ON (BAYESIAN) FINITE ELEMENT MODEL UPDATING OF CIVIL ENGINEERING STRUCTURES BY USING MODAL FEATURES

Blaž Kurent[1], Noémi Friedman[2], Boštjan Brank[3]

[1] University of Ljubljana, Faculty of Civil and Geodetic Engineering, Slovenia, bkurent@fgg.uni-lj.si
[2] Institute for Computer Science and Control, Budapest, Hungary, n.friedman@ilab.sztaki.hu
[3] University of Ljubljana, Faculty of Civil and Geodetic Engineering, Slovenia, bbrank@fgg.uni-lj.si

The assessment of the dynamic characteristics – such as natural frequencies, mode shapes, and modal damping ratios – of existing civil engineering structures by performing in-situ measurements has become an appealing research worldwide, see e.g. [1,2,4] and references therein. With the help of the in situ measurements, which may be based either on ambient or forced vibrations, a corresponding high-fidelity finite element model can be developed. In the herein presented framework, the vibration measurements are not only used for an estimation of the dynamic characteristics of an existing civil engineering structure but also for an update of the corresponding finite element model. The new, updated (i.e. calibrated) finite element model can be useful for checking the assumptions of the structural design, for examination of the assumptions adopted when creating the initial (i.e. the best-engineering-judgement) finite element model, and for enabling more accurate predictions of the response of the considered structure under various loading conditions. The calibrated model can also be used for assessing the suitability of different numerical models that may be considered for the given structure, or can serve as a representative model for the structural condition at the time of measurements, which can be further applied for structural health monitoring purposes, see e.g. [2].

As for the in-situ measurements, for civil engineering structures usually output-only ambient vibration tests (AVT) are performed. Such tests measure structural response due to unmeasured ambient excitations, which vary with time, and consequently the related estimates of the dynamic characteristics may vary from one data block of measurements to another. On the other hand, in an input-output modal testing, both the excitation force (that is applied by shakers) and the corresponding dynamic response are measured, which allows to estimate frequency response functions (FRFs) and use them to get more reliable estimation of the as-built structural modal properties in comparison with AVT, see e.g. [3]. In particular, using the FRF-based methodology, the properties of the higher modes of vibration are much easier to measure and investigate. However, the FRF based methods have been seldom applied for civil engineering structures. One reason are the practical difficulties that are related to performing forced excitation of a structure without damaging it, and an other reason is the complication in measuring responses simultaneously across usually large and/or tall civil engineering structures. The later difficulty can be solved by using synchronised wireless accelerometers, see e.g. [3].

Before the finite element model updating is performed, the experimental and the numerical vibration modes need to be correlated, where usually a larger (i.e. numerical) model is reduced to match a smaller model of the experimental data, see e.g. [4]. An important part of the model updating is a judicious choice of the parameters of the model that is to be calibrated. In this step sensitivity analysis can play a crucial role. A deterministic model updating is done by calibrating the chosen parameters such way that the finite element analysis gives a best fit to the measured dynamic characteristics in the sense of some metric, defined by a suitable cost function. This classical optimization procedure, is often easier to perform and demands much less computation time than the Bayesian updating.

The probabilistic framework of Bayesian updating [5,6,7] though can take into account the uncertainties of both the measurements and the model inputs by modeling these uncertainties in the form of probability distributions. With such procedure, instead of finding one deterministic value − a local minimum of some predefined cost function − we compute the conditional probability distribution of our model inputs given the measured value of the modal properties. The resulted updated stochastic finite element model is much more informative than the model that we get from a local minimum point.

For determining the Bayesian posterior distribution of the input parameters, we sample from it using the Markov Chain Monte Carlo (MCMC) method. The procedure requires a large number of deterministic solver calls of the finite element model, which may lead to prohibitively large computational times when one forward analysis of a large and/or tall civil engineering structure takes several minutes. The computational effort can be reduced by constructing a surrogate model (e.g. by general Polynomial Chaos Expansion [8]) for frequencies and mode shapes. However, creating a surrogate model for mode shapes may turn to be a challenging task, because the (higher-order) mode shapes typically rearrange for each new set of the values of updating parameters, and correlation of the mode shapes becomes difficult. Keeping track of eigenfrequency switching may be further complicated when the experimental data have spatial aliasing because the sensors did not capture enough motion of the structure.

In the talk, we will report about our experience with the application of deterministic and Bayesian finite element model updating for civil engineering structures. We have been involved during the past years into a European campaign related to the identification of the dynamic properties of existing tall timber buildings [9]. Therefore, we will present, as a study case, the deterministic and the Bayesian finite element model updating, based on modal features, of the seven-storey building from Glasgow, called Yoker, which is completely made of cross-laminated timber panels. The forced vibration testing of the Yoker building in operation, which was performed by the group of prof. A. Pavic from the University of Exeter, resulted in high-quality experimental data for eight vibration modes, among which the first six and the first five were used for the deterministic (see [10]) and Bayesian finite element model updating, respectively. The results of the deterministic and Bayesian finite element model updating will be presented and the strategies for Bayesian updating incorporating the measured modal properties will be discussed.

Acknowledgements

The support of ERA-NET Cofund Forest Value (DynaTTB project) and the corresponding funding body (Ministry of Education, Science and Sport of the Republic of Slovenia) is gratefully acknowledged. We also acknowledge the financial support of the Slovenian Research Agency (J2-2490) and the Hungarian National Research, Development and Innovation Office (SNN 134368).

References

[1] C. Argyris, C. Papadimitriou, P. Panetsos, P. Tsopelas. *Bayesian Model-Updating Using Features of Modal Data: Application to the Metsovo Bridge*, Sensor and Actuator Networks, 9,27, 2020.

[2] Y. Huang, C. Shao, B. Wu, J. L. Beck, H. Li. *State-of-the-art review on Bayesian inference in structural system identification and damage assessment*, Advances in Structural Engineering, 22(6) 1329–1351, 2019.

[3] W.K. Ao, A. Pavic. *FRF-based modal testing of sway modes using OCXO synchronised accelerometers for simultaneous force and response measurements*, Eurodyn 2020 Conference (online).

[4] N.M.M. Maia, J.M.M. Silva e Silva (eds.), *Theoretical and experimental modal analysis*, Wiley, 1997.

[5] C. Pepi, M. Gioffré, M.D. Grigoriu, H.G. Matthies. *Bayesian updating of cable stayed footbridge model parameters using dynamic measurements*, Eccomas Proceedia UNCECOMP, 330-342, 2019.

[6] H.G. Matthies, E. Zander, B.V Rosić. et al. *Parameter estimation via conditional expectation: a Bayesian inversion*. Adv. Model. and Simul. in Eng. Sci. 3, 24. https://doi.org/10.1186/s40323-016-0075-7, 2016.

[7] N. Friedman, C. Zoccarato, E. Zander, and H. G. Matthies. *A Worked-out Example of Surrogate Based Bayesian Parameter and Field Identification Methods*. Under print, accepted for the chapter in CRC Press Taylor & Francis Group, ed. Juan Chiachio Ruano, Shankar Sankararaman, Manuel Chiachio Ruano, Bayesian inverse problems: Fundamentals and Engineering Applications., 2021
[8] D. Xiu, G. E. Karniadakis *The Wiener–Askey polynomial chaos for stochastic differential equations*. In: SIAM journal on scientific computing 24.2, pp. 619–644., 2002.
[9] R. Abrahamsen, et al. *Dynamic response of tall timber buildings under service load - the DynaTTB research program*. Eurodyn 2020 Conference (online).
[10] B. Kurent, B. Brank, W.K. Ao. *Model updating of seven-storey cross laminated timber building designed on frequency-response-functions-based modal testing*, Structure and Infrastructure Engineering, 2021.