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On long-term fatigue damage and reliability analysis of gears under wind loads in offshore wind turbine drivetrains

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ABSTRACT

In this paper, a long-term fatigue damage analysis method for gear tooth root bending in wind turbine's drivetrains is presented. The proposed method is established based on the ISO gear design codes which are basically developed for gears in general applications, not specifically for wind turbine gears. The ISO procedure is adapted and further improved to include the long-term fatigue damage of wind turbine's gears. The load duration distribution (LDD) method is used to obtain the short-term stress cycles from the input load time series of global response analysis. Dynamic loads and load effects in the gearbox are obtained by two dynamic models; a simplified approach and Multi Body Simulation (MBS) method. A good agreement between these two methods is observed. The long-term fatigue damage is then calculated based on the SN-curve approach by considering all short-term damages and the long-term wind speed distribution. Finally, the reliability and service life probability of failure considering load and load effect uncertainties is calculated. The procedure is exemplified by a 5 MW gearbox designed for a pitch controlled, bottom-fixed offshore wind turbine.

1. Introduction

The recent developments in drivetrain technologies have brought a wide range of options for wind energy industry. Alongside the dominant high ratio gearboxes, medium ratio gear trains, direct drives, hydraulic drives, differential and variable speed gearboxes are available commercially in the wind turbine market. Yet, the majority (90%) of drivetrains in currently installed turbines are based on gear technology [1]. The wind turbine gearbox failure investigations carried out by Musial et al. [2] indicate that the design process may have the biggest contribution to the premature failures of wind turbine gearboxes. The first wind turbine gearbox design code, ISO 81400-4 [3] was issued in 2005 and replaced by the extensively modified IEC 61400-4 standard [4] recently in December 2012. According to this design code, the gears in wind turbines shall be designed based on ISO 6336 [5–9] series for calculation of the gear load capacity. The ISO 6336 design procedures are for gears in general applications and are not customized for any specific usage. Thus, the IEC 61400-4 has set the minimum level of safety factors which should be considered while following ISO 6336 procedures for wind turbine applications. It is, however, unknown what level of reliability can be achieved by using the IEC safety factors.

Part 6 of ISO 6336 [9] – the newest part in the 6336 series with first edition issued in 2006 – covers the calculation of gearbox service life under variable loads for general applications. In order to use the ISO 6336-6 for wind turbine gears, further improvements and adaptations are required. In ISO 6336-6 or IEC 61400-4, no procedure for the long-term fatigue damage calculation is offered. There are few publications about the fatigue analysis of wind turbine gears in which only the short-term fatigue is addressed [10,11].

The stress range and fatigue cycle counting have also their own challenges in wind turbine gears. The load response or stress range for gears is fundamentally different than shafts or other components in the gearbox. In every rotation, a single tooth undergoes root bending or surface pitting stress ranging from zero to a certain peak value which does not explicitly correspond to the input load fluctuations. This is due to the fact that the gear stress range is not only a function of the external load fluctuations but also it is a function of gear rotational speed. In wind turbines, the stress range for different gear stages should be established by taking into account both load and speed variations. Therefore, the stress cycle counting method for gears is not the same as for structural components [4].

In order to overcome the problem with the stress range and cycle counting, the load duration distribution (LDD) method which

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is based on the stress bins, is recommended by IEC 61400-4. The number of stress bins influences the calculated fatigue damage, thus it is important to establish a minimum level for the bin numbers in wind turbine gear design.

In this paper, a long-term fatigue damage calculation method for gears in wind turbine drivetrains is proposed. The method is developed based on the ISO 6336-6 and is customized for wind turbine gears rather than for gears in general applications. The reliability of the gears designed by this method is then calculated by the structural reliability approach considering the load, load effect, and resistance uncertainties. The scope of the paper is limited to the gear tooth root bending fatigue, though the procedure described herein can be used for the pitting damage calculation of gears provided that related gear surface stress equations are used. The method is exemplified by a 5 MW gearbox designed for a bottom-fixed offshore wind turbine.

2. Long-term environmental condition and global analysis

The wind load is the only environmental load considered in this study. Since the wind turbine is bottom-fixed, the influence of wave loads on the drivetrain response can be neglected. The probability density function of 1-h mean wind speed at 10 m above the average sea level is modeled by the 2-parameter Weibull distribution [12,13]:

$$F_U(u) = 1 - \exp\left[-\left(\frac{u}{a}\right)^c\right] \quad (1)$$

a and c are the shape and scale parameters which, for instance, are 8.426 and 1.708 for Northern North sea respectively [12]. The wind speed at hub height is calculated from the power law, with the power value of 0.14 for offshore fields [14]:

$$u_{hub} = u\left(\frac{h_{hub}}{10}\right)^{0.14} \quad (2)$$

It should be noted that the cut-in, rated and cut-out wind speeds given in the wind turbine specifications refer to the wind speed at the nacelle height, 90 m above the average sea level [15].

A decoupled analysis method is used to estimate the drivetrain dynamic response from the environmental load, i.e. the wind load. The global analysis is performed first, using the aero-servo-elastic code HAWC2 [16], followed by a local analysis of the drivetrain using a simplified method and considering the main shaft torque from the global HAWC2 analysis as input. The response analyses are carried out considering the long-term input loading. In order to minimize the statistical uncertainties, 15 simulations are carried out for each wind speed over 800 s. and the first 200 s. is removed to avoid start-up transient effects. The reference turbulence intensity factor is taken as 0.14 for all the wind speeds, according to IEC 61400-1 class B turbine.

3. 5 MW case study gearbox

In this study, a 5 MW gearbox has been designed and utilized to demonstrate the proposed procedure. The gearbox configuration follows the common wind turbine designs with three stages, two planetary gears and one helical gear pair. In order to avoid complexities with respect to the load sharing behavior between planets [17], the planetary stages are designed with three planets. The turbine data are taken from NREL 5 MW fixed offshore reference turbine, presented in Table 1 [18]. For any wind turbine design, there is always more than a single gearbox solution. In practice, apart from the minimum requirements set by design codes, many project-specific factors such as installation issues, weight, manufacturing limitation and material availability influence the gearbox design. The gearbox in this paper is intended to illustrate the gear fatigue design procedure and no optimization with respect to the weight and size is considered. Figs. 1 and 2 and Tables 2 and 3 present the gearbox layout, topology and technical data. All data are provided; thus, one can replicate the proposed procedure through the given example and employ the method for industrial applications.

Table 1
5 MW NREL reference wind turbine [18].

Rated power (MW)	5
Cut-in wind speed (m/s)	3
Cut-out wind speed (m/s)	25
Rated wind speed (m/s)	11.4
Rated rotor speed (rpm)	12.1
Hub height, above mean sea level (m)	90
Rotor diameter (m)	126
Power control system	Pitch

4. Long-term gear tooth root bending fatigue

The aim of the ISO 6336-6 standard is primarily to evaluate the safety factor of an existing design against fatigue damage under variable loads. The ISO procedure starts with establishing torque bins from the input torque time series and calculating the stress bins based on the upper level of each torque bins. The fatigue damage is then obtained from the Palmgren–Miner hypothesis of linear damage and gear SN curve data. The iteration to calculate the safety factor (S_F) continues until the damage is within the range

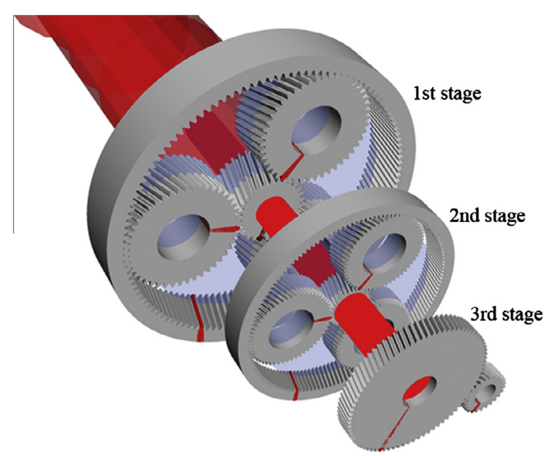

Fig. 1. Three-stage gearbox for 5 MW wind turbine.

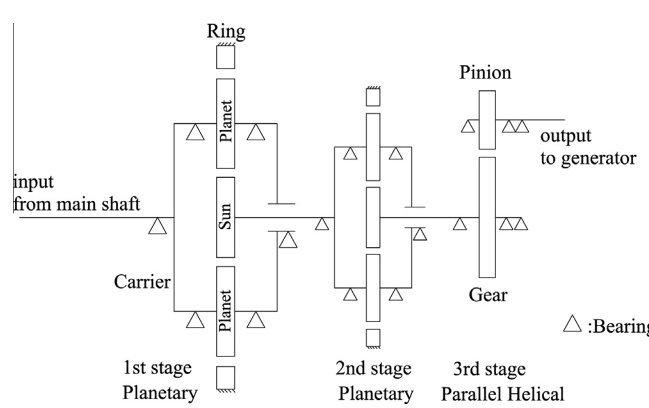

Fig. 2. Topology of the 5 MW gearbox.