Planetary Load Sharing in Three-Point- Mounted Wind Turbine Gearboxes

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Yi Guo and Jonathan Keller

National Renewable Energy Laboratory

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Yi Guo
National Renewable Energy Laboratory
Golden, Colorado

Jonathan Keller
National Renewable Energy Laboratory
Golden, Colorado

LIST OF ACRONYMS

CRB	cylindrical roller bearing
GRC	Gearbox Reliability Collaborative
kN	kilonewton
kNm	kilonewton-meter
kW	kilowatt
MW	megawatt
NREL	National Renewable Energy Laboratory
TRB	tapered roller bearing

INTRODUCTION

Wind turbine gearboxes do not achieve their expected design life [1]. The cost of gearbox replacements and rebuilds and the downtime associated with these failures increase the cost of wind energy. In 2007, the U.S. Department of Energy established the National Renewable Energy Laboratory (NREL) Gearbox Reliability Collaborative (GRC). Its goals are to understand the root causes of premature gearbox failures and improve their reliability. To date, the GRC has focused on a 750-kW drivetrain with a three-stage, three-point-mounted gearbox. A nonproprietary version of the gearbox containing CRBs with C3 clearances in the planetary stage was customized. Two of these gearboxes, GB1 and GB2, were manufactured and then tested in the National Wind Technology Center's 2.5-MW dynamometer and in the field [2]. Major GRC findings include the detrimental effect of rotor moments on planetary load sharing and predicted fatigue, and the risk of bearing sliding in low-torque conditions for three-point configuration drivetrains [3].

Based on the knowledge gained from testing and analysis of the original design, the GRC gearbox was redesigned to improve its load-sharing characteristics and predicted fatigue. This new gearbox is named GB3. As shown in Figure 1, its key improvement is the incorporation of preloaded TRBs that support the planet carrier and planets. Roller loads can be optimized and bearing life maximized with a small preload [4]. These preloaded bearings, along with interference-fitted planet pins, improve alignments and load-sharing characteristics. A semi-integrated planet bearing design also increases capacity and eliminates outer race fretting.

Romax Technology, with Powertrain Engineers and the Timken Company (Timken), completed the redesign. Timken manufactured and instrumented the planet gears and bearings. Brad Foote Gearing manufactured the other gearing and assembled the gearbox.

TESTING AND MODELING

The drivetrain operates in a stall-controlled, three-bladed upwind turbine with a rated power of 750 kW. Both versions of the GRC gearbox design are composed of one low-speed planetary stage with three planet gears and a floating sun. GB1 and GB2 planet bearings are commercially available (NJ2232EM1C3), whereas the bearings for the GB3 were custom made (Timken designation NP527934). Tests were conducted in offline, 10%, 20%, 50%, 75%, and 100% power conditions with rotor moments ranging between ±300 kNm based on field tests [2].

Each GRC gearbox has 36 strain gauge pair measurements of planet bearing loads, evenly split between the upwind and downwind bearings, with the majority located in the expected load zones. The nearly identical helical gearing in each gearbox causes an overturning moment on the planets, resulting in a ±20° offset of the center of each load zone from the bearing top dead center. The GB3 measurements focused on the circumferential load distribution, with only one axial measurement on each bearing inner race. One planet (B) has measurements at 10 circumferential locations per bearing row, nine of which span the expected load zone. The other two planets have measurements at four circumferential locations per bearing row [5].

A three-dimensional, finite-element, contact mechanics model in Transmission3D software was used to predict gearbox planetary loads for each gearbox [6]. Bearing fatigue life calculations were made in RomaxWind [7].

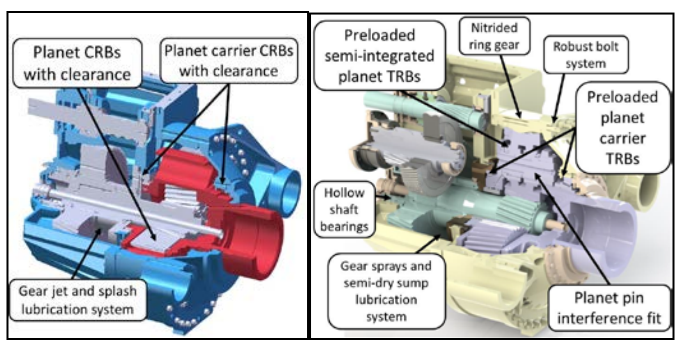

Figure 1. Comparison of the original GB1 and GB2 (left) and the new GB3 (right) design characteristics. *Illustration by Romax Technology*

RESULTS

The planetary bearing loads predicted by the model and measured in dynamometer tests were compared. The roller load at each measurement location was determined by converting the average strain range with calibration factors determined from dedicated bench tests [8, 9]. The bearing loads were calculated by integrating the load zones. The predicted fatigue lives of both planetary designs were also calculated and compared.

Planet Bearing Loads

The upwind and downwind bearing loads can be calculated from the load zones throughout the carrier rotation. The total load supported by both bearings, which is the vector summation of the upwind and downwind bearing loads, can also be calculated. Figure 2 compares these loads nondimensionalized by its theoretical mean over a complete carrier cycle. As shown, the shaft azimuth equals zero at the top, dead center. For GB2, the bearing loads fluctuate over the rotation and are out of phase because of planet and carrier bearing clearances and planet pin compliance. The maximum load carried by the upwind bearing is 43% more than the assumed load, and the minimum load carried by the downwind bearing is 39% less than the assumed load. In this condition, the upwind bearing is accumulating more fatigue than expected; conversely, the downwind bearing has an increased risk of skidding. But because they are nearly 180° out of phase, there is much less fluctuation in the total load than the individual row loads. The bearing loads for GB3 also fluctuate in a manner similar to those of GB2, but with much less amplitude and more in phase as a result of the preload in both the carrier and planet bearings and the interference-fitted planet pins.

Planet Bearing Load Sharing

The accurate estimation of planet bearing loads is a crucial step in calculating the planetary-load-sharing factor, also called the planetary mesh load factor. Figure 3 compares the maximum individual bearing row load and maximum total bearing load (planetary-load-sharing factor) for both gearboxes at full power over the complete range of rotor pitch moments tested. For GB2, the maximum total bearing load ranges from 1.08 at pure torque to just over 1.15. The minimum of the total bearing load does not occur at pure torque but instead around 40 kNm. However, the load carried by the upwind bearing reaches as high as 1.47. Counterintuitively, the maximum value occurs in the pure torque condition and remains high with positive pitch. For GB3, the maximum total bearing load ranges from 1.02 at pure torque to 1.08 for an extreme negative pitch moment. The maximum load of the upwind bearing row is 1.14 in pure toque and no more than 1.17, much lower than GB2, for an extreme positive pitch moment. Detailed discussion on the effects of rotor moments on planetary loads and loads sharing is in [10]. A significant reduction of the maximum loads and improvement in load sharing was achieved with the GB3 design changes.

Planetary Bearing Fatigue Life

L10m life was calculated per DIN ISO 281 Beiblatt 4 (superseded by ISO TS 16281), including a systems life modification factor. As shown in Figure 4, the predicted fatigue life of the upwind bearing was significantly increased in GB3, in addition to a smaller life extension in both bearings because of the larger bearing capacity in the semi-integrated design. The planetary-stage predicted fatigue life has been increased by a factor of 3.5, from 3.4 years for GB1 and 2–11.9 years for GB3 as shown in Figure 4.

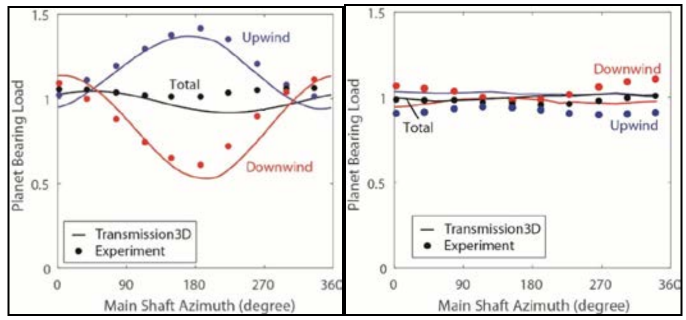

Figure 2. Planet bearing loads in pure torque for GB2 (left) and GB3 (right)

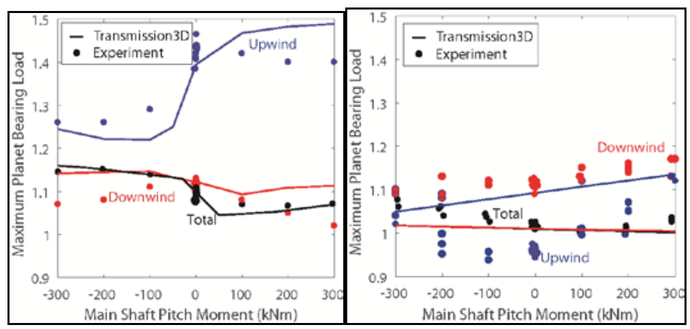

Figure 3. Maximum planet bearing loads for pitch moments for GB2 (left) and GB3 (right)

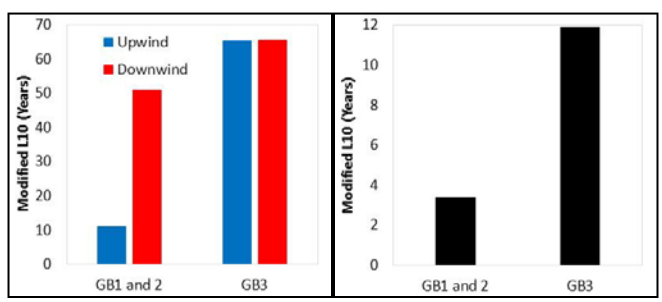

Figure 4. Fatigue life for the planet bearings (left) and planetary bearing stage (right)

Summary

The gearbox design with preloaded TRBs demonstrated improved planetary-load-sharing characteristics in the presence of rotor pitch and yaw moments. Compared to the gearbox with CRBs, the upwind planet bearing loads in the gearbox with preloaded TRBs were reduced significantly from a maximum of

1.47 to 1.14 in pure torque conditions. Furthermore, the upwind and downwind bearing row loads were not significantly affected by rotor moments and the difference between the row loads was also reduced. This reduction and equalization in loads, along with slightly larger capacity bearings as a result of the semi-integrated design, led to a predicted L10m life 3.5 times greater for the gearbox with preloaded TRBs than for the gearbox with CRBs.

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