THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING IN SOLID AND STRUCTURAL MECHANICS

Drive Train System Dynamics Analysis

Application to Wind Turbines

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CHALMERS UNIVERSITY OF TECHNOLOGY

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Cover:
High speed shaft drive train at lab with bearing modelling and bearing fault

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Abstract

To facilitate the design and production of highly efficient and reliable wind turbine drive trains, the project deals with the mathematical modelling and experimental study of drive train system dynamics.
A typical drive train is considered as the subsystem of a wind turbine that transfers mechanical power from the rotor hub to the generator, and thereby plays an important role in the system dynamics and efficiency of wind turbine operation.
The dynamics of wind turbines is complex and a critical area of study for the wind industry. The multidisciplinary nature of wind turbine design adds to the complexity of this task, as the subsystems of a wind turbine need to be tuned with respect to a common objective to achieve a cost effective and optimum structural performance.
The current work contributes to enhanced knowledge in this field with focus on interaction between functional components and system dynamic response, faults modelling and detectability of defects in bearings in wind turbine drive trains.
The overall performance of a drive train can be evaluated from different perspectives. In this thesis, the dynamics behaviour of the high speed shaft drive train is evaluated by proposed objective functions referring to displacements, loads, and frequency responses. To have a better insight into wind turbine dynamics, the global sensitivity analysis (GSA) of high speed shaft drive train dynamics with respect to input structural parameters is considered. The multiplicative dimension reduction method is employed to provide the mapping between the objective functions' sensitivity indices and design variables. The results of such analysis can narrow down the number of input variables for design problem and improve the computational efficiency.
The proposed GSA methodology is applied for the system modelled analysis of high speed shaft subsystem of a drive train. Moreover, by introducing defects in functional components and investigating sensitivity indices, detectability of faults by GSA is proved. The results show that the proposed methodology is capable of detecting damage in the functional components such as bearings in early stage before a complete failure. The application of this methodology within the detection, prediction, and prevention framework has a potential to reduce the maintenance cost for critical components. The results can also provide a better understanding and useful hints in wind turbine drive train system dynamics with respect to different structural parameters, ultimately designing more efficient drive trains.

Keywords: Wind turbine drive train dynamics, Model validation, Global sensitivity analysis, Bearing defects detection

To my beloved family

Neither a lofty degree of intelligence nor imagination nor both together go to the making of genius. Love, love, love, that is the soul of genius.

Wolfgang Amadeus Mozart

Preface

The work presented in this thesis has been started on March 2013 to January 2016 at the Division of Dynamics at Chalmers University of Technology. This project is financed through the Swedish Wind Power Technology Center (SWPTC). SWPTC is a research center for design of wind turbines. The purpose of the centre is to support Swedish industry with knowledge of design techniques as well as maintenance in the field of wind power. The Centre is funded by the Swedish Energy Agency, Chalmers University of Technology as well as academic and industrial partners.
The main supervisor of this project is Professor Viktor Berbyuk and I would like to acknowledge him for all the support and encouragement he has provided during these years.
I would like to thank my co-supervisor, Senior Lecturer Håkan Johansson for his guidance, kindness, fruitful discussions, positive energy.
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Last but not least, I would like to thank my family for their love and support.

Gothenburg, January 2016

Saeed Asadi

Thesis

This thesis consists of an extended summary and the following appended papers:

Paper A	Asadi S., Berbyuk V., Johansson H., Global Sensitivity Analysis of High Speed Subsystem of a Wind Turbine Drive Train, To be submitted for international publication
Paper B	Asadi S., Berbyuk V., Johansson H., Vibration Dynamics of a Wind Turbine Drive Train High Speed Subsystem: Modelling and Validation, ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. 2015: August 2-5, 2015, Boston, Massachusetts, USA, paper DETC2015-46016
Paper C	Asadi S., Berbyuk V., Johansson H., Structural Dynamics of a Wind Turbine Drive Train High Speed Subsystem: Mathematical Modelling and Validation, In Proc. of the International Conference on Engineering Vibration, Ljubljana, 7 - 10 September ; [editors Miha Boltezar, Janko Slavic, Marian Wiercigroch]. - EBook. - Ljubljana: Faculty for Mechanical Engineering, 2015 p. 553-562

The appended papers were prepared in collaboration with the co-authors. The author of this thesis was responsible for the major progress of the work in preparing the papers, i.e. took part in planning the papers, took part in developing the theory, performed all implementations and numerical calculations, and took part in writing the papers.

Contents

Part I
Extended Summary

The outline of the current research is described in this part. After a brief overview concerning the background and aims of the project, the test rig of the high speed subsystem of the dive train built in the lab and mathematical model developed for the analysis are introduced. Ultimately, an overview on system modelling of the wind turbine drive train, fault modelling, global sensitivity analysis problem formulation and methodology are presented. The part ends with conclusions and outlooks of future research.

1 Background and Motivation

The need for alternatives to the finite fossil fuels and the negative effects of them for the environment have driven the fast developments in the wind industry in the last 20 years. To further improve the cost efficiency of wind turbines, advanced engineering analysis of a wind turbine design is needed, both in terms of reliability and the design of larger turbines and ultimately cost efficiency. The cost efficiency in wind turbine industry can be scrutinized from different points of view. The maintenance cost and down-time due to faults and failures occurring in drive train functional components such as bearings, gearbox, and coupling are some of the most significant challenges in this field [1, 2].
The drive train system is here considered as the electromechanical subsystem comprising shafts, bearings, gearbox, shaft couplings, mounts, and other functional components of a wind turbine that transfers mechanical power from the rotor hub to the electric power generator, and thereby plays an important role in a wind turbine dynamics [3, 4]. Although so-called ”direct driven” design without gearbox is getting increased attention nowadays, this thesis focuses on the indirect arrangement comprising low-speed shaft powered by the wind, planetary and intermediate stages, and the high-speed shaft of the generator as shown in Fig. 1.1.

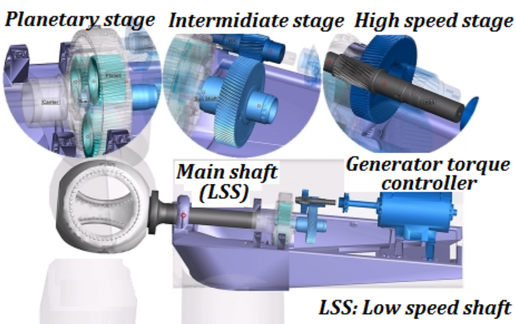

Figure 1.1: *The GRC drive train and gearbox [5]*

Premature failures in wind turbines components' (gearbox, bearings, etc) have impacted the financial payback, and is of major concern for the industry. For example, high speed bearing failures, gear teeth damages due to gear misalignment as well as bearing damages, predominantly on the high speed shaft in terms of so-called White Etch Cracks (WEC), and axial cracks in bearing raceways have become a major cause of premature gearbox failures recently [6]. Since gearbox and main bearing failures are among the costliest of wind turbine failures, there is a significant demand to be able to detect, predict and prevent faults and failures in the drive train of a wind turbine and its functional components. A predictive maintenance scheme of wind turbines, allowing an early detection of faults, becomes essential to reduce maintenance costs and ensure continuity of production.

Since some faults in wind turbine drive trains are not yet well understood, there is a demand for experimental study to have better insight into faults sources. For example, NREL (National Renewable Energy Laboratory) initiated the Gearbox Reliability Collaborative (GRC). That project comprises analysis, modelling, condition monitoring, and development of a failure database to determine why wind turbine gearboxes do not always achieve their expected design life [7]. The gear manufacturer ZF designed a wind turbine drive train test rig capable to 13.2 MW and developed a dynamic model for it using Simpack [8], which presents an experimental and simulation investigations into the dynamic response of modern wind turbines. However, little research has been conducted on drive train dynamics to prevent resonance in wind turbines according to rigid-flexible coupling dynamic theory and with experimental verification.

In general, the wind turbine drive train is a nonlinear dynamical system with highly interconnected elements. A change in an specific structural parameter to improve a specific output, might worsen another system objective function. Consequently, as an initial stage in wind turbine drive trains design and optimization, it is crucial to study the effects of different structural components on wind turbines' dynamics to reduce the number of parameters, which significantly reduces the computational efforts in design optimization. In this regard, several studies on the structural analysis and dynamic behaviour of wind turbine drive trains, upscaling and sensitivity analysis are done [9, 10, 11, 12]. The global sensitivity analysis of the high speed shaft dynamics behaviour with respect to the input structural parameters related to the drive train components is of huge interest. Monte Carlo simulation is one of the most widely-used procedures in sensitivity analysis of mechanical systems. However, the computational effort for Monte Carlo simulation is large, especially when a design analysis requires a large set of loading conditions to be evaluated, and it is necessary to use a more time efficient algorithm. Based on the multiplicative version of dimension reduction method (M-DRM), a closed form solution for the global sensitivity indices has been proposed by Zhang et al. [13]. This method can dramatically reduce the computational efforts required for the global sensitivity analysis compared to Monte Carlo simulation, while the results obtained are within the same order of accuracy. This method is applied in this thesis to solve the global sensitivity analysis problem of the high speed shaft drive train dynamics of a wind turbine. Based on the results attained from such an analysis, one can identify those structural parameters that have the most important influence on drive train dynamic behaviour. This is the subject of **PAPER A**.

2 Research Aim

In order to contribute to the understanding of occurrence of faults in wind turbine drive trains, the current project has been proposed by the Swedish wind power technology center (SWPTC). The project includes both theoretical and experimental study of wind turbine drive train, and focusses on the high speed shaft subsystem of indirect drive wind turbines. The overall aim of the project is to understand and predict how bearings, gearbox, high speed shaft couplings and generator (including its mounts) interact with respect to external loads, misalignments and other excitations. In this thesis, we present system modelling of the high speed shaft drive train as subsystem of wind turbine, and apply the global sensitivity analysis (GSA) within the developed models. Then, we use GSA to investigate the detectability of proposed faults in functional components (torque ripple in motor, backlash in coupling, inner race defect in bearing).
One of the main objectives in this thesis is to study how GSA can be used as a tool in a methodology to detect, predict and prevent faults and failures in functional components in early stage, especially bearings in the wind turbines, which is of huge interest of wind industry due to heavy costs of these failures.

3 The Experimental Set-up

The test rig of the high speed shaft drive train system has been developed in order to conduct experimental studies of the drive train dynamics, and to validate mathematical models, and ultimately, to evaluate the response of the real wind turbine after upscaling. The progress of the development is reported in [14, 15, 16], **PAPER B** and **PAPER C**. The test rig illustrates a high speed shaft drive train, where the motor represents generator and the disk with an eccentric mass simulates uneven loads applied to the high speed shaft. The first version of the drive train system test rig is assembled (See Fig. 3.1) to study high speed shaft subsystem dynamics of an indirect drive wind turbine equipped with a shafts' coupling between gearbox and generator. The bearing housing has been constructed with springs, to emphasize the gearbox housing flexibility and serve as mounting to displacement sensors (as an output end of the gearbox). By pretension of the springs via screws, the "neutral" position of the shaft can be set at a priori misaligned, and moreover, by adjusting the springs, the system can have different stiffness in vertical and horizontal directions. By using the instrumented bearing housing, the forces acting on the high speed bearing can be calculated.

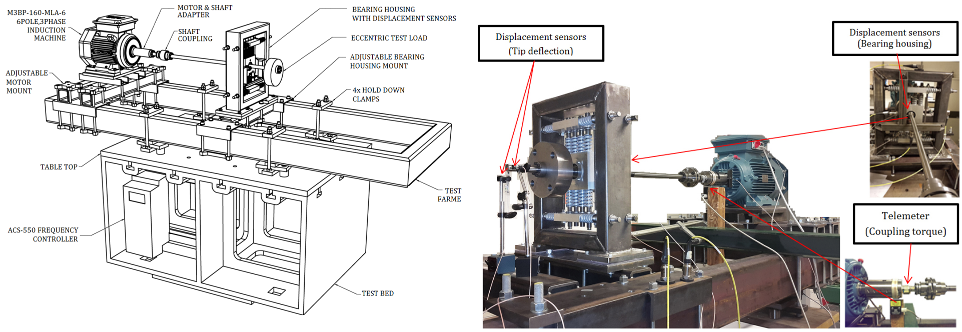

Figure 3.1: *A sketch of the test rig (left) and its picture with sensors' location (right)*

SKF WindCon condition monitoring system has been added to the set-up in order to acquire the data from the sensors placed in specific locations along the test rig (as shown in Fig. 3.1).
The test set-up was used to provide data for model validation (**PAPER B** and **PAPER C**).
It is planned to further develop the test rig to study the dynamics of complete drive train, bearings internal dynamics, interaction between mechanical and electrical subsystems (bearing frequency analysis by observing the time waveform [17] and the spectrum to see differences between healthy and faulty bearings, integration of motor phase current monitoring, estimate transmission error for different levels of misalignment, others issues).

4 Modelling of High Speed Shaft Drive Train

The following sections include system modelling of high speed shaft drive train test rig and faults modelling within wind turbine drive train applications.

4.1 High speed subsystem modelling

Mathematical models of high speed shaft drive train has been developed. The development of the models considers bending flexibility of shafts (**PAPER B**), and the torsional vibration, assuming torsional flexibility of coupling and motor torque ripples (**PAPER C**) (See Fig. 4.1). The models have gone through validation tests. The deflection fields and loads in different components have been investigated. In both cases fundamental eigenmodes have been studied via Campbell diagram. Campbell diagram is used to illustrate the influence of the rotational speed on the eigenfrequencies of a structure, and the resonance points of the system could be identified with respect to different system frequencies. This identifies critical points to avoid resonance of the system.

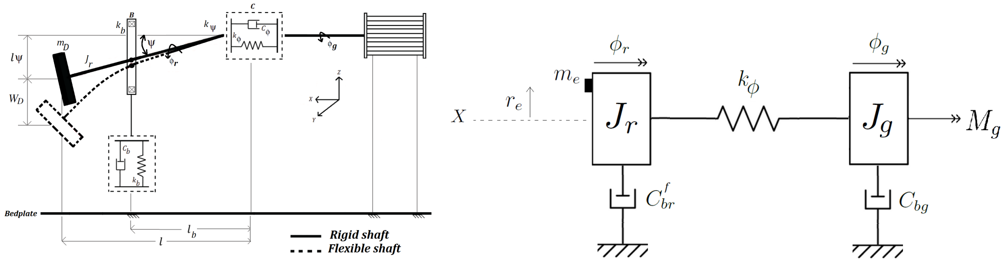

Figure 4.1: *The overview of system modelling in bending flexibility model (left) and torsional vibration model (right)*

4.2 Faults modelling

Here, we have modelled some system defects. Backlash in the coupling, bearing defect due to the rolling elements and motor torque ripple are assumed within the modelling of the test rig.

4.2.1 Torque ripple in the motor

Torque ripples are primarily caused by non-ideal geometry of motor windings. The fluctuating torque of electric motors is reflected as speed ripples (also known as speed cogging). At low speeds, the torque ripple produced by the machine could cause undesirable speed pulsations and inaccuracies in motion control. At the same time, machine performance could be negatively affected by the power converter. Although the reduction of torque ripples has been an aim subject to research [18], but there are still unsolved problems in the rotating machinery systems regarded by torque ripple.
The effect of the torque ripple on high speed shaft susbsystem dynamics has been studied in **PAPER C**.

4.2.2 Backlash modelling

In a gear system, backlash is the distance between two teeth in contact. Generally, there are scenarios, e.g. load reversals due to wind gusts at low speed, where backlash has a contribution to the peak forces. A backlash between the teeth give rise to complex behaviour.

Backlash is not an important issue for gearbox used in applications where there is no load reversal or the angular position after a reversal is not critical [19]. In order to study the effect of backlash in the test rig, we introduce it in the coupling component in **PAPER A**. The model of the coupling toque due to backlash used in **PAPER A** is presented in Fig. 4.2, where, Δ represents the torsional misalignment of the coupling.

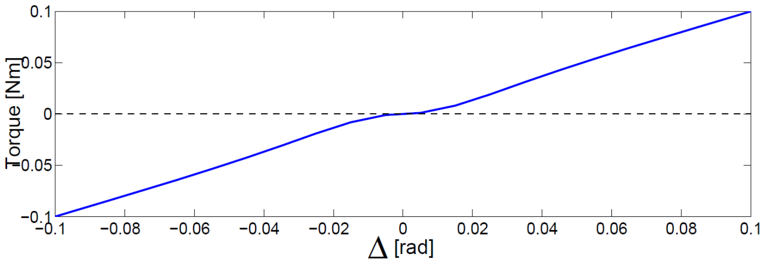

Figure 4.2: *Nonlinear torque response due to backlash*

4.2.3 Bearing faults modelling; Rolling elements defects

Bearing fault diagnosis is important in condition monitoring of any rotating machine. Early fault detection in machineries can save significantly maintenance cost. Different techniques are used for fault analysis such as short time Fourier transform, Wavelet analysis, and Model based analysis [20].

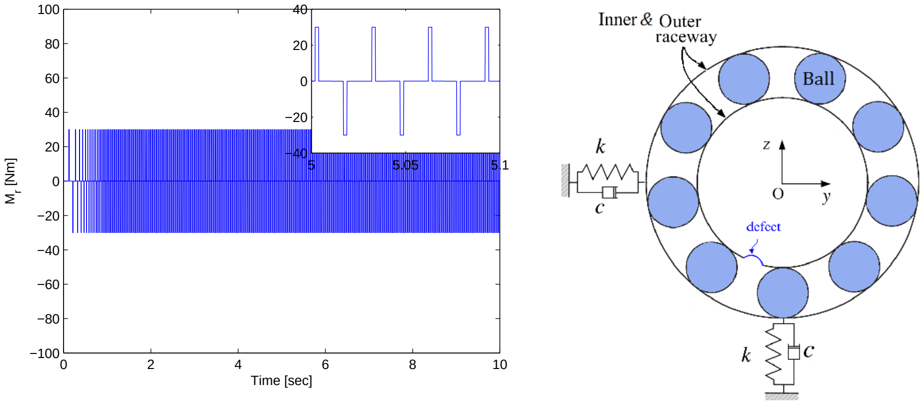

Figure 4.3: *Disturbance torque response (in bending and/or torsion) with zoom (left) and inner race defect modelling sketch with rolling bearing elements (right)*

When a defect is first initiated, the bearing may vibrate (or resonate). The shock wave propagates from the point of contact very quickly. The vibration that results will be very weak, and thus difficult to detect, since the modes decay out in short time. This characteristic impulse-response signal is detected by the vibration monitor and is reported as simple trending variables.
In **PAPER A** we analyse the detectability of bearing defects by considering the illustrated external torque imposed on inner ring of the bearing (Fig. 4.3).

5 Global Sensitivity Analysis

Generally, an arbitrary objective function OF of structural parameters $\mathbf{X}$ could be expressed in terms of set of design parameters $\mathbf{X} = [X_1, X_2, \ldots, X_n]^T \in \Omega$, through the deterministic function $OF(\mathbf{X})$ [13]. The nominal structural parameters may not be known exactly in complex systems. Thus by treating $\mathbf{X}$ as random with a proper distribution we could study the system response and investigate the effect of each parameter to OF.
Global sensitivity analysis (GSA) is used as a methodology to analyse complex systems that can provide informative design insights. In this section, some basic concepts on the global sensitivity analysis formulation that is basis of **PAPER A** is presented. The primary (S_i) and total (S_{T_i}) sensitivity indices are defined throughout the following relations [13, 21, 22, 23]:

$$S_i = \frac{E_i(V(OF|X_i))}{V(OF(\mathbf{X}))} \tag{5.1}$$

$$S_{T_i} = 1 - \frac{E_i(V(OF| \sim X_i))}{V(OF(\mathbf{X}))} \tag{5.2}$$

Here, E_i denotes for expected value of the function and, the subscripts i refers to X_i input parameter. The primary sensitivity index, S_i gives an indication of how strong the direct influence of input parameters $\mathbf{X}$ is on the objective functions OF without any interactions with other variables. The total sensitivity index, S_{T_i} gives the total effect of the variance in variable X_i on the output variance of OF plus the effects from variance of the interaction of variable X_i with all the other variables $(\sim X_i)$ in the system. The total sensitivity index, gives an indication of the total influence of X_i on OF from its own direct effects along with its interaction with other variables [21, 22]. The differences between the primary and total sensitivity indices then give an indication of how important the interactions of X_i are with other variables in influencing OF. If the main effect is small, whereas the total effect is large, then X_i does influence OF but only through interactive effects with other system inputs.
In order to compute the global sensitivity indices, multidimensional integrals have to be calculated, which are computationally expensive. Thus it is of priority to apply efficient algorithm to reduce the computational costs. The M-DRM method could approximate the global sensitivity indices efficiently and accurately [24]. This approach has been applied in **PAPER A** to solve the global sensitivity analysis of high speed shaft drive train system with respect to input drive train structural parameters.
By applying GSA methodology and investigating the sensitivity response of objective functions with respect to randomized parameters, considering uncertainties of other parameters, we could demonstrate the detectability of that fault in the system structure. This could contribute to early detection of faults in functional components of a wind turbine such as bearing which is of great interest in wind industry community.

6 Summary of Appended Papers

- **Paper A:**
  Global sensitivity analysis of high speed shaft subsystem of wind turbine drive train.
  This work considers variance based global sensitivity analysis of wind turbine drive train structure. Here, we investigate the sensitivity indices for developed models in different operational scenarios related to the wind turbine applications. A mathematical model considers both torsional vibration by introducing a simplistic motor model and shaft flexibilities in term of bending within Euler-Bernoulli beam theory. Dynamic analysis was carried out to investigate the transient and steady state and during shut down responses of the drive train system. The variance based global sensitivity indices are introduced and the Gaussian quadrature integrals are employed to evaluate the contribution of input structural parameters correlated to the objective functions. For each operational scenario, the most effective parameters have been recognized for high speed shaft drive train. The study examines the primary and total sensitivities of the objective functions to each input parameter. In particular, the GSA can provide better understanding of wind turbine drive train system dynamics with respect to different structural parameters, ultimately useful tool when designing more efficient drive trains. Finally, the proposed GSA methodology demonstrates the detectability of faults in different components.

- **Paper B:**
  Vibration Dynamics of Wind Turbine Drive Train High Speed Subsystem: Modelling and Validation.
  In this paper the dynamics of a wind turbine drive train high speed subsystem is studied both by modelling and experiments with focus on system torsional and flexural vibrations and transient events which can reduce fatigue life of functional components (gearbox, bearings, shafts, couplings, others). A scaled down drive train high speed shaft test rig has been developed and equipped with measurement system comprising a set of accelerometers and displacement sensors, data acquisition hardware and software (SKF WindCon3.0). Mathematical and computational models of the test rig have been developed and went through validation tests. The system kinematic and dynamic responses are studied for different operational scenarios and structural parameters (ratio of shaft bending stiffness and stiffness of mounting structures, unevenly inertia load distribution, others).

- **Paper C:**
  Structural Dynamics of a Wind Turbine Drive Train High Speed Subsystem: Mathematical Modelling and Validation.
  The paper studies the dynamics of a wind turbine drive train high speed subsystem, both by modelling and experiments with focus on system torsional vibration and transient events which can reduce fatigue life of functional components. Mathematical and computational models of the torsional response have been developed and went through validation tests. The system dynamic response is studied for different

operational scenarios and structural parameters (transient-steady state-shut down cycle with and without eccentric mass). A simplistic motor model with slip and torque ripples initiating from the motor are assumed within the system modelling. This gives an insight in how faults sources can contribute to the system dynamics of drive trains.

7 Conclusion and Future Work

The thesis describes the theoretical and experimental study of high speed shaft drive train as subsystem of wind turbine [25, 26]. The mathematical models of high speed shaft subsystem of wind turbine drive train have been developed using Lagrangian formalism. The test rig of high speed shaft drive train that has been built and instrumented with condition monitoring system was used to experimentally study system vibration dynamics and load distribution. By using the obtained measurement data, the developed mathematical and computational models have gone through model validation by qualitative comparison of simulation and experimental data.

Based on Multiplicative Dimensional Reduction Method (MDRM), the global sensitivity analysis of high speed shaft drive train of wind turbine with respect to input structural parameters has been considered as one of the key stages of drive train design. In this regard, a reliable and computationally efficient algorithm has been used for the analysis, which can give a beneficial insight into solving different optimization and design problems for functional components of wind turbines. Global sensitivity analysis results obtained in this thesis can reduce the costs associated with wind turbine drive train design by narrowing down the number of the input parameters for optimization problems of wind turbine drive trains component.
The results also indicate that the current system modelling could be decomposed into two main simpler subsystems focusing on torsional and bending flexibilities separately.
Dynamic modelling and vibration simulation are important for fault mechanism studies to provide proofs for defect detection and fault diagnose. In this regard, it has been demonstrated that the proposed models could be used within GSA in order to investigate the detectability of faults in different components.

Some further research could be done within the wind turbine drive train system dynamics as listed below:

- Dimensional analysis and upscaling of the test rig results:
  - Apply GSA for structural parameters relevant to a real wind turbine, for example NREL 5 MW benchmark wind turbine, and investigate sensitivity indices. This would demonstrate the applicability of the proposed methodology to real wind turbines.
  - In order to consider the stochastic nature of wind loads, it would be interesting to study the current model based on calculated aerodynamic loads extracted

from wind turbine system simulation software such as FAST.

  - By use of Pi Buckingham theory the minimal number of dimensionless parameters can be identified, which could lead to upscale the structure and predict the real wind turbine behaviours.

- GSA and advanced bearing modelling to be applied for detection and diagnoses of faults and failures [17]:
  - Improve bearing model to study bearing defects and its detectability in more detail.
  - Studying how bearings internal dynamics affect drive train system dynamics.

- Electromechanical interaction of wind turbine drive train components and GSA. Since wind turbine contains both mechanical and electrical components, to have better understanding of drive train dynamics, this interaction should be considered.
  - Applying the Park model [27] for 3 phase induction motor modelling, would be interesting to investigate the dynamic loads and faults parameters interactions with electrical parameters such as power and currents.

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