Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 00 (2017) 000–000

Procedia Engineering

www.elsevier.com/locate/procedia

X International Conference on Structural Dynamics, EURODYN 2017

On the importance of cross-sectional details in the wind tunnel testing of bridge deck section models

Bartosz Siedziako*, Ole Øiseth

Department of Structural Engineering, Norwegian University of Science and Technology, Richard Birkelands vei 1A, 7491 Trondheim, Norway

Abstract

Experimentally derived aerodynamic derivatives are used to predict and prevent undesirable aeroelastic behavior of bridges and are currently considered indispensable in the design of long-span bridges. The aerodynamic derivatives are functions of the reduced frequency of motion and depend strongly on the shape of the cross-section. Therefore, the experimental results are sensitive to the degree of detail of the section model of the bridge deck, the precise modelling of the bridge railings and the testing method applied. This paper investigates how differences in the aerodynamic derivatives caused by the listed factors influence the buffeting response and critical flutter speed of a long-span suspension bridge.

Keywords: Flutter; Buffeting; Section model tests; Forced vibration; Free vibration; Bridge details

1. Introduction

Flutter and buffeting responses are crucial concerns when designing long-span bridges. The aerodynamic properties of the bridge deck play an essential role in the analysis of these phenomena. The concept of aerodynamic derivatives (ADs) introduced by Scanlan and Tomko [1] to describe the aerodynamic performance of the cross-section of a bridge was widely appreciated and extensively used in the field of bridge aerodynamics. ADs are most commonly identified experimentally by wind tunnel tests of section models using one of the two available methods. In the free vibration method, the bridge deck is suspended on springs, while the bridge is forced into a prescribed oscillatory motion in the forced vibration tests. However, section models of the bridge decks for wind tunnel testing can be modelled with only limited precision. This is due to the limitations of the equipment available for the model

* Corresponding author. Tel.: (+47) 73594541; fax: (+47) 73594701.
E-mail address: bartosz.siedziako@ntnu.no

1877-7058

production, possible issues related to the flow around the fine details that are sensitive to the Reynolds number or even a lack of knowledge of the final shape of the fine details such as bridge railings in the early design phase. It has been shown that even small changes in the modelling of the bridge deck details can have a great impact on the ADs since they might significantly influence the flow around the section [2]. This paper addresses how the degree of detailing of the cross-section geometry, the bridge deck details, the testing method and also the wind tunnel applied can influence the estimation of the ADs and consequently prediction of the buffeting response and stability limit of long-span bridges.

2. Wind tunnel testing

A cross-section of the Hardanger Bridge, which is currently the longest suspension bridge in Norway, is investigated in this study. The aerodynamic performance of its deck was studied by section model tests during the design of the bridge using the buffeting free vibration method [3], [4] and recently using the recently developed forced vibration rig [5], [6]. The geometry of the models used in the tests considered in this paper is compared to that of the actual bridge deck in Fig. 1, and more properties are presented in Table 1.

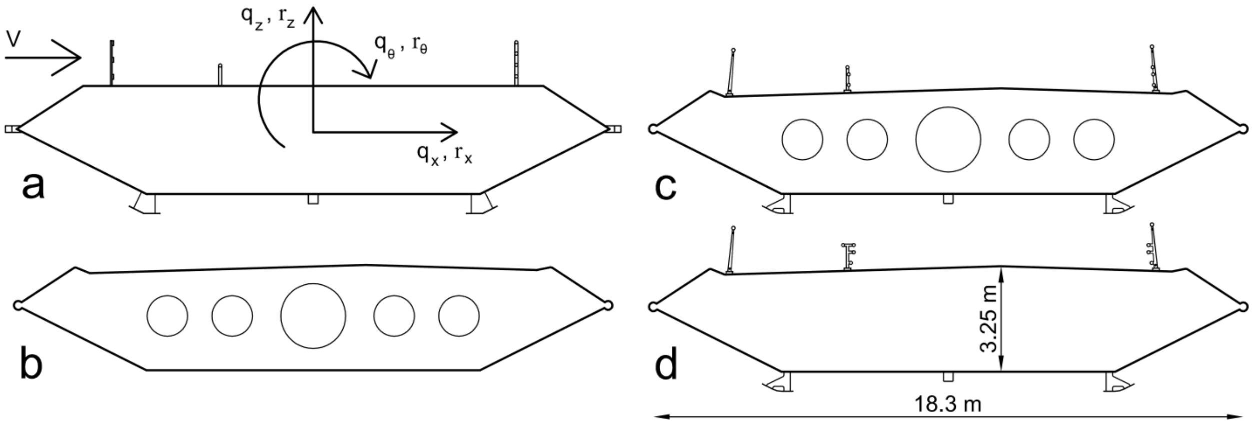

Fig. 1. Cross-sections tested with (a) free v. method (detailed), (b) forced v. (no details), (c) forced v. (detailed) and (d) the true geometry.

Table 1. Comparison of the section models used in free and forced vibration tests.

Section model	Mass [kg]	Length [m]	Scale	Production method	Bridge details	Range of reduced velocities - V_{red} covered by the data
Free vibration	7.72	1.7	1:50	Built up as a shell with lightweight filler	Handmade based on the initial design	0.75-2.48 (hor. motion) 0.54-2.07 (torsional) 1.37-4.33 (vertical)
Forced vibration	5.45	2.68	1:50	Milled	3D printed based on a prototype	0.69-10.43

It can be seen that the geometry of the bridge deck for the section model used in the free vibration tests is slightly simplified compared to the real geometry. This is also the case for the railings. The model used in the forced vibration tests was made after the bridge was complete, eliminating the uncertainties related to the final geometry. The production process also allowed the accurate reproduction of all the bridge deck curves, road inclinations and bridge details, since the bridge deck was milled and the details were 3D printed. Some changes to the railings and guide vanes were necessary to avoid Reynolds number scaling issues and to make the printed details robust enough. Although all the aerodynamic derivatives presented in Fig. 2 were identified at a zero angle of attack, it must be noted that the laboratory conditions and testing technique may have an influence on the final result [7]. This influence is, however, considered to be rather small for streamlined sections, making the differences in geometry the main source of the discrepancies observed in this paper.

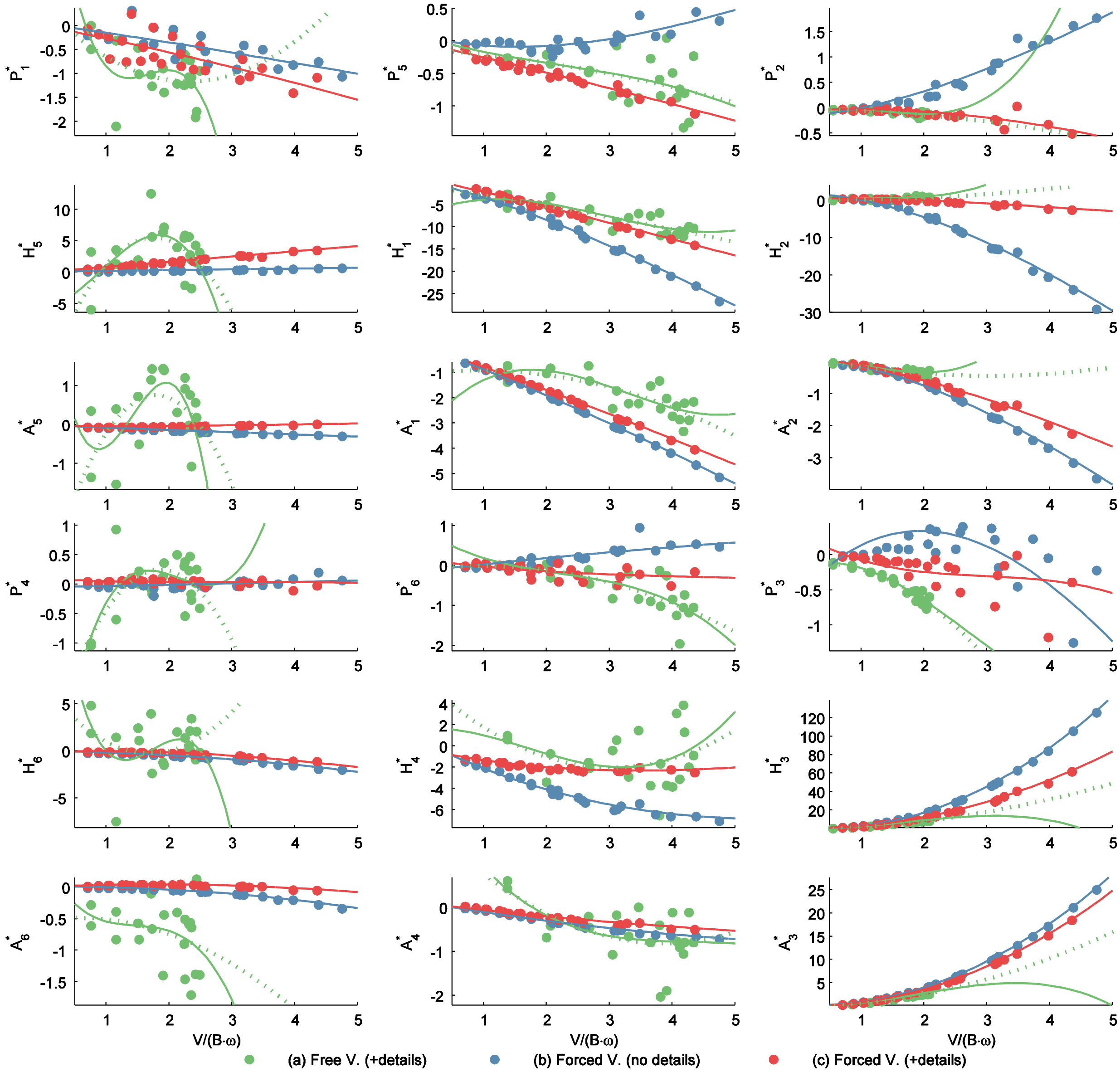

Fig. 2. Comparison of aerodynamic derivatives related to velocities and displacements for sections (a), (b) and (c). Solid and dotted lines represent, respectively, 3rd- and 2nd-order polynomial fits to the data.

3. Flutter analysis

Flutter analysis was carried out with the most advanced frequency domain method for estimating the critical wind speed known as the multi-mode technique, where many still-air vibration modes can participate in the flutter motion. The stability limit is defined at the mean wind velocity when one of the eigenvalues of the system has a zero real part corresponding to zero damping. This implies that the flutter stability limit of the combined structure and flow system can be assessed by the characteristic equation [8]–[12]:

$$(\lambda^2\mathbf{M}_0 + \lambda\left(\mathbf{C}_0 - \mathbf{C}_{ae}(V,\omega)\right) + \left(\mathbf{K}_0 - \mathbf{K}_{ae}(V,\omega)\right))\{\phi\} = \{0\} \tag{1}$$

Here, λ and ϕ represent the complex eigenvalues and eigenvectors of the combined structure-flow system, while $\mathbf{M_0}$, $\mathbf{C_0}$ and $\mathbf{K_0}$ symbolize the generalized still air mass, damping and stiffness matrices, respectively, and the generalized aerodynamic stiffness and damping matrices are denoted as $\mathbf{K_{ae}}$ and $\mathbf{C_{ae}}$. The generalized still-air properties have been obtained from an Abaqus model of the Hardanger Bridge, while the elements of the modal aerodynamic stiffness and damping matrices have been calculated using the ADs in Fig. 2; see [13] for details.
Since the aerodynamic derivatives are functions of the frequency of motion and thus the imaginary part of the eigenvalues, Eq. (1) is solved iteratively [9]. The study presented by Øiseth et al. [13] showed that three still-air modes provide the main contributions to the flutter motion. The first two horizontal, first three vertical and first torsional modes have therefore been used to calculate the critical flutter wind speed in this study. A probabilistic approach is used when calculating the critical speed where uncertainties in the input variables can be taken into account. Canor et al. [14] compared and reviewed different existing numerical approaches that can be applied along with eigenvalue analysis to assess bridge flutter probability Another researches [15] investigated the effects of various parameters on the flutter reliability of suspension bridges. Based on that work, it can be deducted that the vast majority of the variability in the estimated flutter speed can be captured by modeling uncertainties in the modal damping ratios and flutter derivatives. Therefore, the damping ratio for all 6 selected modes is assumed to be lognormally distributed with a coefficient of variation of 0.4 [16], and a mean value of 0.5%, while the aerodynamic derivatives are modelled as 2nd-order polynomials fitted to the data presented in Fig. 2. The variation in the ADs is modelled using the expected values, and the covariance matrix of the coefficients obtained by curve fitting the experimental data; see [17] and Fig. 3 for further details.

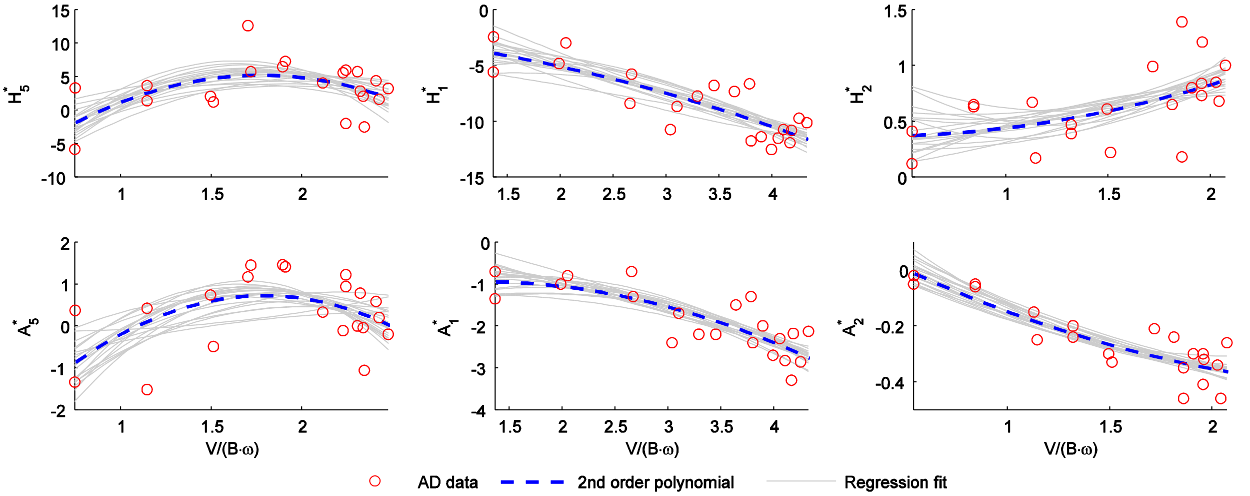

Fig. 3. An example of regression analysis on the free vibration data. Solid lines show 20 realizations of 2nd-order polynomials used in the Monte Carlo simulations, while dashed lines present a most likely least squares fits to the data represented by the circles.

Calculations are performed using Monte Carlo simulations, commonly applied technique in the probabilistic approach to the estimation of the critical flutter speed [11], [12], using a sample size of 10000 what allowed to evaluate accurately the tails of the output distributions. To assess the effect of the damping variability on the distribution of the flutter speeds, calculations were performed two times considering deterministic and lognormally distributed damping. In the second case, it is assumed that the variables are independent. Fig. 4 shows the obtained probability density functions of V_{cr}, and Table 2 summarizes the results.

Table 2. Calculated critical flutter speeds based on the ADs of cross-sections (a), (b), (c) and measured values with the free vibration setup.

Method	(a) - Free V. (detailed)	(b) - Forced V. (no details)	(c) - Forced V. (detailed)	(a) - Measured (detailed)	Measured (no details)
Mean V_{cr} (± 95% confidence intervals) [m/s]	80.93 (±5.48)	61.36 (±2.00)	70.05 (±2.79)	79.5	71.6

It can be seen that there is a significant difference in both the average and the distribution of the flutter speed among the sections. Depending on the chosen set of ADs, the mean V_{cr} differs by up to 19.6 m/s when using data for sections (a) and (b). As expected, the distributions of V_{cr} for sections (b) and (c) that were tested with a forced vibration technique clearly have less variance than (a), since the free vibration data are more scattered. As Fig. 4 shows, the variability in the damping ratio contributes heavily to the total variance of the critical flutter speed for sections (b) and (c), while it is less significant when the ADs are identified from the free vibration data. The measurements of the critical flutter speed with the free vibration setup included in Table 2 show that by including the bridge details, the flutter speed can be increased by 7.9 m/s. Using multi-mode flutter analysis and forced vibration data for sections (b) and (c), V_{cr} increased by 9.1 m/s when details were considered.

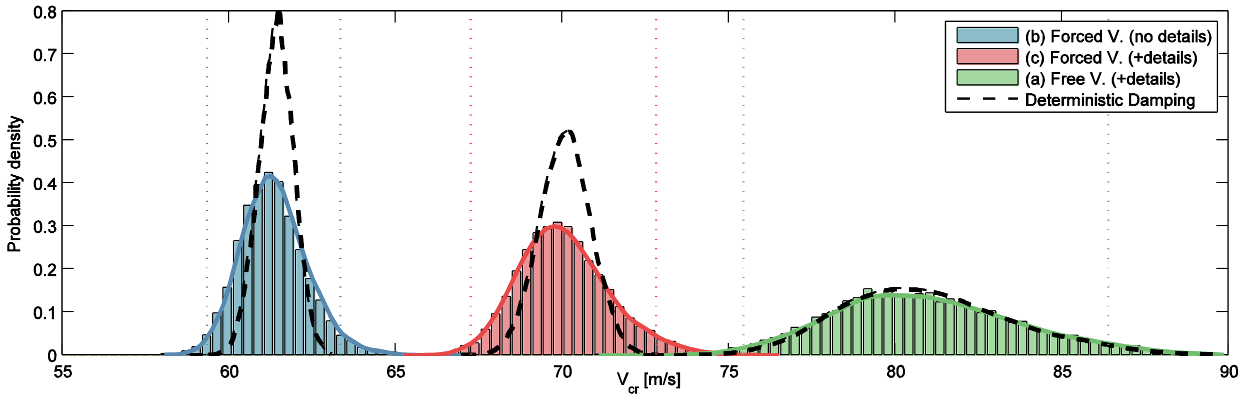

Fig. 4. Distributions of critical flutter speed for sections (a), (b) and (c). Solid and dashed lines present fitted kernel distributions to the obtained results considering deterministic and variable damping respectively, while dotted lines show 95% confidence intervals around the mean values.

4. Buffeting analysis

The influence of the aerodynamic derivatives from sections (a), (b), (c) on the buffeting response of the Hardanger Bridge is evaluated by comparing the standard deviations of the horizontal, vertical and torsional displacements at the mid-span of the bridge obtained by

$$\sigma_{ii}^2(x) = \int_0^\infty \mathbf{S}_{R_{ii}}(\omega, x)\,\mathrm{d}\omega \tag{1}$$

The cross-spectral density matrix of the response is defined as

$$\mathbf{S}_R(\omega, x) = \mathbf{\Phi}(x)[\mathbf{E}_\eta^{-1}(\omega)\mathbf{S}_{Q,Buff}(\omega)\mathbf{E}_\eta^{-1*}(\omega)]\mathbf{\Phi}^T(x) \tag{2}$$

Here, $\mathbf{\Phi}(x)$ is the mode shape matrix containing selected still-air modes, $\mathbf{E}_\eta$ is the impedance matrix, and $\mathbf{S}_{Q,Buff}$ is the cross-spectral density matrix of the generalized wind load, see Øiseth et al. [13] for further details. The first 20 natural modes of the Hardanger Bridge have been used in the analysis. The buffeting response has been calculated for wind speeds in the range from 10 to 50 m/s with a 2.5 m/s interval. The aerodynamic derivatives have been modeled as 3rd-order polynomials for the forced vibration data, while 2nd-order polynomials combined with quasi-steady theory to provide ADs related to the horizontal motion were used for the free vibration data, as they are more scattered and are available in a limited range. The results of the buffeting analysis are presented in Fig. 5.

It can be seen that the standard deviations of the displacements calculated using different sets of ADs agree relatively well, especially for the vertical response, while some dissimilarities appear for the horizontal and torsional directions at higher wind speeds. The largest differences in the buffeting response are caused by a lack of data. Due to the low natural frequency of motion, predicting the buffeting response above V=50 m/s in the horizontal direction requires data at large reduced velocities $V_{red}>8.6$, while ADs at $V_{red}<0.48$ must be available to predict the torsional response below 20 m/s. As a result, the horizontal response based on free vibration data can be realized only using quasi-steady theory. At the same time, the torsional response at lower wind speeds highly depends on the chosen set of ADs, as the data points used in the analysis had to be extrapolated and depend on the fit properties.

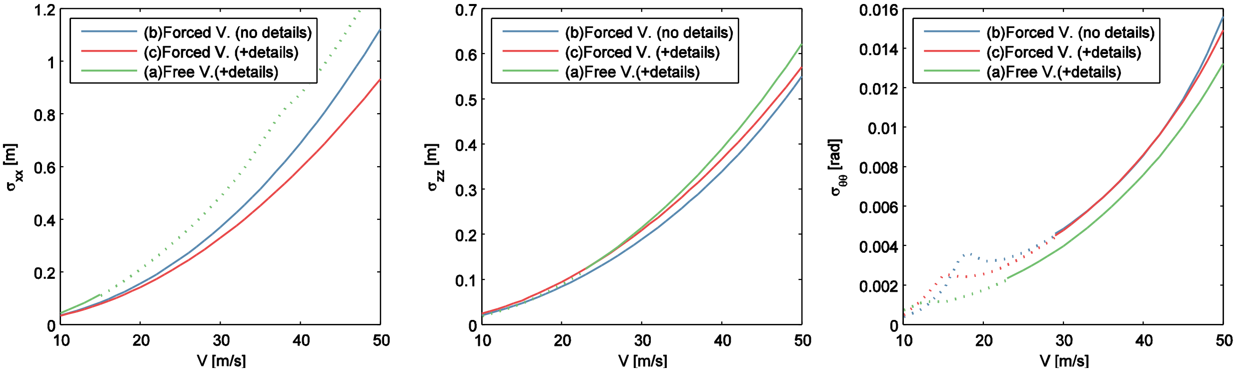

Fig 5. Comparison of the standard deviations of the horizontal, vertical and torsional buffeting responses at the mid-span of the Bridge. Dotted lines indicate range of data where aerodynamic derivatives were not available.

5. Summary

In this paper the effects of differences in the flutter derivatives arising from the degree of detail of the bridge cross-section on the aeroelastic behavior of the Hardanger Bridge have been studied. Multi-mode flutter and buffeting analyses have been performed using both free and forced vibration data. It has been shown that railings, guide vanes, spoilers and small changes in the geometrical shape of the bridge cross-section may have significant influences on the estimation of the critical wind speed, while those factors are less significant for the buffeting response. Therefore, the authors suggest that any cross-sectional change in terms of the initial design should be investigated to assess its impact on the flutter speed. The probabilistic analysis of the critical wind speed performed here shows that by using forced vibration data, the variability in the estimation of the flutter speed was greatly reduced compared to that obtained using the free vibration. It has been showed that introduction of the bridge deck details to the section model of the Hardanger Bridge had a positive effect on the flutter boundary, postponing it by 9.1 m/s. However, it led also to the broader confidence intervals showing that testing complicated geometry can make extracted aerodynamic derivatives more scattered. Finally, it can be concluded that aerodynamic derivatives should be accessible for a very wide range of reduced velocities to perform a full buffeting analysis, as their extrapolation can lead to significant errors.

Acknowledgements

This research was conducted with financial support from the Norwegian Public Roads Administration. The authors gratefully acknowledge this support.

References

[1] R. H. Scanlan and J. Tomko, “Airfoil and bride deck flutter derivaitves,” J. Eng. Mech. Div, vol. 97, 1971, pp. 1717–33.

[2] N. P. Jones, R. H. Scanlan, P. P. Sarkar, and L. Singh, “The effect of section model details on aeroelastic parameters,” J. Wind Eng. Ind. Aerodyn., vol. 54–55, 1995, pp. 45–53.

[3] Svend Ole Hansen ApS, “The Hardanger Bridge. Static and dynamic wind tunnel tests with a section model Prepared for: Norwegian Public Roads Administration Revision 2”, 2009.

[4] J. Bogunović Jakobsen and E. Hjorth-Hansen, “Determination of the aerodynamic derivatives by a system identification method,” J.

Wind Eng. Ind. Aerodyn., vol. 57, 1995, pp. 295–305.

[5] B. Siedziako, O. Øiseth, and A. Rönnquist, “A new setup for section model tests of bridge decks,” Proc. 12th UK Conf. Wind Eng., 2016.

[6] B. Siedziako, O. Øiseth, and A. Rønnquist, “An enhanced forced vibration rig for wind tunnel testing of bridge deck section models in arbitrary motion,” J. Wind Eng. Ind. Aerodyn., vol. 164, 2017, pp. 152–163.

[7] P. P. Sarkar, L. Caracoglia, F. L. Haan, H. Sato, and J. Murakoshi, “Comparative and sensitivity study of flutter derivatives of selected bridge deck sections, Part 1: Analysis of inter-laboratory experimental data,” Eng. Struct., vol. 31, 2009, pp. 158–169.

[8] O. Øiseth, A. Rönnquist, and R. Sigbjörnsson, “Time domain modeling of self-excited aerodynamic forces for cable-supported bridges: A comparative study,” Comput. Struct., vol. 89, 2011, pp. 1306–1322.

[9] Y. J. Ge and H. Tanaka, “Aerodynamic flutter analysis of cable-supported bridges by multi-mode and full-mode approaches,” J. Wind Eng. Ind. Aerodyn., vol. 86, 2000, pp. 123–153.

[10] T. J. A. Agar, “Aerodynamic flutter analysis of suspension bridges by a modal technique,” Eng. Struct., vol. 11, 1989, pp. 75–82.

[11] T. Argentini, A. Pagani, D. Rocchi, and A. Zasso, “Monte Carlo analysis of total damping and flutter speed of a long span bridge: Effects of structural and aerodynamic uncertainties,” J. Wind Eng. Ind. Aerodyn., vol. 128, 2014, pp. 90–104.

[12] S.-D. Kwon, “Uncertainty of bridge flutter velocity measured at wind tunnel tests,” Proc. Fifth Int. Symp. Comput. Wind Eng. (CWE2010), Chapel Hill, 2010.

[13] O. Øiseth, A. Rönnquist, and R. Sigbjörnsson, “Simplified prediction of wind-induced response and stability limit of slender long-span suspension bridges, based on modified quasi-steady theory: A case study,” J. Wind Eng. Ind. Aerodyn., vol. 98, 2010, pp. 730–741.

[14] T. Canor, L. Caracoglia, and V. Denoël, “Application of random eigenvalue analysis to assess bridge flutter probability,” J. Wind Eng. Ind. Aerodyn., vol. 140, 2015, pp. 79–86.

[15] J. Cheng, C. S. Cai, R. C. Xiao, and S. R. Chen, “Flutter reliability analysis of suspension bridges,” J. Wind Eng. Ind. Aerodyn., vol. 93, 2005, pp. 757–775.

[16] A. G. Davenport and G. Larose, “The Structural damping of long span bridges: an interpretation of observations,” Presented at the Canada-Japan Workshop on Bridge Aerodynamics, Ottawa, Canada, 1989.

[17] O. Øiseth, A. Rönnquist, and A. Naess, “System reliability of suspension bridges considering static divergence and flutter,” 12th Int. Conf. Appl. Stat. Probab. Civ. Eng. ICASP, 2015.