



American
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Technical Resources

12FTM06

AGMA Technical Paper

Virtual Optimization of Epicyclic Gearbox Planet Bearings in Wind Turbines

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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

Demand for higher reliability, robustness and performance in epicyclic gearboxes have led SKF to develop Design for Six Sigma (DFSS) based simulation tools and methods.

This paper will illustrate the advantages of using simulation driven design in the development of planetary gearboxes for multi megawatt wind turbines. The simulation example will show the influence of the housing flexibility and of the non-linear bearing and gear stiffness on the gearbox performance under transient load. In particular the load distribution and deformation of the planetary gears and bearings will be analyzed.

The flexibility and accurate stiffness description led to non-intuitive results. The gear deformation and load distribution led to significantly different results compared to results obtained by using traditional calculation tools and methods. A comparison between advanced and standard calculation methods is given as evidence that advanced analyses should be used to design reliable, robust and high performing gearboxes.

A virtual design of experiments was used to determine the most influential parameters affecting the gearbox performance. This paper will highlight the results of this DFSS study.

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1001 N. Fairfax Street, Suite 500
Alexandria, Virginia 22314

October 2012

ISBN: 978-1-61481-037-7

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Introduction

Optimization of design parameters in wind turbine gearboxes has become increasingly important to achieve longer bearing service life. To answer the demand for improved performance a detailed simulation model of an epicyclic gearbox was created. By means of numerical simulations the computer model was used to analyze the performance at different loading conditions. The simulation model was also used to perform a Design and Analysis of Simulation Experiments (DASE). The DASE analysis consisted of a virtual design of experiments aimed at understanding the relationship between various design parameters and the maximum contact pressure at the bearing raceway location. By applying virtual optimization methodologies it is possible to explore the design space without investing in expensive prototypes and without biases from manufacturing errors. An optimized choice of design parameters makes the system more robust to variation in its noise factors and loading conditions.

Bearing fatigue life

This chapter will present two different life calculations. The first is the Basic rating life method. The second is the DIN ISO 281 addendum 4 method. The bearing life referenced to in this report is the calculated L10 raceway fatigue life. L10 bearing life is defined as 90% of the bearings exceeding the calculated value.

ISO basic rating life

The basic rating life in hours is calculated according to ISO 281 without environmental effects and operating conditions considered as:

$$L_{10h} = (C/P)^p \times 16667/N \quad (1)$$

where

- C is basic dynamic load rating, kN;
- P equivalent dynamic bearing load, kN;
- p is exponent of the life equation;
- N is revolutions/minute.

Fatigue life DIN 281 addendum 4

The second life calculation method presented here is the DIN ISO 281 Addendum 4 method. This method considers the individual rolling element loads to calculate the equivalent dynamic load. This life method is based on rolling element load and does not include rolling element contact stress integration. The modification factor for lubrication and contamination a_{DIN} is averaged over all roller elements.

The NREL collaboration project

The National Renewable Energy Laboratory in Golden, CO, USA started a wind energy program, the Gearbox Reliability Collaborative (GRC), to address reliability issues on wind turbine gearboxes. The input data used in this article was provided by NREL. This includes 3D models, 2D drawings and loading conditions. This allows the simulation to be representative of real operating conditions in wind turbines.

Gearbox model

The gearbox is composed of three stages: an epicyclic stage and two parallel, helical stages. The main focus of this analysis was the low-speed epicyclic stage as shown in the following pictures. To achieve a better understanding of the system interactions and a higher modeling accuracy the simulation model has been developed including all stages and the housing. The model was created using SKF Advanced Simulator, which is an SKF-proprietary simulation software. See Figure 1.

Optimization using numerical simulation

The approach followed in this study is shown in Figure 2. Note: The yellow box in Figure 2 covering Boundary diagram all the way through to Variation modes and effects analysis are the tools that require brain storming sessions with different key participants.

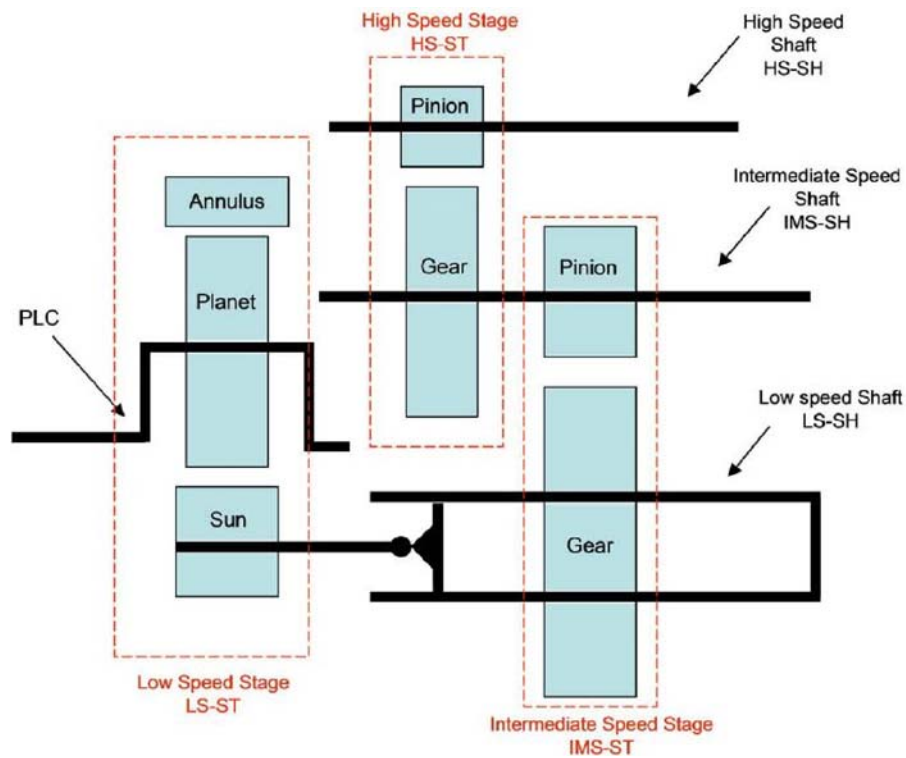


Figure 1. Wind turbine gearbox

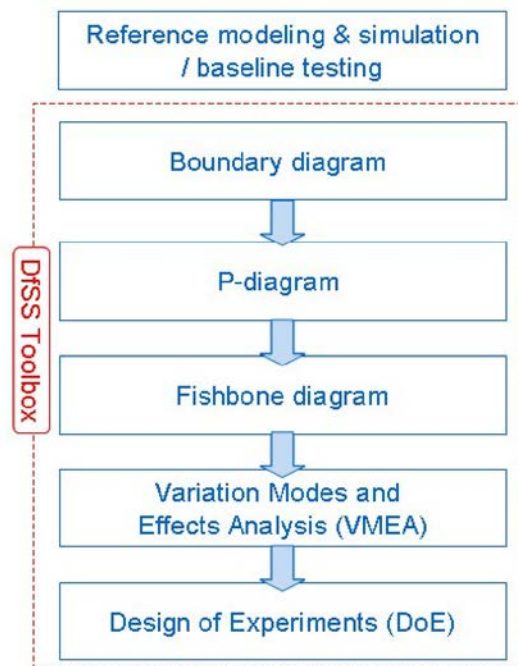


Figure 2. Approach

The design for six sigma approach

The design for six sigma, DFSS, approach addresses quality when it is easiest and cheapest to improve, when the design is still on paper. By assessing the variations that a product experiences during manufacture, shipping, storage, installation and use, it is possible to minimize the effects as a product performs its intended function regardless of these variations; such a product is “robust.” DFSS is a process to determine the extent to which uncertainties in the model affect the results of an analysis. Based on a probabilistic characterization, DFSS enables users to quantify the quality of product, addressing issues such as functional performance, minimization of warranty costs and reliability. DFSS goes one step further than a probabilistic characterization by allowing users to optimize individual design variables to achieve system optimization including the product performance, material, and manufacturing costs.

Boundary diagram: The boundary diagram is a diagram which defines and lists out the different components in the system and their interaction. It is important at this phase to list out all the components in the system, their interaction mode with each other and its surrounding environment.

Parameter diagram: Is a diagram that lists the inputs to the system and the desired outputs. This diagram also contains the details of the design parameters and the noise parameters/factors that could potentially affect the desired output.

Variation modes and effects analysis, VMEA: All the noise factors that affect the particular control parameter are ranked according to its influencing effect on the desired output. This ranking process helps systematically isolate the most important parameters to be considered for the sensitivity analysis.

Design of experiments, DoE: Now that the most relevant parameters are chosen and the limits on its extremes decided, a design of experiments analysis will be performed on the selected parameters using virtual simulation.

System boundary diagram

In order to be able to define the important parameters influencing the calculated bearing L10 fatigue Life of the planet bearings, a tool known as the boundary diagram was utilized. A boundary diagram defines the interactions of the components of the planetary stage and its immediate surrounding components, including the inputs and desired responses. During the design of the diagram, it was decided to focus on the ISO/TS 16281 (DIN ISO 281 addendum 4) L10 fatigue life and the Basic rating L10 fatigue life of the planet bearings Figure 3 below shows the boundary diagram from the planet stage. The interactions between different components in the planet stage are shown within the dotted red box. The inputs are listed on the left, and the output from the system and the desired response are listed on the right.

System parameter diagram

The boundary diagram developed facilitates using information for additional processing using a tool called the Parameter diagram (P-Diagram), Figure 4. This diagram helps identify and sort the control (or design parameters) and the noise parameters that could potentially affect the desired response. The control/design parameters are parameters that can be controlled (control parameters) and factors that cannot be controlled or noise in the system are (noise factors/parameters). This structure helps to identify all the control and noise parameters that can be of importance for the desired outcome (Calculated planet bearing L10 fatigue life).

The noise factors are further divided into five different categories, Figure 5.

Variation modes and effects analysis, VMEA

In the variation modes and effects analysis, VMEA, tool each of the noise factors was ranked for its ability to affect the desired response. Table 1 below presents a portion of the VMEA spread sheet. The ranking numbers in the sheet were determined together with experts in the field of gearbox design, bearing consultants, wind turbine manufactures, testing experts and other members of the NREL analysis collaborative. The final risk priority number for the different design parameters and noise factors are calculated based on these rankings. Based on the prioritization created in the VMEA, six parameters were identified as most critical.