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Uncertainty quantifications in HFFB dynamic analyses of a complex tall building

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Abstract. High frequency force balance (HFFB) technique attributable to its simplicity and versatility is widely adopted for the assessment of wind loads acting on a tall building. Although a number of HFFB-based analysis methods have been proposed to predict generalized wind forces of a tall building, these methods or models are mostly developed based on various assumed forms of wind load distributions and/or their correlations, which introduce different levels of inherent uncertainties and lead to a practical problem of method/model selections among available HFFB based methods. It is necessary to quantify uncertainties in selecting the most robust and reliable model to carry out wind-induced response analysis with minimum uncertainties. Novel contributions of this paper include implementing a Bayesian framework to quantify the model-selection uncertainty for weighting up the superiority among the candidate HFFB-based analysis models. Utilizing the synchronous multi-pressure sensing system (SMPSS) test in the wind tunnel, the benchmark results of the wind effects (i.e. base reactions, generalized forces and responses) on a complex tall building can be established, such that the uncertainties of model selection among different candidate models can be quantified and compared to each other.

Keywords: Tall Building; HFFB Technique; Spatial-temporal Load Distribution; Modal Analysis; Uncertainty Quantification;

1. Introduction

High frequency force balance (HFFB) technique attributable to its simplicity and versatility is widely adopted for the assessment of wind loads acting on a tall building in terms of generalized wind forces (Holmes *et al*. 2003, 2014, Chen and Kareem 2005, Boggs 2014, Chen *et al*. 2014, Tse *et al.* 2014, Ho *et al.* 2014, Lim and Bienkiewicz 2014). The generalized wind forces, necessary for solving a set of generalized equations of motion, are the essential components to be determined. For buildings with uncoupled linear translational mode shapes and a uniform torsional mode shape, the generalized wind forces are precisely equal to the base bending and torsional moments measured from a wind tunnel HFFB test, using a scaled building model under the simulated wind field. For more complicated buildings with nonlinear and three-dimensional (3D) coupled mode shapes, a number of HFFB-based analysis methods have been proposed to predict generalized wind forces. These methods include the

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conventional methods using mode shape correction (MSC) factors (Holmes *et al.* 2003, Chen and Kareem 2004, Spence *et al.* 2011, Bernardini *et al.* 2012a), recently proposed linear-mode-shape (LMS) and advanced linear-mode-shape (ALMS) methods (Tse *et al.* 2009, 2014, Huang *et al.* 2010). Alternative HFFB data analysis methods, i.e., the Yip-Flay approach (Yip and Flay, 1995) in frequency domain and the Xie-Irwin approach (Xie and Irwin, 1998, Xie and Garber, 2014) in time domain, were also developed to determine generalized wind forces without the empirical MSC factors by identifying the spatial-temporal varying wind load distributions over the building height. To sum up, the main limitation inherent to the HFFB-based models in predicting generalized wind forces lies in the underline assumption concerning the actual wind load distribution. The uncertainties associated with the wind load distribution assumption can be propagated from the estimated HFFB wind loads to the displacement and acceleration responses through analysis or modelling process, causing the response-prediction uncertainty or predictive uncertainty, which represents the difference between an estimated result and the true value. Furthermore, for a building complex which commonly does not exhibit ideal mode shape characteristics (i.e. linear translational mode shapes and a uniform torsional mode shape), the variability introduced by the selection of different HFFB-based models to determine generalized wind forces and analyze the wind-induced responses, can be classified as model-selection uncertainty. As used here, the HFFB-based model is meant to be any above mentioned method for predicting or estimating generalized wind forces and wind-induced responses of a tall building.

In wind engineering, much of the work done in uncertainty quantification has focused primarily upon the quantification of input-variable or parametric uncertainty (Kareem 1988, Solari 1997, 2002, Bashor *et al.* 2005, Bashor and Kareem 2007, Ciampoli *et al.* 2011, Spence and Gioffrè 2011, 2012, Bernardini *et al.* 2012a, 2012b). The work on the other two forms of uncertainties (i.e. model-selection uncertainty and response-prediction uncertainty) is still lacking in structural wind engineering community. In other fields like finance and statistics, the Bayesian model averaging (BMA) approach has been regarded as an effective tool for incorporating the model-selection uncertainties into the decision making process (Leamer 1978, Draper 1997, Hoeting *et al.* 1999, Droguett and Mosleh 2008, Ando 2008, Vrugt *et al.* 2008, Wright, 2009). Recently, the application of BMA approach has been extended to solve more complex design problems in aerospace engineering and geotechnical engineering. Riley and Grandhi (2010, 2013) quantified the model-selection and predictive uncertainties in the calculation of the flutter velocity of a wing using Bayesian model averaging for deterministic models. Zhang *et al.* (2014) constructed candidate probability models with limited amount of data available in geotechnical practice to quantify the model-selection uncertainty and to compare the validity of the candidate models based on the BMA approach. Therefore, it is necessary to introduce the BMA approach to investigate and quantify uncertainties associated in the selection of various candidate HFFB-based analysis models in wind engineering practice.

The aim of this paper is to investigate the possible discrepancies in the response prediction among four representative HFFB-based models (i.e. MSC model, ALMS model, Yip-Flay model and Xie-Irwin model) and two newly constructed revised models, which are related to the original Yip-Flay approach