ICWE 16
August 27-31, 2023
FLORENCE - ITALY
16th International Conference on Wind Engineering

Reducing the computational cost of forced-motion simulations to obtain flutter derivatives

G. Martínez-López [1,2], M. Péntek [3], S. Warnakulasuriya [4], C. Lázaro [5], K.-U. Bletzinger [6]

[1]Lehrstuhl für Statik, Technische Universtität München, Munich, Germany, guillermo.martinez-lopez@tum.de
[2]Universitat Politècnica de València, Valencia, Spain
[3]Lehrstuhl für Statik, Technische Universtität München, Munich, Germany, mate.pentek@tum.de
[4] Institut für Statik und Dynamik, Technische Universität Braunschweig, Germany, s.warnakulasuriya@tu-braunschweig.de
[5] Dept. of Structural Mechanics, Universitat Politècnica de València, Valencia, Spain, carlafer@mes.upv.es
[6] Lehrstuhl für Statik, Technische Universtität München, Munich, Germany, kub@tum.de

SUMMARY:
We investigate two strategies to reduce the computational cost of forced-motion simulations in obtaining flutter derivatives. First, the multi-frequency approach, consisting of exciting a cross-section at more than one frequency at a time, is analysed in detail. Several LES-type investigations are carried out to determine the limits of this methodology, comparing the results with the classical single-frequency simulations. Second, we explore the possibilities of a URANS-based approach. Both turbulence models are developments in the context of the finite element method. Our strategies are applied to find the flutter derivatives of two cross-sections: a rectangular cylinder with proportions 5:1 and a generic streamlined bridge cross-section. Here we only include an excerpt of the results for the latter shape. The results obtained from the multi-frequency simulations show excellent agreement with the ones obtained through classical means. However, when it comes to decreasing the computational cost, the URANS simulations are considerably more efficient, remaining a viable option for estimating the flutter derivatives. We highlight the possibility of combining these strategies, potentially leading to a computational cost of less than 1% of the original effort.

Keywords: flutter derivatives, CFD, multi-frequency, URANS

1. INTRODUCTION

The critical flutter wind speed of a long-span bridge is usually evaluated through indirect means. First, the flutter derivatives – originally proposed by Scanlan and Tomko (1971) – are obtained, and then the equations of motion are solved to find the divergence point. These derivatives are traditionally extracted from free-vibration or forced-motion experiments, which can be physical or numerical. Unfortunately, the derivatives are a function of the so-called reduced frequency, so multiple tests must be conducted to obtain them, implying a high computational cost.

When using Computational Fluid Dynamics (CFD) simulations, the forced-motion approach is especially suitable since the excitation can be imposed more easily than in a wind tunnel experiment. Several authors have already reduced the computational cost of such a campaign by solving the Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations (Huang & Liao, 2011; Šarkić et al., 2012; Nieto et al., 2015) instead of using Large Eddy Simulation (LES) turbulence modelling or Direct Numerical Simulation (DNS).

As an alternative, some authors concentrated on improving the forced-motion methodology. This document focuses on the multi-frequency approach, first mentioned by Huang & Liao (2011), which consists of exciting the analysed cross-section simultaneously at more than one frequency. That produces aeroelastic forces which can be decomposed into different frequencies, finding several values of a derivative only with one simulation. Other authors further explored this methodology (Xu et al., 2014; Siedziako et al., 2017; Abbas et al., 2020), including exciting different Degrees-Of-Freedom (DOFs) or even imposing non-sinusoidal motions. However, while they provide a sufficient premise for subsequent work, the limits and optimal setup parameters of this approach remain to be mostly unexplored.

In this study, we focus on enhancing the forced-motion methodology by using a multi-frequency approach and solving the URANS equations. The simulations were done with the open-source software Kratos Multiphysics, based on the Finite Element Method (FEM). Our main focus is to investigate the multi-frequency approach, so its limits and optimal setup can be clarified. As a second step, we also aim to consolidate the existing knowledge about URANS simulations, applying it to the FEM context. When combined, these strategies can potentially reduce the required computational effort by a factor of more than 100 when compared to the purely LES-based single-frequency forced-motion approach.

The project is based on a CFD validation campaign for two cross-sections: a rectangular cylinder with proportions 5:1 and a width of 0.25 m, corresponding to the BARC benchmark (Bruno et al., 2014); a bridge streamlined deck with a width of 0.366 m based on the work from Šarkić et al. (2012). Single-frequency forced-motion simulations were carried out using LES-type turbulence modelling, and the results constitute the reference in this document.

2. METHODOLOGY FOR IMPROVED EFFICIENCY

The multi-frequency simulations is carried out with an identical setup to the one of the single-frequency campaign. This approach represents one part of the reduction of computational cost. The Reynolds number is $Re = 5 \cdot 10^4$, taking the height of the cross-section as a reference. The total domain size has a width, height, and length of $3B$, $16B$, and $32B$, with B as the width of the cross-section. After a mesh convergence study, the smallest element size leads to $B/125$, and to the time step $\Delta t = 4 \cdot 10^{-4} B$ s. The frequency of the motion depends on the value of the reduced wind speed U_{red}. The decks are excited with two frequencies at a time, leading to the reduced wind speed pairs of 1-4, 2-6, 6-15 and 10-20. Two variations are presented in the current abstract: one, where a single DOF is excited with both frequencies; the other, where each frequency is applied to a different DOF (heave or pitch).

URANS simulations imply the same mesh and domain sizing as the ones previously explained, with the difference of the domain being two-dimensional. Such an approach to solving the flow represents another viable option for increased efficiency, as it leads to a substantial reduction in computational cost. We include results from single-frequency simulations, found using the k-ω SST turbulence model and turbulent kinetic energy-based wall functions, part of the work from Katili (2022) at our institute. Further investigations are planned to explore various sets of parameters exploiting the URANS methodology.

3. RESULTS AND DISCUSSION

Fig. 1 shows the flutter derivatives obtained with the different methodologies. Here we include only a selection of the results obtained for the bridge cross-section. Our broader campaign deals with multiple combinations of frequencies, DOFs and turbulence models.

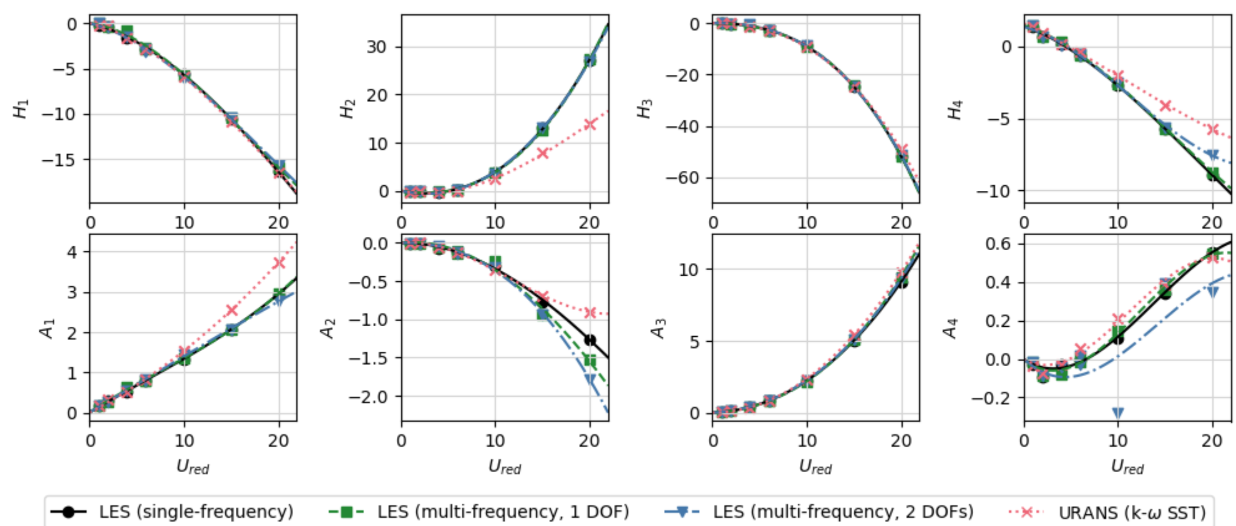

Figure 1. Flutter derivatives for the bridge cross-section obtained with different methodologies, with the notation according to Simiu and Scanlan (1996).

It can be observed that the multi-frequency approach is in excellent agreement with the original derivatives. The only discrepancy worth mentioning appears in the values for A_4^*, where the results from exciting two DOFs simultaneously have an outlier at $U_{red} = 10$. The reason for this remains to be investigated, but the difference might be reduced by increasing the simulation time and potentially improving curve fitting. Typically, the A_4^* derivative does not have the most significant influence when calculating the critical wind speed. Regarding URANS, the results have higher discrepancies, still being within acceptable ranges. Considering the computational cost of each strategy (Table 1), URANS simulations are a viable option.

Table 1. Approximate compute core-hours needed to determine flutter derivatives of the bridge cross-section

Methodology	Nº of sims.	Total cost [core-hours]	CPU
LES (single-frequency)	14	140,000	Intel Xeon Platinum 8174 (3.1 GHz, 33 MB Cache)
LES (multi-frequency, 1 DOF)	8	80,000	
LES (multi-frequency, 2 DOFs)	8	80,000	
URANS (single-frequency)	14	< 1,000	Intel i9-9900 (3.1 GHz, 16 MB Cache)

5. CONCLUSIONS

Our results show the potential for the combined usage of the multi-frequency approach with URANS to calculate the flutter derivatives, also exciting different DOFs. The derivatives obtained from multi-frequency simulations are in very good agreement with the single-frequency version while reducing the computational cost by half. Moreover, more frequencies can be superimposed, further decreasing the effort. Solving the URANS equations to resolve the flow represents another considerable improvement while still providing acceptable results. Both methodologies can be combined to reach an even higher efficiency, providing an excellent alternative for parametric studies and early design stages.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Gauss Centre for Supercomputing e.V. (www.gauss-centre.eu) for funding this project by providing computing time on the GCS Supercomputer SuperMUC-NG at Leibniz Supercomputing Centre (www.lrz.de).

Method development was partially funded by the German Federation of Industrial Research Associations' support of research and development in SMEs, as part of the collective research project AiF-ZIM ZF4066103MC8.

The project that gave rise to these results received the support of a fellowship from "La Caixa" Foundation (ID 100010434). The fellowship code is LCF/BQ/EU20/11810069.

C. Lázaro gratefully acknowledges the support for his stay at the Technical University of Munich provided by the retraining grant of the Spanish Ministry of Universities (RD 289/2021 and UNI/551/2021) funded by the European Union NextGenerationEU program.

REFERENCES

Abbas, T., Kavrakov, I., Morgenthal, G., & Lahmer, T. (2020). Prediction of aeroelastic response of bridge decks using artificial neural networks. Computers & Structures, 231, 106198.

Bruno, L., Salvetti, M. V., & Ricciardelli, F. (2014). Benchmark on the aerodynamics of a rectangular 5: 1 cylinder: an overview after the first four years of activity. Journal of Wind Engineering and Industrial Aerodynamics, 126, 87-106.

Huang, L., & Liao, H. (2011). Identification of flutter derivatives of bridge deck under multi-frequency vibration. Engineering Applications of Computational Fluid Mechanics, 5(1), 16-25.

Katili, A. M. (2022). Evaluation of bridge deck flutter derivatives using FEM simulations and the k-ω SST URANS turbulence model. Master thesis, Chair of Structural Analysis, Technical University of Munich.

Kratos Multiphysics open-source project. Available online: https://github.com/KratosMultiphysics/Kratos (accessed on 20th January 2022).

Nieto, F., Owen, J. S., Hargreaves, D. M., & Hernández, S. (2015). Bridge deck flutter derivatives: Efficient numerical evaluation exploiting their interdependence. Journal of Wind Engineering and Industrial Aerodynamics, 136, 138-150.

Šarkić, A., Fisch, R., Höffer, R., & Bletzinger, K. U. (2012). Bridge flutter derivatives based on computed, validated pressure fields. Journal of Wind Engineering and Industrial Aerodynamics, 104, 141-151.

Scanlan, R. H., & Tomko, J. J. (1971). Airfoil and bridge deck flutter derivatives. Journal of the engineering mechanics division, 97(6), 1717-1737.

Siedziako, B., Øiseth, O., & Rønnquist, A. (2017). An enhanced forced vibration rig for wind tunnel testing of bridge deck section models in arbitrary motion. Journal of Wind Engineering and Industrial Aerodynamics, 164, 152-163.

Simiu, E., & Scanlan, R. H. (1996). Wind effects on structures: fundamentals and applications to design (Vol. 688). New York: John Wiley.

Xu, F. Y., Ying, X. Y., & Zhang, Z. (2014). Three-degree-of-freedom coupled numerical technique for extracting 18 aerodynamic derivatives of bridge decks. Journal of Structural Engineering, 140(11), 04014085.