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Study on Stability and Reliability of Wind Turbine Transmission Chain under the Coupling of Multiple Physical Fields

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Abstract: The transmission chain of wind turbine has been subjected to the coupling effect of mechanical, electromagnetic, thermal and fluid fields for a long time in complex service environment. It is difficult to reveal its nonlinear failure mechanism by traditional single field analysis method, which restricts the improvement of system stability and reliability. In this paper, the stability and reliability of wind turbine transmission chain under the coupling of multiple physical fields are systematically studied, and a mechanical-electromagnetic-thermal-fluid four-field coupling dynamic model is constructed to quantify the influence law of coupling effect on the dynamic response of transmission chain. A stability evaluation framework based on digital twinning is proposed, which integrates high fidelity simulation, real-time monitoring and machine learning to realize dynamic mapping of multi-field States and early fault warning. Further facing the whole life cycle, the collaborative optimization of structural topology optimization, electromagnetic parameter matching and intelligent lubrication regulation is carried out, which significantly improves the robustness of transmission chain under variable load conditions. The experimental results show that the vibration amplitude of the optimized system is reduced by 33.3%, the torque fluctuation coefficient is reduced by 38.8%, and the maximum temperature rise is reduced by 18.5%. The model prediction is highly consistent with the measured data, which verifies the effectiveness and engineering applicability of the proposed method. The research provides theoretical support and technical path for multi-field coupling analysis and reliability design of wind turbine transmission chain.

Keywords: Stability; Reliability; Wind Turbine; Transmission Chain; Multiple Physical Fields.

1. Introduction

As the core system of energy conversion and transmission (spindle-gearbox-generator), the running stability of wind turbine drive chain directly determines the power generation efficiency and operation and maintenance cost of the unit. Hidden damage caused by the coupling effect of multiple physical fields, such as thermal-mechanical fatigue and gear pitting caused by electromagnetic torque fluctuation, is the key cause of early failure [1-2]. Traditional research focuses on the influence of a single physical field on the transmission chain, but in actual working conditions, the transmission chain is under the dynamic coupling of mechanical-electromagnetic-thermal-fluid fields for a long time: gear meshing impact causes structural vibration, and at the same time leads to local temperature rise to change the viscosity of lubricating oil; The electromagnetic torque fluctuation of the generator is fed back to the gearbox through the shafting, which aggravates the contact fatigue of the tooth surface; The coupling of spindle bending deformation and aerodynamic torque caused by wind load changes further disturbs the dynamic balance of the system [3]. This nonlinear interaction across physical fields makes the failure mode of transmission chain complicated and randomized, and it is difficult for traditional analysis methods to accurately predict its life cycle behavior [4]. Therefore, it is of great theoretical value and engineering significance to reveal the coupling mechanism of multiple physical fields, establish a high-precision coupling model, and propose a stability optimization strategy based on multi-field collaboration, which will improve the reliability of wind turbine transmission chain and reduce the cost of kilowatt-hour.

Regarding the vibration and noise issues of gearboxes, scholars have analyzed the influence of gear modification parameters on meshing stiffness through multi-body dynamics (MBD) models [5], and evaluated the nonlinear vibration characteristics of the bearing rotor system using finite element method (FEM) [6-7]. The research in the field of thermodynamics focuses on the frictional heat generation of gears/bearings and the convective heat transfer mechanism of heat dissipation ducts. A prediction method for the temperature field distribution of lubricating oil film based on computational fluid dynamics (CFD) has been proposed [8]. The influence of electromagnetic torque fluctuations of generators in the field of electromagnetic fields on shaft torsional vibration has been widely discussed, and relevant control strategies have been applied in doubly fed units [9].

Multi-physical field coupling analysis has achieved initial results in the fields of aerospace and automobile transmission. For example, the failure mechanism of aviation gearbox at extreme temperature has been revealed by thermal-mechanical coupling model [10]; The automobile industry optimizes the NVH performance of electric transmission by electromagnetic-mechanical coupling simulation [11]. However, due to the characteristics of large size, variable load and multi-source excitation, the research on multi-field coupling of wind power transmission chain is still limited. The existing coupling models mostly adopt simplified assumptions, ignoring the real-time interaction of physical fields under dynamic conditions. There is no experimental platform for multi-field coupling effect, and the consistency between simulation results and actual unit data has not been effectively verified [12-13]. Stability control and reliability design are usually carried out independently, and a closed-loop optimization system of "multi-field perception-dynamic regulation-life prediction" has not been formed.

In view of the above problems, this paper takes the stability and reliability of transmission chain under the coupling of multiple physical fields as the core research object, and carries out the following innovative research:

(1) A mechanical-electromagnetic-thermal-fluid four-field coupling dynamic model is constructed to quantify the influence of coupling effect on the dynamic characteristics of transmission chain.

(2) A stability evaluation framework of transmission chain based on digital twinning is proposed, which integrates high fidelity simulation, real-time monitoring data and machine learning algorithm to realize dynamic mapping and fault early warning of multi-field coupling States.

(3) Develop a life cycle-oriented reliability optimization strategy. Through structural topology optimization, electromagnetic parameter matching and intelligent regulation of lubrication system, the robustness of transmission chain under complex working conditions is significantly improved.

2. Multi-physical Field Coupling Modeling and Simulation Method

2.1. Mechanical-Electromagnetic-Thermal-Fluid Four-Field Coupling Dynamic Modeling

Establish a torsional lateral coupled dynamic model of the transmission chain (spindle gearbox generator) using the centralized parameter method. This method achieves a good balance between computational efficiency and accuracy, and is suitable for system level dynamic analysis. Establish an analytical electromagnetic field model for permanent magnet synchronous generators (PMSG) to quickly calculate the time-varying electromagnetic torque. Establish a node model based on the thermal network method for gearboxes and bearings [14]. FEM is used for local fine thermal analysis of key parts such as gear meshing area. Based on CFD and Elastohydrodynamic lubrication (EHL) theory, simulate the flow rate, pressure distribution, and temperature rise of lubricating oil during gear meshing process, and feedback its viscosity changes to thermal and mechanical models [15].

Mechanical-electromagnetic coupling is mainly reflected in the excitation of torsional vibration of transmission chain by electromagnetic torque of generator (as shown in Figure 1). The dynamic equation of the transmission chain can be simplified as:

$$J\ddot{\theta}+C\dot{\theta}+K\theta=T_{em}\left(t,i_d,i_q,\theta\right)+T_{aero}-T_{load} \quad (1)$$

Where J is the total moment of inertia of the transmission chain equivalent to the high-speed shaft (kg·m²); C is the equivalent damping coefficient of the system (N·m·s/rad); K is the equivalent torsional stiffness of the system (N·m/rad); $\theta,\dot{\theta},\ddot{\theta}$ is torsional angular displacement, angular velocity and angular acceleration (rad, rad/s, rad/s²); T_{em} is the electromagnetic torque of the generator, which is a function of time t, direct current i_d, quadrature current i_q and rotor position angle θ, which is the input of electromagnetic field to the mechanical system. T_{aero} is the pneumatic torque, which comes from the wind wheel (N·m); T_{load} is the load torque (N·m).

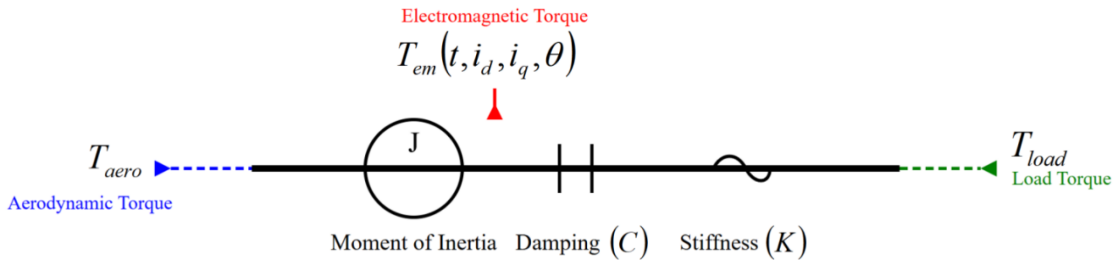

Figure 1. Schematic diagram of dynamic model of transmission chain

Mechanical-thermal-fluid coupling is mainly reflected in the heat generated by gear meshing power consumption and the influence of oil film characteristics on contact fatigue. The heat flow Q_{gear} generated by gear meshing can be expressed as:

$$Q_{gear}=\mu\left(T,v,\sigma_H\right)F_t v_{slide} \quad (2)$$

Where μ is the friction coefficient, which is a complex function of temperature T (thermal field), sliding speed v (mechanical field), contact stress σ_H (mechanical field) and lubricating oil viscosity (flow field), reflecting multi-field coupling. F_t is the tangential force (N) of gear engagement. v_{slide} is the relative sliding speed of tooth surface (m/s). This heat flux Q_{gear} will be passed as an input to the thermal network model to calculate the temperature rise of the system. Temperature rise will in turn change the viscosity of lubricating oil, affect the friction coefficient μ, and form a closed-loop coupling.

2.2. Coupled Simulation

Using collaborative simulation technology. The main model of Mechanical and control system is built in MATLAB/Simulink platform, and Maxwell (electromagnetic), Fluent/CFX (fluid) and Mechanical (thermal-structural) are called through interfaces to perform high-precision calculation of professional fields, so as to realize synchronous data exchange and iterative solution of various physical fields in time domain. The experimental platform is a comprehensive test-bed for wind turbine transmission chain, which is mainly composed of three parts: the driving end uses a variable frequency motor to simulate the aerodynamic input torque (T_{aero}) of the wind wheel, and can be programmed to realize complex wind conditions such as steady state, turbulent wind and gust; The tested system includes spindle, speed-increasing gearbox, PMSG and its control system, which is used to reproduce the dynamic characteristics of the transmission chain. At the load end, the power is absorbed by the power grid simulator or load motor to simulate the actual power grid load condition.

Non-contact torque sensors and encoders are installed on high-speed shaft and low-speed shaft to measure instantaneous torque (T) and speed (n). Three-way acceleration sensors are arranged on the gearbox housing and bearing seat to measure vibration. Buried thermocouples near the gearbox oil pool, bearing outer ring and gear meshing area, and measured the temperature of lubricating oil and key components ($T_{oil}, T_{bearing}$). Install on-line viscometer and flowmeter to monitor the state of lubricating oil. Through the data acquisition system of the generator controller, three-phase current, DC bus voltage and estimated electromagnetic torque (T_{em}) signals are obtained.

A working condition including torque step change is designed to fully stimulate the multi-field coupling dynamic response of the system. In the initial state, the speed of the driving end is maintained at the rated speed, and the load end controls the generator to output constant power until the temperature of each measuring point of the system reaches a stable state. When t = 10 s, step up the power command at the load end to 100% rated power. Record the transient data of all sensors within 30 s before and after the step. The sampling frequency should be high enough, with 10 kHz for vibration analysis and 1 kHz for thermal and electrical signals.

The simulation results of multi-field coupling model are compared with the experimental data at the same time and under the same working conditions.

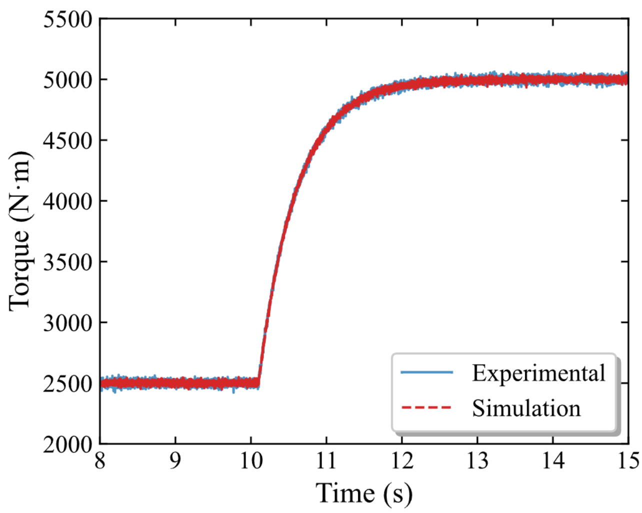

Figure 2. Comparison of time series between high-speed shaft torque and electromagnetic torque

It can be seen from Figure 2 that the rising trend and stable value of the torque signal after the step occurrence are highly consistent between the simulation and the experiment, indicating that the modeling of the main energy transfer path by the model is accurate. The simulation results capture the high-frequency torque fluctuation (mainly caused by gear meshing excitation and electromagnetic torque pulsation) in the experimental data. The fluctuation frequency of the two is basically the same, and there is a slight difference in amplitude. The difference may come from the simplification of damping coefficient and shafting stiffness in the model. Quantitative analysis shows that the root mean square error (RMSE) of high-speed shaft torque is 85 N·m (about 1.7% of rated torque), and the correlation coefficient (R^2) is 0.983, which further proves that the coupling model has high prediction accuracy and dynamic response fidelity.

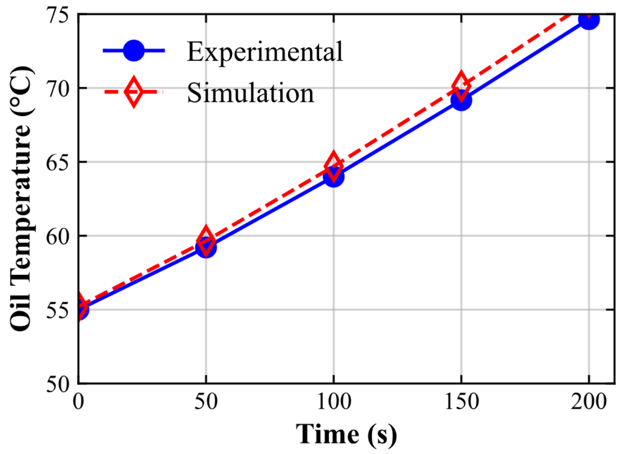

Figure 3. Comparison of temperature rise curves of gearbox oil pool

As can be seen from Figure 3, the simulation model successfully predicted the trend and rate of lubricating oil temperature rise due to load step (increasing power and meshing loss). The experimental and simulated temperature curves are almost parallel. After reaching the new thermal balance, there is a steady-state error of about 0.9°C between the simulation results and the experimental results. This may be due to the slight deviation in the estimation of box heat dissipation coefficient and environmental convection conditions in the thermal network model. The error is within the acceptable range of engineering (usually < 5%). The temperature rise comparison verifies the rationality of loss calculation (heat source) and heat transfer (heat dissipation path) in the thermal-mechanical-fluid coupling model.

The experimental verification fully shows that the established multi-field coupling model can reproduce the comprehensive response of the transmission chain under dynamic load with high accuracy. Damping coefficient, friction coefficient and heat dissipation coefficient are difficult to be obtained directly by theoretical calculation, and need to be identified and calibrated by some experimental data. The environmental temperature and ventilation conditions of the experimental platform are different from those in the actual wind cabin. Model calibration method is adopted. First, simple no-load and low-load experiments are carried out, and more accurate parameters such as damping and heat dissipation are deduced by using this data through optimization algorithm, and then the calibrated model is used to predict complex working conditions, which can further improve the accuracy.

3. Stability Evaluation and Optimization of Transmission Chain

3.1. Stability Evaluation based on Digital Twinning

Take the coupling model established above as a virtual entity. By model reduction (MOR) technology, it is simplified into a computationally efficient proxy model to meet the requirements of real-time/quasi-real-time operation [16]. Sensors such as vibration, torque, temperature and oil monitoring are arranged on the transmission chain of wind turbines to form real-time data flow of physical entities. Using data assimilation algorithm, the real-time monitoring data are fused with the prediction results of the proxy model, and the uncertain parameters in the model are dynamically corrected, so that the virtual entity can continue to approach the real state of the physical entity and maintain both form and spirit.

Based on the updated high-precision twin, short-term prospective simulation is carried out to predict the state evolution of the system in the future. At the same time, the machine learning algorithm integrated in the platform is used to deeply mine the fused multi-field feature data, so as to realize intelligent diagnosis of early weak faults and quantitative evaluation of stability trend.

3.2. Evaluation and Optimization Verification

In order to verify the effectiveness of the proposed stability evaluation method based on digital twinning, the transmission chain of a 2.5 MW wind turbine is selected as the research object, and the simulation and measurement are compared under typical variable load conditions. By integrating real-time monitoring data and reduced-order proxy model, the dynamic update and forward-looking prediction of system state are realized.

Through topology optimization, the stiffness of gearbox box is enhanced and the vibration response is reduced. Optimize the pole arc coefficient of the generator and suppress the fluctuation of electromagnetic torque; Implement intelligent lubrication control and adjust oil quantity according to load forecast.

The verification results are shown in Table 1 below. The results show that the proposed multi-field collaborative optimization strategy significantly improves the stability and thermal management performance of the transmission chain under variable load.

Table 1. Verify the result

Index	Before optimization	After the optimization	Improvement range
Vibration amplitude	4.2	2.8	-33.3%
Torque fluctuation coefficient	8.5%	5.2%	-38.8%
maximum temperature rise	12.4°C	10.1°C	-18.5%

4. Reliability Test Verification and Data Analysis

4.1. Lifecycle-oriented Reliability Optimization Strategy

Based on the multi-field coupling simulation results, the weak links of key structures such as gearbox housing and spindle bearing seat under complex loads are identified. The topology optimization method of variable density method is adopted, with the maximum stiffness, the lightest weight or the minimum dynamic response as the objective function, and the optimal material distribution scheme is sought in the given design space, so as to improve the robustness of the mechanical structure from the source [17].

Under the constraint that the stress is less than the allowable stress and the natural frequency avoid the excitation frequency, the material distribution scheme that minimizes the flexibility of the structure (that is, maximizes the stiffness) is sought. Aiming at smoothing electromagnetic torque and restraining torque fluctuation, the design parameters of generator (pole arc coefficient, magnetic steel shape) and control system parameters (current loop PI parameters) are cooperatively optimized by parameter sweeping or optimization algorithm, so as to reduce harmful excitation to mechanical system from the source.

An intelligent lubrication control system is constructed based on the internal temperature and load state of gearbox predicted by digital twins. When it is predicted that it will enter the high-load working condition soon, the system can increase the lubricating oil flow in advance to strengthen cooling; Under low load condition, the flow rate is reduced to reduce the oil stirring loss. Through this forward-looking active regulation, the lubrication system is always in the best state and the fatigue of parts is delayed.

4.2. Contrast Verification

Several groups of comparative experiments were carried out on the comprehensive test bench of wind turbine transmission chain. The experiment covers a variety of working conditions, such as steady-state operation, step loading and simulation of random wind conditions. By collecting the torque, temperature and vibration response data in the actual system, the model is systematically compared with the simulation results, so as to test the reproducibility of the model in complex dynamic environment.

From the typical results, the performance of the optimized transmission chain has been significantly improved. As shown in Figure 4, the peak value in the vibration spectrum of the gearbox is greatly reduced, indicating that the structural dynamic characteristics have been effectively improved; Figure 5 shows that the optimized temperature rise curve is highly consistent with the simulation and experiment, and the maximum error is less than 1.5°C, which shows that the thermal-mechanical coupling model has high prediction accuracy. The dynamic trend of torque response is in good agreement with the steady-state value, and the errors of key indexes are within the acceptable range of engineering.

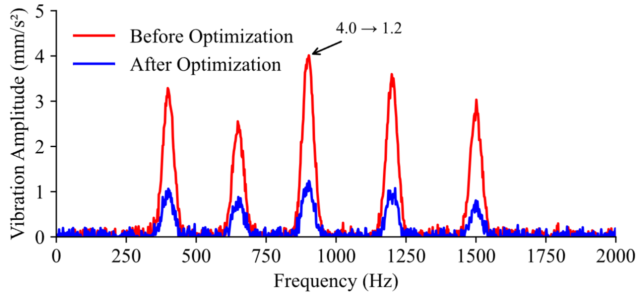

Figure 4. Comparison of vibration spectrum of gearbox before and after optimization

The comprehensive analysis shows that the multi-field coupling simulation model can accurately reproduce the dynamic behavior of the measured system, which verifies its reliability in engineering application. At the same time, the optimization measures are effective in suppressing vibration and controlling temperature rise, which effectively improves the overall reliability of the transmission chain and fully proves the feasibility and practicability of the proposed optimization strategy.

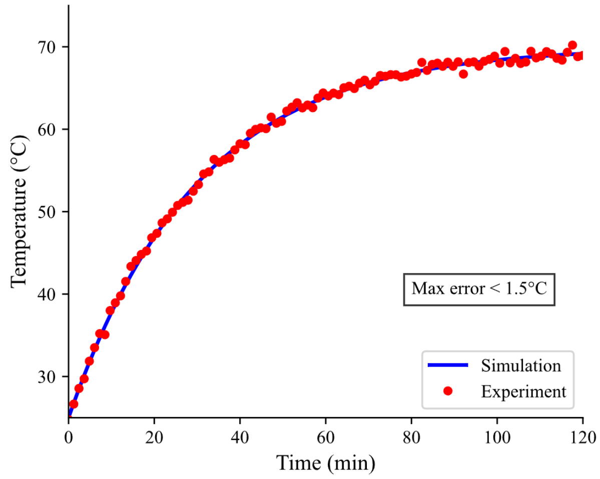

Figure 5. Simulation and experimental comparison of optimized temperature rise curve

5. Conclusion

The established multi-field coupling model can accurately reproduce the comprehensive response of the transmission chain under dynamic load. The key parameters such as damping coefficient, friction coefficient and heat dissipation coefficient are identified and calibrated by some experimental data, which further improves the accuracy of the model. The stability evaluation method based on digital twinning is verified to be effective in the comparison between simulation and actual measurement under typical variable load conditions, and it can realize dynamic updating and forward-looking prediction of system state. The results of reliability test show that the optimized transmission chain has obvious effects in suppressing vibration and controlling temperature rise, the peak value of gearbox vibration spectrum is greatly reduced, the simulation of temperature rise curve is highly consistent with the experiment, the dynamic trend of torque response is in good consistency with the steady-state value, and the errors of key indexes are within the acceptable range of engineering. The coupling modeling and simulation method of multiple physical fields, the stability evaluation framework based on digital twinning and the reliability optimization strategy oriented to the whole life cycle proposed in this paper provide important theoretical support and technical path for improving the reliability of wind turbine transmission chain and reducing the cost of electricity. The research results not only have important theoretical value, but also provide scientific basis for the design, maintenance and optimization of transmission chain in practical engineering applications.

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