Dynamic Analysis on Fixed Speed Wind Turbine Gear Box

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Abstract:
The dynamic analysis of the wind turbine drivetrain, specifically focusing on the gearbox, is a critical aspect in ensuring the optimal design, operation, and longevity of wind turbines. This paper investigates the complexities associated with dynamic modelling of the wind turbine gearbox system. The gearbox, being an essential component of the drivetrain, transmits the mechanical power generated by the wind to the generator. Given the dynamic loads and varying operating conditions, it is necessary to develop an accurate and robust model that can predict the gearbox's performance, stress, and vibration behaviour under real-world operating conditions. This work employs Lagrange's formulation for modelling the gearbox system and uses a combination of analytical methods and computational techniques to achieve a comprehensive dynamic analysis.
The mathematical modelling of the wind turbine gearbox involves addressing the complexities of gear meshing, shaft deflections, bearing dynamics, and the coupling effects between various components. These challenges are particularly significant due to the non-linear nature of gear teeth interactions, the stiffness and damping characteristics of the gearbox components, and the varying loads induced by the fluctuating wind speeds. By applying Lagrange's formulation, the equations of motion for the system are derived. This approach allows for the direct inclusion of rotational degrees of freedom, angular displacements, and forces between interacting components, making it well-suited for modelling complex, multi-body systems such as a wind turbine drivetrain.

Keywords
Dynamic analysis,modelling,wind speeds

1. *INTRODUCTION*

The installation of wind turbines has been increasing rapidly for last few decades. In the currently booming market of wind turbines, a clear focus is put on the design of reliable and cost effective subsystems such as the gear box. Gear box is the most critical component of wind turbine as its failure will lead to more down time. The speed step up ratios will be generally vary from 40:1 to 135:1 in a typical wind turbine gearbox. The small amount of acceleration at the input of the gearbox will gets multiplied by almost up to 135 times at the generator output.

- Flexible multi body modelling technique is used to perform the dynamic analysis of wind turbine gearbox by accounting the support bearing elasticity, potential energy terms associated with variable tooth stiffness.
- By modelling the aerodynamic torque with an empirical approach, the dynamic behaviour of a two stage spur gear system used in wind turbine is investigated.
- A detailed multi body dynamic model is developed for torsional vibration behaviour of the wind turbine drive train.
- The gearbox modal behaviour is assessed by means of three complex multibody modelling techniques: purely torsional, rigid six degree of freedom with discrete flexibility and flexible multibody modelling.
- In literature not much work has done on dynamic analysis of the entire wind turbine drive train by considering the inertia of rotor and generator. The present dynamic model will account for the gear tooth stiffness, support bearing elasticity and shaft stiffness. The coupled torsional bending vibration is simulated for a typical

wind turbine drive train data from the literature. The lumped mass dynamic model is developed to get the dynamic behaviour of the entire wind turbine drive train. The dynamic model will consist of eight torsional and ten bending degrees of freedom. The resulting governing equations of motion are obtained from Lagrange's formulation. The numerical results for the dynamic response are obtained from Implicit Newmark time integration algorithm.

DYNAMIC ANALYSIS:

the study of forces, motions, and behaviors of mechanical systems under dynamic (changing) conditions, as opposed to static conditions where forces and motions are constant or unchanging. Dynamic analysis focuses on how a system responds to time-varying loads, vibrations, and other dynamic forces.

KEY CONCEPTS IN DYNAMIC ANALYSIS

Vibration Analysis:

- Studies the vibrations that a mechanical system undergoes when subjected to dynamic loads.
- Helps in understanding natural frequencies of the system, resonance conditions, and dampening effects.
- Used to design systems that can withstand or reduce vibrations, such as in machinery, vehicles, or buildings.

Modal Analysis:

- A type of dynamic analysis that investigates the natural modes of vibration of a structure or mechanical system.
- It identifies the frequencies and shapes (mode shapes) at which the system vibrates.
- Important for predicting and preventing unwanted resonances that may lead to system failure.

Transient Dynamic Analysis:

- Examines the system's response to time-varying loads or forces, such as impact, shock, or varying loads over time.
- Helps in designing systems that can handle sudden changes or shocks, such as in crash testing for vehicles or during product testing in manufacturing.

Frequency Response Analysis:

- Determines how a system responds to sinusoidal (cyclic) loads at different frequencies.
- This is important for ensuring that mechanical systems do not resonate or amplify certain frequencies that could cause failure.

Nonlinear Dynamic Analysis:

- Studies the behavior of systems with nonlinear components, such as those where the response does not directly scale with the input force (e.g., systems with friction, large deformations, or material nonlinearity).
- This is used for more complex systems where linear models do not accurately predict the system's behavior.

METHODOLOGY:

Methodology for Dynamic Analysis of a Wind Turbine Drive Train:

Introduction: Wind energy is one of the fastest-growing renewable energy sources, and wind turbines play a crucial role in harnessing wind power. The efficiency and reliability of a wind turbine depend significantly on the dynamic performance of its drive train. The drive train, consisting of a rotor, gearbox, and generator, is subjected to fluctuating aerodynamic and mechanical loads. These loads can lead to vibrations, fatigue, and even failure if not properly analyzed and controlled. This study focuses on the dynamic analysis of a fixed-speed wind turbine drive train using a mathematical model based on Lagrange's formulation. The methodology involves modeling the system, computing aerodynamic torque, formulating equations of motion, solving them numerically, and analyzing the results.

3.1 Problem Definition and Objectives: The primary objective of this study is to develop a mathematical model that accurately predicts the dynamic behavior of a wind turbine drive train under varying wind conditions. The main challenges include accounting for:

- Gear tooth stiffness variations
- Bearing elasticity and support flexibility
- Shaft flexibility and misalignments
- Torsional and bending vibrations

The analysis aims to determine the system's natural frequencies, mode shapes, and dynamic response to external excitations, particularly wind fluctuations.

3.2 Development of the Mathematical Model: A lumped mass model is employed to represent the wind turbine drive train, simplifying the complex multi-body system while retaining its essential dynamics. The drive train consists of three primary components:

- Rotor – Converts wind energy into mechanical energy.
- Gearbox – Steps up the rotor speed to match the generator's operational speed.
- Generator – Converts mechanical energy into electrical power.

The Lagrange formulation is applied to derive the equations of motion, considering both kinetic and potential energy.

3.3 Energy Considerations: The kinetic energy (KE) of the system is computed for rotating and orbiting gears, while potential energy (PE) includes contributions from:

- Dynamic transmission errors due to gear meshing irregularities
- Bearing stiffness affecting rotational motion
- Shaft stiffness influencing bending and torsional behavior.

3.4 Computation of Aerodynamic Torque: Wind turbines operate in fluctuating wind conditions, making it essential to accurately model aerodynamic torque. This study employs an empirical approach where the wind speed is represented as a sinusoidal function:

$U_\infty(t) = U\_moy[1 - 0.2 \cos(\omega 1\ t) - 0.05 \cos(\omega 2\ t)]$ where:

- U_moy is the average wind speed,
- $\omega 1$ and $\omega 2$ are angular frequencies.

The power coefficient (Cp) is computed as a function of the tip-speed ratio (λ) and blade pitch angle (β). The instantaneous aerodynamic torque acting on the low-speed shaft is given by:

$T\_turb = (1/2)\ \pi\rho\ R^3\ Cp(\lambda, \beta)\ V^3(t)$

3.5 Formulation of Equations of Motion: The drive train dynamics are governed by coupled torsional-bending equations. The system consists of:

- 8 rotational degrees of freedom (DOFs) – Representing rotational displacements of the rotor, carrier, planets, sun, gears, and generator.
- 10 translational DOFs – Accounting for shaft flexibility and bearing displacements.

Using Lagrange's equations, we derive the dynamic equations for both torsional and bending vibrations, incorporating gear meshing stiffness and damping effects.

3.6 Numerical Solution and Simulation: The governing differential equations are solved using the Implicit Newmark Time

Integration Algorithm, which is well-suited for stiff dynamic systems. The key computational steps include:

- Eigenvalue analysis – To determine natural frequencies and mode shapes.
- Time domain response – To observe system behavior over time under fluctuating wind loads.
- Frequency domain analysis – Using Fast Fourier Transform (FFT) to identify dominant excitation frequencies.

3.7 Results and Interpretation:

3.7.1 Eigenvalue Analysis

- The first two natural frequencies correspond to pure torsional modes.
- Higher frequency modes exhibit coupled torsional-bending behavior.

3.7.2 Acceleration Response

The output gear (gear3) experiences the highest acceleration, making it the most vulnerable to failure.

- Monitoring acceleration at gear3 can help in early failure detection.
- Conclusion and Recommendations This study presents a detailed methodology for the dynamic analysis of a wind turbine drive train. Key findings include:
- Low-frequency excitations dominate torsional vibrations.
- Wind-induced oscillations directly affect gearbox reliability.
- Gear3 at the generator output is the most critical component requiring monitoring.

Future Work:

- Condition monitoring techniques such as vibration analysis and machine learning-based fault detection.
- Design optimizations for reducing gearbox vibrations.
- Advanced damping strategies to mitigate excessive accelerations.

RESULTS:

- The wind turbine drive train data is takenfrom3 for the current simulation has shown in Appendix in Tables A1 and A2. The Eigen values and Eigen vectors of the present dynamic model are presented in Table1. The Eigen values are presented only in the frequency range of interest. At lower modes the torsional displacements are dominating but at higher modes bending displacements are also equally dominant with torsional.

Eigen values and Eigen vectors of drive train:

Eigen values (Hz)	Angular displacements($x10^{-3}$rad)							
	Φ_1	Φ_2	Φ_3	Φ_4	Φ_5	Φ_6	Φ_7	Φ_8
0.4	0.0546	0.0301	0.0481	-0.1401	-0.1401	0.4305	-1	-1
4.7	0.0001	-0.0068	0.0394	-0.1147	-0.1193	0.3717	-0.9940	-1
177.9	0	-0.0217	0.1177	-0.3293	-0.3399	1	-0.0917	0.0133
602.2	0	-1	-0.0765	0.1266	-0.0292	0.2660	-0.0359	0.0004

Eigen values (Hz)	Linear Displacements(mm)									
	y_l	z_l	y_s	z_s	y_1	z_1	y_2	z_2	y_3	z_3
0.4	0	0	0	0	0	0	0.0001	0.0003	0	0
4.7	0	0	0	-0.0001	0	-0.0002	0.0001	0.0004	0	0
177.9	0	0	0.001	0.0003	0.0003	0.0015	-0.0004	-0.0011	0.0003	0.0008
602.2	0	0.0001	-0.0003	-0.0052	-0.0016	-0.0101	0.0014	0.0038	0.0001	0.0003

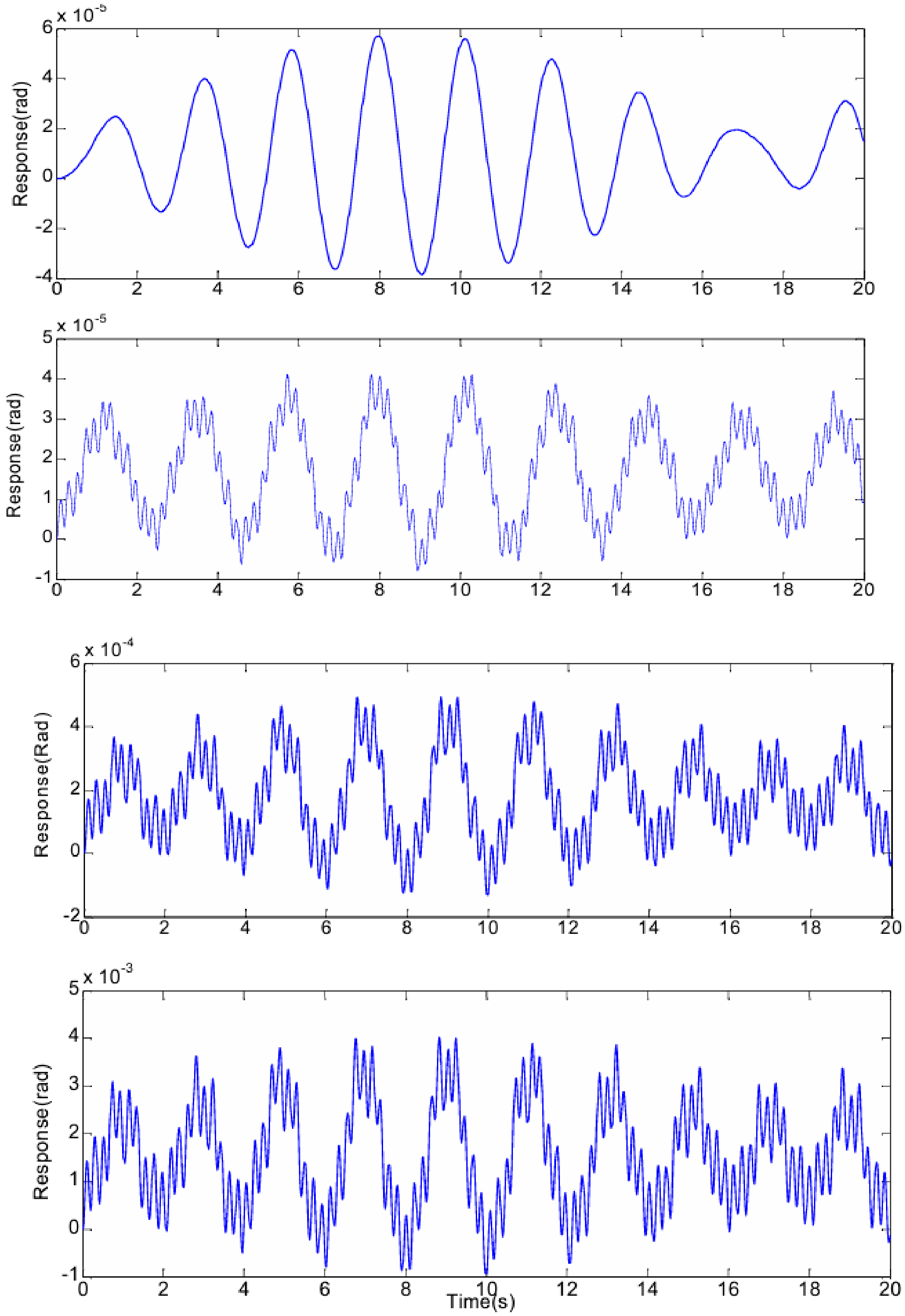

Figure 4 Time domain responses from top: Rotor, carrier, gear1 and gear3

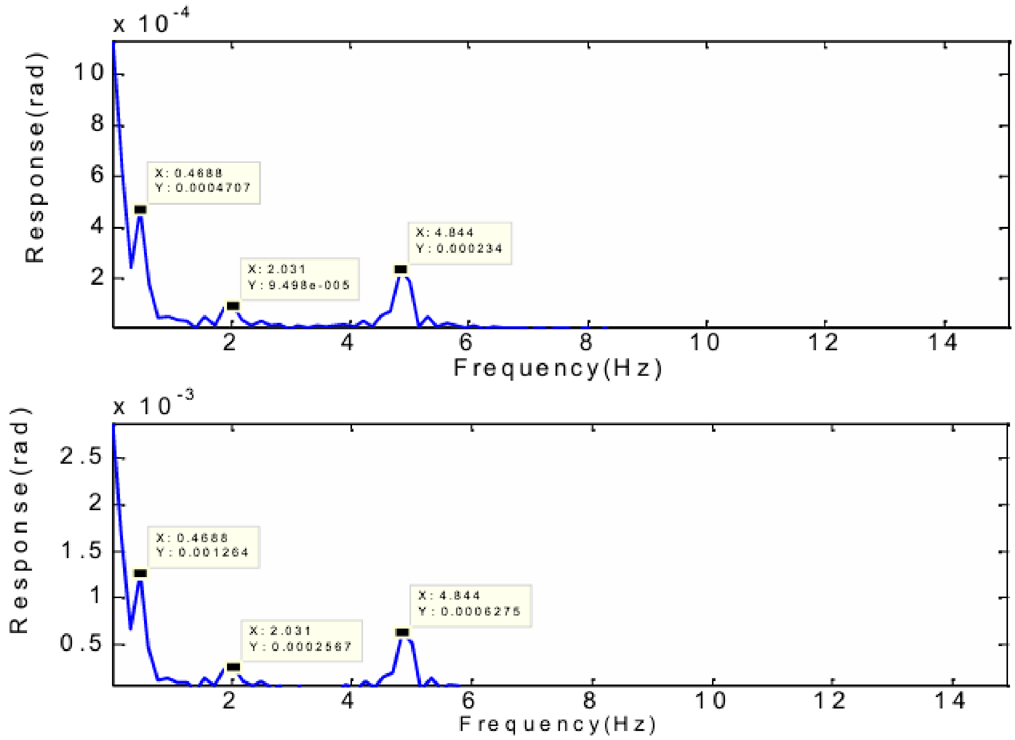

Figure 5 Frequency domain responses from top: gear1, gear3

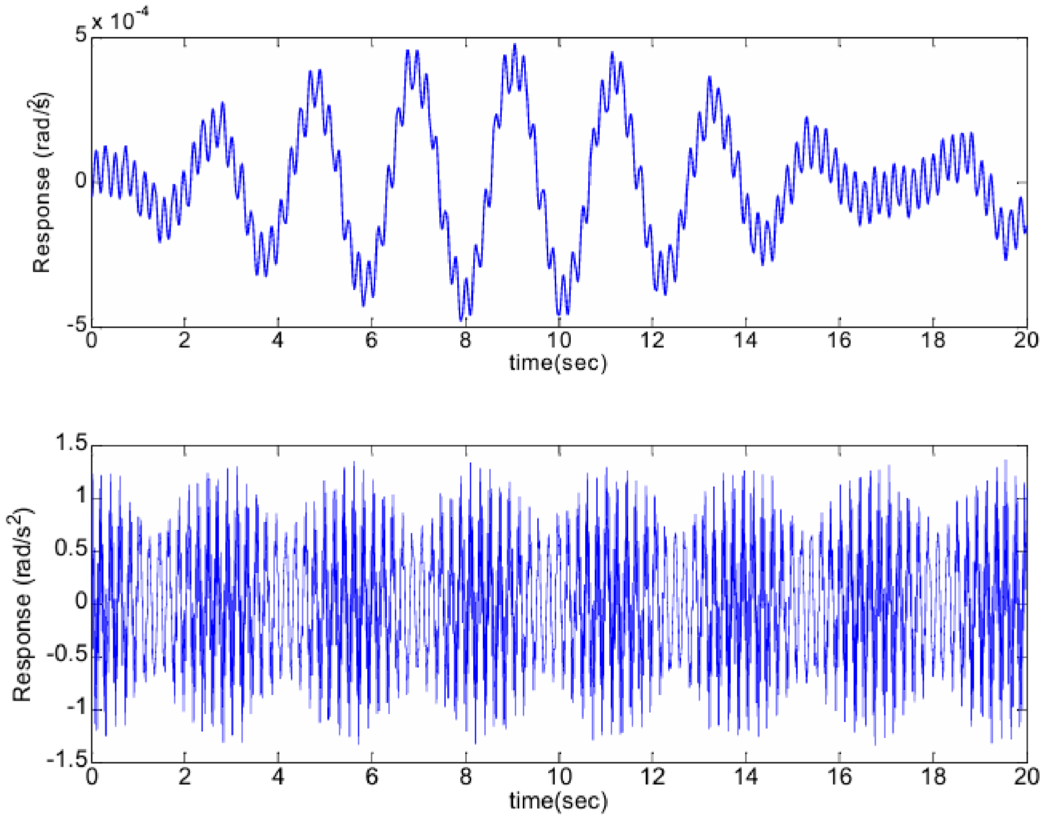

Figure 6 Acceleration Response from Top: Rotor and gear3

FUTURE SCOPE:

The dynamic analysis of the wind turbine drivetrain, particularly the gearbox, plays a vital role in enhancing the design, performance, and reliability of wind turbines. While the current study employs Lagrange's formulation and an implicit Newmark time integration algorithm to model the dynamic behavior of the gearbox under fluctuating wind loads, there are several avenues for future research and advancements in this area. These include improvements in modeling techniques, inclusion of more complex load conditions, and the development of predictive maintenance strategies. The following outlines key areas where further work could significantly advance the field.

CONCLUSION:

Conclusion of Dynamic Analysis of Wind Turbine Drive Train Conclusion A detailed dynamic modelling of the entire wind turbine drive train using Lagrange’s formulation has been presented in this study. The aerodynamic torque was modeled as a nonlinear function based on an empirical approach. The Eigenvalues and Eigenvectors of the system were obtained for a typical wind turbine drive train. The study yielded the following key conclusions:

- Natural Frequencies:
- The first two natural frequencies exhibit almost pure torsional behavior, which is within the practical frequency range of interest.
- At higher frequencies, bending modes become equally dominant along with torsional vibrations.
- Frequency Excitation:
- The first two natural frequencies are excited by external disturbances, particularly wind fluctuations.
- Frequency domain analysis clearly shows that wind frequencies influence the system’s response.
- Acceleration at Gearbox Output:
- The acceleration at Gear3 (output gear) is significantly high.
- This increased acceleration raises the likelihood of failure, necessitating a condition monitoring system for the gearbox.