular sharp-edged sections with $B/D \leqslant 10$ while coupled flutter occurs if $B/D \geqslant 12.5$. This is not in agreement with [21] and was not confirmed for the $B/D = 10$ section recently published in [2]. Because of the contradictory results for A_2^* in the past, this issue needs to be investigated in more detail.

1.3. Present paper

The present paper is organized as follows. Wind tunnel free vibration tests and procedures are described in Section 2. In Section 3, the equations of motion for free decay tests are defined. A validation method, based on the R^2 coefficients of determination, is introduced in Section 4 in order to evaluate the estimated model parameters. The most accurate modal parameters estimated by an iterative variation of CBHM method [4,13,14] where the number of time lags is optimized are used as the initial estimate for the MULS method [3]. The influence of measurement time, number of time lags and accuracy of the initial estimate on the final accuracy of the MULS estimates are described in Section 4.3. It is shown that the flutter derivatives can be estimated after the onset of flutter by the present combination of the CBHM and MULS method. In Section 5, the estimated flutter derivatives are presented and compared with results known from the literature. Furthermore, the influence of static rotations and the pitching motion amplitude on the flutter derivatives are investigated. The estimated FD's presented in Section 5 are used in an iterative mode by mode flutter analysis presented in Section 6.

2. Wind tunnel tests

The spring suspended section model shown in Fig. 1 was subjected to free decay tests in the wind tunnel at Svend Ole Hansen Aps in Copenhagen, Denmark. Initial vertical and torsional conditions were obtained by using an electromagnetic release system. The length, width and depth of the section were $L = 1.7$ m, $B = 0.24$ m and $D = 0.024$ m respectively. Drag wires were used to restrain the lateral degree of freedom during the tests. The static angle of rotation of the section was set as close to zero as possible by using a digital inclinometer on the section model before the free decay tests were conducted. At each wind speed, five free decay tests were conducted and the response was measured in 120 s with a sampling rate of $f_s = 500$ Hz. The initial torsional displacement in the free decays was $\alpha_0 \approx 4.8°$ deg while the vertical initial conditions were $h_0 \approx -43$ and -51 mm for series 1A and 1G respectively. More details about the tests are available in [2]. The

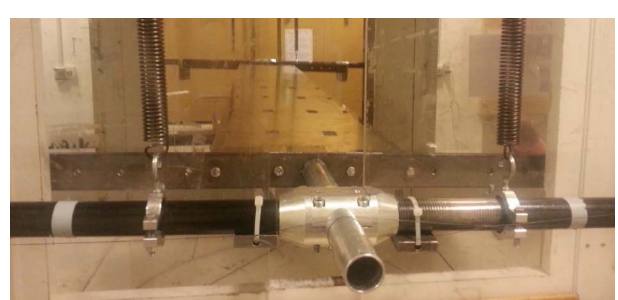

Fig. 1. The rectangular $B/D = 10$ section in the wind tunnel. From [15].