Project title	Validation of Wind Turbine Structural Dynamics Models
Project number	TG4-1
Organisation	Chalmers University of Technology, Applied Mechanics
Project leader	Thomas Abrahamsson
Other participants	Majid Khorsand (PhD student)
Report for	2014-10-01 – 2015-09-30
Participating companies	GE Wind Energy

Project description

In this project, the validity of structural dynamics models of wind turbines is studied. The model validity considered is of hierarchical dual level. On one hand, a detailed structural dynamics model needs to be substantiated by good correlation between experimental results of wind turbine testing and theoretical simulation results using that model. One the other hand, after that detailed model has been validated, a model of significantly lower order based on the detailed model needs to be validated by a good model-to-model correlation. With the connection between models, this implies that also the lower-order model is implicitly validated by testing.

The use of two model levels is strongly motivated by their different focal points. The detailed structural dynamics model, most often a finite element model, is motivated by its strong connection to the observed fundamental physical laws. The purpose of this model is to give real physical insight to observations made during physical testing. Such models can be used to study the impact of backlash, elastic material properties, geometrical dimensions, material density variation, temporal and spatial load variations, component dynamics, properties of structural joints, temperature changes, wing twisting, non-linear effects, etc. The low-order model is motivated by its fast evaluation. The main purpose of this model, often called a black-box model, is to give a correct representation of the stimuli-to-response characteristics of the system in an efficient simulation environment. Such low-order model is highly suitable for system optimization and probabilistic design that rely on fast, accurate and efficient calculations and simulations. In the wind turbine application, the stimuli are the loadings from wind, waves, mechanical and electrical braking, etc. The response is the structural motion in component interfaces, stresses and strains at critical sections, wing deflection and twist, etc. The low-order models may be either linear or non-linear.

The project treats two important aspects of validation. The first is the focus on pre-test planning, i.e. the planning of the test such that test data (when that becomes available) is informative with respect to the physical properties that need to be validated. The second aspect is on the model calibration in itself. Model calibration can be seen as an optimization problem in which one searches for the model that gives a minimal deviation from test observations. However, it has been found that the selection of a proper formulation of the criterion function for such deviation is far from trivial. Various formulations that may suite the wind turbine application will be evaluated. Also, within the time-frame of the project, it is believed that real test data becomes available and model calibrations can be made. A collection of lessons learned from this (and from other sources) will be summarized to help future structural dynamics modellers to set up better models at first hand.

Results

The work done during stage 2 of the centre focused on the following three topics:
(1) a novel stochastic FE model updating framework is developed for estimation of the uncertainty in model parameters and predictions from the measured frequency responses. This framework combines the technique of “FE model calibration with damping equalization” with the principles of bootstrapping. The performance of the former is improved in dealing with noisy measurements by: (*i*) use of a new dedicated frequency sampling strategy that gives the frequencies at which the experimental FRF of the structure needs to be measured, and (*ii*) use of a weighted log-least-squares objective function. The bootstrapping technique is used to take into account the uncertainties in the measurements and forward simulations in order to quantify the uncertainty in the parameters and to assess their effects on the predictions made by the FE model.
(2) A modal parameter estimation algorithm is developed that satisfies the following criteria: (*i*) it allows for fast and robust identification of MIMO systems of a given order, (*ii*) it avoids high dimensional optimization, (*iii*) it

provides uncertainty bounds on the estimated modal parameters, and (*iv*) it needs no user-specified parameters or thresholds. This algorithm combines the principles of bootstrapping for uncertainty quantification with the technique of subspace based system identification and also with unsupervised learning algorithms. The key to success of the engaged unsupervised learning algorithm is a novel correlation metric that is able to treat the problems of spatial eigenvector aliasing and non-unique eigenvectors of coalescent modes simultaneously.

(3) *Approximate Bayesian computation by subset simulation*, ABC-SubSim, is a recently appeared algorithm for Approximation Bayesian Computation (ABC) which exploits the subset simulation for efficient rare-event simulation. The merits of ABC-SubSim stems from the facts that (*i*) it does not suffer from the curse of dimensionality, and (*ii*) it bypasses the explicit evaluation of the likelihood function and, as a result, is applicable to any model for which forward simulation is available. One example of such models is a nonlinear state-space model with state and output uncertain prediction errors for which an analytical formula for the likelihood function is difficult to establish. Here, a dynamic problem is formulated in form of a general hierarchical state-space model to show that the ABC-SubSim algorithm is performing an exact Bayesian updating for a new model in which its output is corrupted by a uniform additive error term. This formulation not only allows understanding the quality of the ABC approximations of the posterior distribution and model evidence, but also makes it possible to independently approximate the model evidence for each of the competing models as a simple by-product of the ABC-SubSim algorithm. Therefore, in the case that there exists several competing models to represent a real structure, the model evidence, which is a simple by-product of the ABC-SubSim algorithm, can be used to rank these models.

Outcomes of the aforementioned studies are written in form of five journal papers of which three papers are accepted for publication and two papers are submitted for international publications. Furthermore, the results of these studies were presented in international conferences.

Fulfilment of SWPTC's goals

This project has contributed to the research aimed at achieving optimal wind turbines. Outcome of this project has been incorporated in an MSc course entitled *Structural Dynamics – Model Validation*, thus MSc students are learnt theory and obtained skills useful in wind power engineering. The project has contributed to the scientific output of the centre in form of scientific papers.

Deviations from project plan

No major deviation from plan can be reported. The cooperation between the industrial partner and the university that started with strong intensity when GE Wind Energy had a local office in Karlstad, was terminated prematurely. However, it is anticipated that work with other partners can fill this gap for the purpose of this project.

Publications

Theses

M. K. Vakilzadeh, Stochastic model updating and model selection with application to structural dynamics, Doctoral thesis, Göteborg: Chalmers University of Technology

Journal papers

- **M. K. Vakilzadeh**, J.L. Beck, T. Abrahamsson, Using Approximate Bayesian Computation by Subset Simulation for Efficient Posterior Assessment of Dynamic State-Space Model Classes, submitted to *SIAM Journal on Scientific Computing.*
- V. Yaghoubi, **M. K. Vakilzadeh**, A.T. Johansson, T. Abrahamsson, Automated Modal Parameter Estimation Using Correlation Analysis and Bootstrap Sampling, submitted to *Mechanical Systems and Signal Processing*.
- **M. K. Vakilzadeh**, V. Yaghoubi, A.T. Johansson, Thomas J.S. Abrahamsson, "Stochastic Finite Element Model Calibration Based on Frequency Responses and Bootstrap Sampling", *Mechanical Systems and Signal Processing*, 2016, under revision.
- **M. K. Vakilzadeh**, Y. Huang, J. L. Beck, T. Abrahamsson, "Approximate Bayesian Computation by Subset Simulation Using Hierarchical State-Space Models", Mechanical Systems and Signal Processing, Available online 4 March 2016, ISSN 0888-3270, http://dx.doi.org/10.1016/j.ymssp.2016.02.024.

- S. Rahrovani, **M. K. Vakilzadeh**, T. Abrahamsson, Modal Dominancy Analysis Based on Modal Contribution to Frequency Response Function H_2-norm, *Mechanical Systems and Signal Processing*, 48(1-2), pp. 218-231, 2014.

Conference papers

- **M. K. Vakilzadeh**, A. Sjögren, A. T. Johansson, T. Abrahamsson, "Sequential Gauss-Newton MCMC algorithm for high-dimensional Bayesian model updating", IMAC XXXV, California, USA, Jan. 30-Feb. 2, 2017.
- **M. K. Vakilzadeh**, Y. Huang, J. L. Beck, T. Abrahamsson, "Approximate Bayesian Computation by Subset Simulation for Parameter Inference of Dynamical Models", IMAC XXXIV, Florida, USA, January 25-28, 2016.
- V. Yaghoubi, **M. K. Vakilzadeh**, A.T. Johansson, T. Abrahamsson, "Stochastic Finite Element Model Updating by Bootstrapping", IMAC XXXIV, Florida, USA, January 25-28, 2016.
- **M. K. Vakilzadeh**, V. Yaghoubi, T. McKelvey, T. Abrahamsson, L. Ljung, "Experiment Design for Improved Frequency Domain Subspace Identification of Continuous-Time Systems", IFAC, Beijing, China, 2015.
- **M. K. Vakilzadeh,** V. Yaghoubi, A.T. Johansson, T. Abrahamsson, "Towards an Automatic Modal Parameter Estimation Framework: Mode Clustering", International Modal Analysis Conference IMAC XXXIII, Florida, USA, February 2-7, 2015.
- Vahid Yaghoubi, **M. K. Vakilzadeh***,* Thomas J.S. Abrahamsson, "A parallel solution method for structural dynamics response analysis", IMAC XXXIII, Florida, USA, 2015.
- **M. K. Vakilzadeh**, A.T. Johansson, T.J.S. Abrahamsson "Bayesian Finite Element model calibration using manifold based Metropolis adjusted Langevin dynamics", IX International Conference on Structural Dynamics, Porto, Portugal, June 30-July 02, 2014.
- **M. K. Vakilzadeh**, A.T. Johansson, C.-J. Lindholm, J. Hedlund, and T.J.S Abrahamsson, "Comparison of Model Reduction Techniques of an NREL 5MW Offshore Wind Turbine Blade", Presented at IMAC XXXII, Orlando, Florida, USA, 2014.

External activities

The PhD student participated in a four-month visiting program at California Institute of Technology (Caltech) in which the outcomes of this visit are two journal papers and one conference paper.