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Combined Effects of Gravity, Bending Moment, Bearing Clearance, and Input Torque on Wind Turbine Planetary Gear Load Sharing

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

This computational work investigates planetary gear load sharing of three-mount suspension wind turbine gearboxes. A three-dimensional multibody dynamic model is established, addressing gravity, bending moments, fluctuating mesh stiffness, nonlinear tooth contact, and bearing clearance. A flexible main shaft, planetary carrier, housing, and gear shafts are modeled using reduced degrees-of-freedom through modal condensation. This drivetrain model is validated against the experimental data of the Gearbox Reliability Collaborative for gearbox internal loads.

Planet load sharing is a combined effect of gravity, bending moment, bearing clearance, and input torque. Influences of each of these parameters and their combined effects on the resulting planet load sharing are investigated. Bending moments and gravity induce fundamental excitations in the rotating carrier frame, which can increase gearbox internal loads and disturb load sharing. Clearance in carrier bearings reduces the bearing stiffness, and thus the bending moment from the rotor can be transmitted into gear meshes. With bearing clearance, the bending moment can cause tooth micropitting and can induce planet bearing fatigue, leading to reduced gearbox life. At low input torque, planet bearings are susceptible to skidding. At rated torque and beyond, planet bearings are at risk of fatigue.

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Introduction

Wind turbines have traditionally experienced premature gearbox failures [1]. The cost of gearbox rebuilds, as well as the down time associated with these failures, has elevated the cost of wind energy. The National Renewable Energy Laboratory Gearbox Reliability Collaborative (GRC) was established by the U.S. Department of Energy in 2006; its key goal is to understand the root causes of premature gearbox failures and improve their reliability using a combined approach of dynamometer testing, field testing, and modeling [2]. A major modeling activity of the GRC is to evaluate assumptions and uncertainties in current design practices that could affect gearbox reliability. As a part of the GRC program, this paper investigates planetary gear load-sharing in three-mount suspension wind turbine drivetrains that affects the load path and gearbox component life.

Compared to parallel axis gears, planetary gear systems provide high power density by splitting the input torque into multiple, parallel sun-planet and ring-planet load paths. Planetary gear systems are commonly used in wind turbine drivetrains and they use nearly or exactly equally-spaced planet gears, theoretically leading to equally shared loads at each planet. However, in reality planet gear loads are not always equally shared among planets [3] [4] [5] [6] [7] [8] [9] [10] [11]. With unequally shared loads, planet bearing forces increase, leading to reduced bearing life and potential premature failure. Planetary gear load sharing is an important design parameter for drivetrain reliability. The degree of unequal load sharing has implications for tolerance schemes and gearbox loads.

Early studies by Hidaka and Terauchi [3] investigated disturbed load sharing by manufacturing and assembly errors on a Stoekicht planetary gear. This unequal load sharing was not significant when the mesh frequency was lower than 1000 Hz. Hayashi [5] developed a method to measure the planet gear shearing stress and studied the influences of gear tooth profile error and eccentricity on load sharing. Ligata [6] investigated the effect of pin position error on planet load sharing and a method for computing the planet load sharing from root strain-time histories was proposed. Singh [12] found that the tangential pin position error has a greater effect on the load sharing compared to the radial error. It was also shown that the sensitivity to pin position error increases as the number of pinions in the planetary gear set increases [6] [12]. Singh [13] [14] developed a formulation to estimate load sharing considering the unequal planet spacing for three to seven planetary gears. The analytically predicted load sharing factor was compared against a finite element analysis using the program developed by Vijayakar [15].

Various techniques have been investigated to improve load sharing. Studies show using a flexible ring gear improved load sharing when a number of manufacturing and assembly errors were present [4] [16]. Kahraman investigated the effects of ring gear flexibility on planetary gear loads using a finite element model and experiments and found contradictory results [15] [17]. They found that adding flexibility to the ring gear was not as effective as a floating sun in improving load sharing. Kahraman [9] developed a two-dimensional lumped-parameter model to calculate tooth and bearing loads of planetary gears. The study also investigated the effect of a floating sun on load sharing and found it did not improve disturbed load sharing due to pin position errors. Similar results were shown in the study by Singh [12].

This aforementioned research on load sharing is limited to unequally spaced planets due to manufacturing errors and eccentricity. Input torque is considered as the only applied load to these planetary gears in prior studies. Nearly all horizontal-axis wind turbine gearboxes carry various combinations of input torque and non-torque loads. The non-torque loads include bending moments caused by the rotor weight and tower

shadow, wind induced moments, moments caused by the controller, thrust, etc. Three-mount suspension drivetrains studied by NREL GRC show significant bending moment on the main shaft, which is mainly caused by the rotor weight and aerodynamic forces [2]. This bending moment has the same order of magnitude as input torque [2] [18]. Other wind turbine designs adopt a two main bearing configuration to reduce the transmission of these non-torque loads into gearboxes. These turbines still have a small amount of bending moment present on the main shaft.

The measured load spectrum of the GRC turbine considering various wind and weather conditions is shown in Figure 1. Over 90% of the time, the GRC wind turbine operates below rated torque. Within the entire load spectrum, the turbine operates below 10% of rated torque over 50% of testing period. Gearbox reliability at low input torque has received little attention in the past because prior research has mainly focused on the low bearing and tooth loads with low input torque. Influences of bending moment are not considered for the low load conditions.

With the increasing size of wind turbines, gravity induced excitation in the rotating carrier frame becomes an important vibration source. Gravity led to tooth wedging, a potential source for premature planet bearing failure, in a wind turbine planetary gear investigated by Guo and Parker [19]. Clearance is introduced in rolling element bearings to account for thermal expansion, interference fit, and surface roughness during operation. Clearances in wind turbine bearings are large and can cause gear tooth misalignment, leading to uneven tooth and bearing load distribution and increased bearing vibration [19] [20] [21].

This study investigates the combined effects of gravity, bending moment, bearing clearance, and input torque on planetary load sharing of three-mount suspension wind turbine gearboxes. Gearbox internal loads at low input torque – a wind turbine operating condition that is rarely considered – are also studied under effects of bending moment.

GRC wind turbine drivetrain description

This study investigates the 750 kW turbine drivetrain used by the NREL GRC. This drivetrain has a spherical roller main bearing that supports the main shaft and rotor weight, and two trunnion mounts that support the gearbox. The gearbox includes a helical planetary stage with three equally-spaced planets and two parallel stages, with stage ratios of 5.71, 3.57, and 4.00, respectively. The rated input speed is 22.2 rpm. A cutaway view of the gearbox is shown in Figure 2. There are two parallel carrier bearings supporting the carrier. Each planet gear is supported by two identical cylindrical bearings. The sun shaft is connected to the intermediate shaft through a spline connection with 300 μm backlash to partially float the sun. The ring is bolted to the gearbox housing. This drivetrain configuration represents the majority of the existing three-mount suspension wind turbine drivetrains. Key parameters of the planetary section are listed in Table 1 and Table 2. Additional details of this gearbox are described in [22].

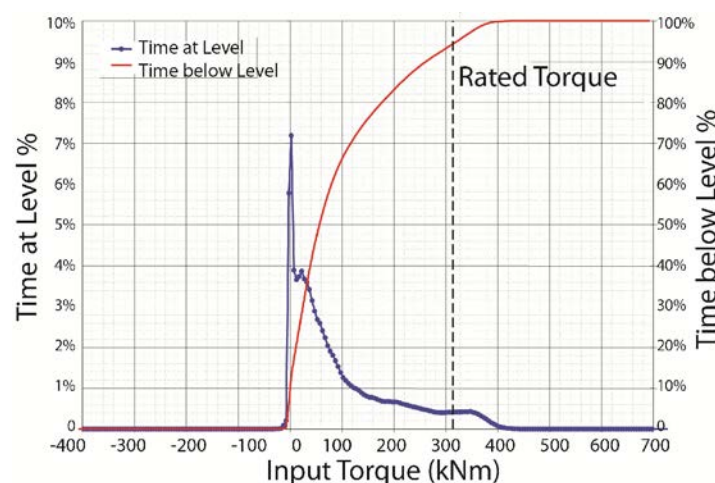


Figure 1. Torque distribution throughout measurement campaign on NEG Micon NM48/750 turbine [2] [18]

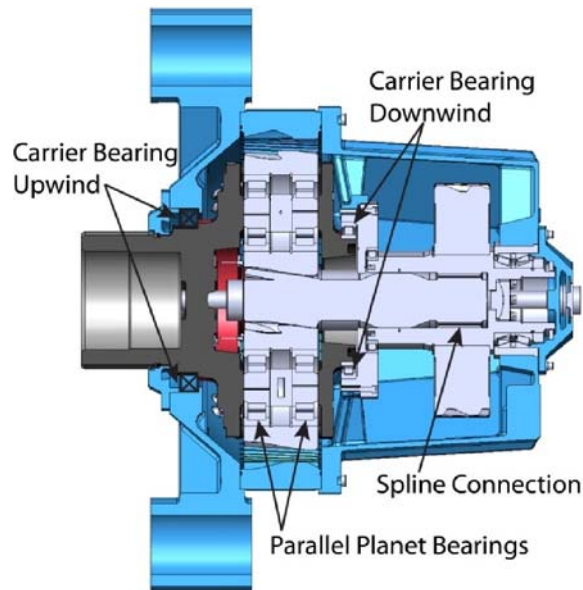


Figure 2. Cut-view of the GRC gearbox configuration

Table 1. Geometric parameters of the planetary gear

	Sun	Planet	Ring
Number of teeth	21	39	99
Pitch diameter, mm	215.6	400.4	1016.4
Root diameter, mm	186.0	372.9	--
Base diameter, mm	198.8	369.3	937.4
Whole depth constant	2.4	2.4	2.4
Tooth thickness, mm	16.84	18.80	8.55
Module, mm	10.0	10.0	10.0
Helix angle, degrees	7.4947 (right)	7.4947 (left)	7.4947 (left)
Backlash, mm	0.25/0.29	0.25/0.29	0.30/0.36
Pressure angle, degrees	20.0°		
Center distance	308.0		

Table 2. System parameters of the planetary gear

	Sun	Carrier	Planet	Ring	Housing
Mass, kg	181.6	756.9	104.0	480.0	1213.0
I_{xx} , kg m ²	1.26	59.1	3.20	144.2	340.0
I_{yy} , kg m ²	24.0	60.3	2.04	75.4	554.4
I_{zz} , kg m ²	24.0	60.3	2.04	74.4	424.8

Experimental setup and instrumentation

The GRC project instrumented two identical 750 kW wind turbine gearboxes for dynamometer (Figure 3) and field testing. Internal measurements include gear tooth loads, main shaft torque and bending, internal component deflections and misalignments, and planet bearing loads. The full description of instrumentation is detailed in [2].