EFFECT OF PITTING ON EXCITATION BEHAVIOUR OF A PLANETARY GEAR SET WITH SEQUENTIAL MESH PHASING

Uwe Weinberger, M.Sc., Dipl.-Ing. Bernhard Kohn, Dipl.-Ing. Max Fromberger, Dr.-Ing. Michael Otto and Prof. Dr.-Ing. Karsten Stahl

Technical University of Munich, Gear Research Centre (FZG), Garching, GER

email: weinberger@fzg.mw.tum.de, kohn@fzg.mw.tum.de, fromberger@fzg.mw.tum.de, otto@fzg.mw.tum.de, fzg@fzg.mw.tum.de

Compared to gearboxes with cylindrical gear stages, planetary gear stages have an increased power density. Hence gear failures could lead to a malfunction of the whole gear box. Condition monitoring helps to detect gear failures.

Pitting on the flanks of gear wheels is one mechanism of gear failure. Pitting does not lead to instant failure, but increases during running time. Hence the characteristics of the excitation behaviour of a planetary gear stage worsen during running time.

Due to rotating planet shafts, measurements on separate gear meshes are connected with great effort. Measurement results for transmission error of a single stage, e.g. transmission error of the stage sun-planet, are usually not available. Thus it is more common to measure the total transmission error (TTE) or the orbit of the sun of planetary stages.

Especially for planetary gear sets with a sequential mesh phasing, where the torque excitation is quite small compared to other sorts of mesh phasing, it is challenging to implement condition monitoring for planetary stages by using TTE. An alternative to using TTE to monitor the excitation behaviour could be to monitor the sun orbit. In an initial step, the influence on excitation of pitting on is therefore analysed by simulation.

The FZG employs a simulation tool called RIKOR3D, which is capable of performing a quasi-static analysis of a whole gearbox, including planetary gear stages. This software is based on RIKOR, a FVA software application, and it calculates the deformations of discrete mesh positions for the whole gear box system. The results of this analysis of a planetary stage are the TTE between input and output as well as the deflections of the different gear wheels.

Keywords: Planetary Gear Stage, Excitation Behaviour, Transmission, Transmission Error, Simulation

1. Introduction

The importance of efficiency is increasing all the time. Hence the weight and therefore the power density of gearboxes are gaining in importance. Due to the high power density of planetary gear stages compared to cylindrical gear stages, the use of the former is favoured, especially because a wide range of gear ratios can be achieved with them. These advantages have led to the usage of planetary gear stages in wind turbine gear boxes. Due to a minimum design life of twenty years for wind turbine gear boxes [1], the importance of the reliability of the gear boxes is significant [2].

Notwithstanding this focus on high reliability, it is still possible for gear failures to develop towards the end of the design life. If such failures occur, they may lead to a breakdown of the gearbox.

Since downtimes lead to costs for the operator, downtime should be prevented or shortened. One way to do this is to implement gear failure detection. There are gear failure mechanisms on the flanks of gear wheels. One of them is pitting. Once pitting occurs, it progresses over the running time. In other words, it does not lead to an instant failure of the gear wheel [3]. This characteristic makes it possible to detect this failure by evaluating the excitation behaviour of the gear stage. It is common to use an observation of the acceleration at the housing in the direction of the gear mesh to detect gear failures [4, 5]. By adding some absolute rotary sensors, it is even possible to identify the faulty tooth of the mesh being investigated [6].

Using planetary gear stages with a ring gear mounted to the housing is common practice in a variety of applications. Hence the planet carrier and the planets are rotating. This means that the meshes between sun and planet and between planet and ring gear do not have a fixed orientation, which makes it more difficult to analyse the acceleration measurements at the housing. [2]

Lei et al. [7] investigate diagnostic parameters for fault detection in planetary gearboxes. In their paper they show that it is feasible to compare the sprektra of measurements without and with gear failure to detect faults. The dynamic response of a planetary gear failure has been investigated by Chari et al. [8].

Investigations show that the characteristic of the transmission error (see section 3.1) of a helical gear stage deteriorates during running time, if pitting occur [4, 5]. Hence it is obvious that the transmission error could also be used for condition monitoring. Due to a complex application and limited installation space, measurement results for the transmission error of a single gear stage, e.g. the transmission error of the stage sun-planet, are usually unavailable [2]. But it is possible to measure the total transmission error between input and output of the planetary gear stage (see section 3.2) and the movement of one of the central shafts. The influence of pitting on the excitation behaviour of an exemplary planetary gear stage with sequential mesh phasing is examined in this paper.

2. Fatigue Gear Failure Pitting

As described in [2] pitting is a gear failure that is suitable for condition monitoring. Fig. 1 shows an example of pitting failure on a tooth flank of a test gear. It is commonly known that pitting is more likely to occur in areas with negative specific sliding, which means that pitting occurs in the dedendum of the gear wheel [9]. The characteristic appearance of pitting are shell-shaped outbreaks [9]. These outbreaks are generally initiated by surface cracks [9]. In general pitting starts with small

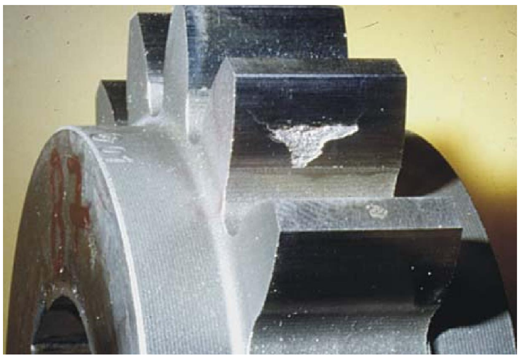


Figure 1: Example of pitting on a cylindrical gear stage [9]

outbreaks which increase during running time. Hence pitting does not lead to an instant failure of the gear stage, but the contact conditions in the area of pittings and the load dependent deflections are different to those in an undamaged tooth flank. Thus it is reasonable to detect pitting by monitoring the excitation behaviour of the gear stage. [9]

3. Excitation Behaviour of Gear Stages

3.1 Transmission Error

Different parameters are used to characterize the excitation behaviour of gear stages in calculation. Quasi-static and dynamic calculations are ways to obtain those parameters [10]. A quasi-static analysis is sufficient as characterization of the excitation behaviour if the operating point of the gear box is in the subcritical domain of the vibration behaviour [11]. The transmission error is a commonly known parameter for characterization of the excitation behaviour of cylindrical gear stages, for example Feki [12] describes the use of transmission error measurements to detect pitting. The deflection due to the applied load along the line of contact is called the transmission error (TE). In general, the transmission error is specified in mm of line of contact. [10]

The stiffness of gear teeth during their contact is variable along the line of contact. This leads to a deflection from the perfect involute shape. Hence the Transmission Error fluctuates. The decisive parameter for characterization of the excitation behaviour of a single gear stage is the fluctuation range of the transmission error, which is called Peak-to-Peak-transmission rrror (P2P-TE) [13]. Fig. 2 shows the Transmission Error and the Peak-to-Peak-transmission error (P2P-TE) of the gear mesh sun-planet of a similar gear box as shown in section 4.

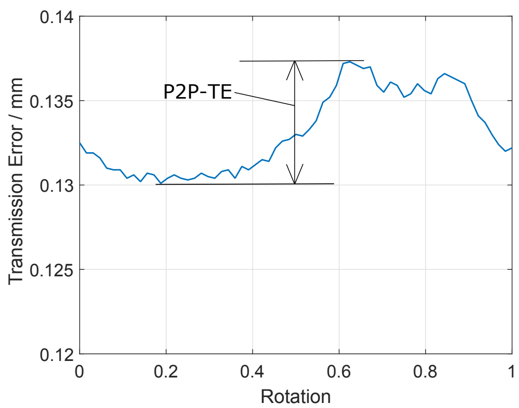


Figure 2: Example of a transmission error in a sun-planet gear mesh [2]

3.2 Total Transmission Error in Planetary Gear Stages

While designing macro and micro geometry for the single gear stages in planetary gears, the transmission error is commonly used to characterize the excitation behaviour. Garcia [4] shows that it is possible to use the transmission error for condition monitoring. Regarding planetary gears with a rotating planet carrier a significant effort is necessary to measure the transmission error. The total transmission error is a more suitable parameter parameter to characterize the impact of the excitation behaviour of a gear box on the attached machines at input and output. Smith [14] defines the total transmission error as the difference between the actual position of the output shaft of the gear box and the position that the output shaft of the gear box would have without errors and deflections. The total transmission error is characterized by Neubauer in the same way [15] .

3.3 Influence of Mesh Phasing on the Excitation Behaviour

According to a number of authors [13, 16] the mesh phasing (e.g. symmetric or sequential) has an influence on the excitation behaviour of planetary gear stages. With a symmetric mesh phasing, all the meshes in a planetary gear stage are in the same mesh position, hence there is a strong excitation in the circumference and a small excitation in radial direction. Since the meshes are not in the same mesh position in other mesh phasings (e.g. sequential or star-shaped), the characteristics of these mesh phasings show a smaller excitation around the circumference and a higher excitation in radial direction.

3.4 Calculating the quasi-static Excitation Behaviour with the Simulation Tool RIKOR3D

The simulation tool, used to calculate the quasi-static excitation behaviour of a planetary gear stage, is called RIKOR3D. The model for the calculations in RIKOR3D is described by Neubauer [17].

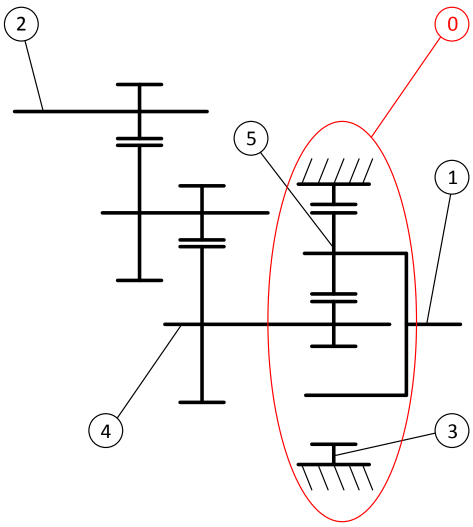
To obtain the model, the first step is to create the element stiffness matrices of all the machine elements that need to be considered for the calculations. Apart from the gear mesh, the most important machine elements are the shafts and the bearings. The shafts are connected to each other by the gear mesh or the bearings. The bearings also connect the shafts to the housing. The element stiffness matrix of the gear meshes is calculated separately for each mesh position, according to Schmidt [18] and Weber/Banaschek [19]. Following assembly, the element stiffness matrices and the boundary conditions, such as the input torque, the model is solved.

After creating and solving the model for each mesh position, the total transmission error is extracted from the results. [15] Since the flank modifications influence the excitation behaviour, they have to be considered in the calculations.

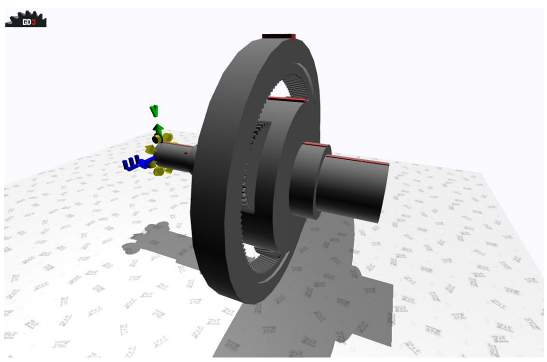
Multi-body models are also used by Inalpolat and Kahraman [20] and Guo and Parker [21] for the analysis of the excitation behaviour of planetary gear stages.

4. Calculated Sequential Planetary Gear Stage

A similar planetary stage, which was employed in [2], is used to show the influence of pitting in this paper. The difference between the two planetary gear stages is the mesh phasing and hence the teeth numbers. Here, the planatery gear stage (see Fig. 3b) has a sequential mesh phasing. The gearbox, in which this planetary stage is included, is used in a wind turbine. A diagram of the gearbox is shown in Fig. 3a. As described in [2] this gearbox consists of two cylindrical gear stages and a planetary gear stage and has a gear ratio of 0.0128.



(a) Schematic representation of the wind turbine gear box with planet carrier as input (1) and the output shaft (2). The planetary gear stage (0) with its planets (5) and its sun shaft (4), which is discussed here, is marked in red. [2]



(b) 3D representation of the model of the planetary gear stage

Figure 3: Wind turbine gear box and planetary gear stage

The following table shows the main geometry data of the planetary gear stage:

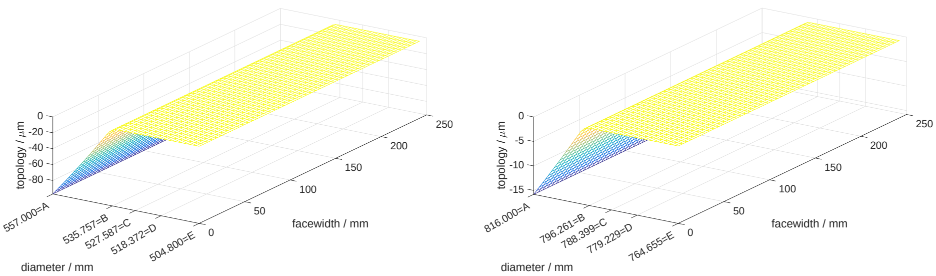
Table 1: Macro Geometry of Planetary Gear Stage

	Sun	Planet	Ring-Gear
Module	16 mm		
Number of Teeth	32	48	-127
Pressure Angle	20°		
Active Tip Diameter	557.00 mm	816.0 mm	-2075.00 mm
Facewidth	242 mm	242 mm	242 mm
Helical Angle	$+12°$	$-12°$	$+12°$
Transverse Contact Ratio	1.503		
Overlap Ratio	1.001		
Length of Path of Contact	72.398 mm 72.392 mm		

This geometry leads to a gear ratio of 0.2012 of the planetary gear stage between carrier and sun. The carrier of the planetary gear stage is the input. The sun of the planetary gear stage is used as output of the planetary gear stage. The ring gear is fixed to the housing. The power of the gear box is 2 MW.

Mesh phasing has a great influence on excitation behaviour. In comparison to the planetary gear stage discussed in [2], this gear stage has a sequential mesh phasing.

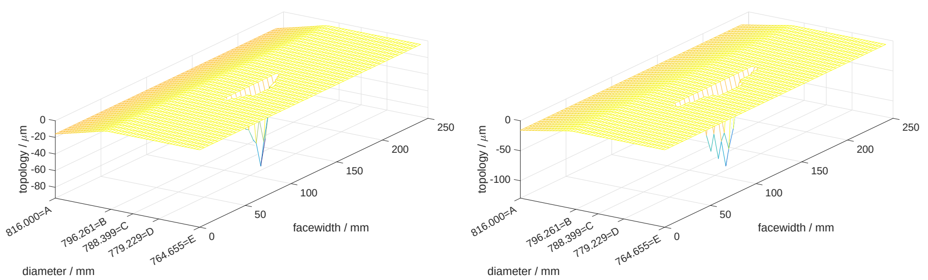
As already discussed, the excitation behaviour of a cylindrical gear stage is influenced by the flank modifications. In this case, both the sun gear and the planet gear have a tip relief. Both are shown in Fig. 4. To analyse the influence of pitting on the excitation behaviour of planetary gear stages, four



(a) Tip relief of sun gear (b) Tip relief of planet gear

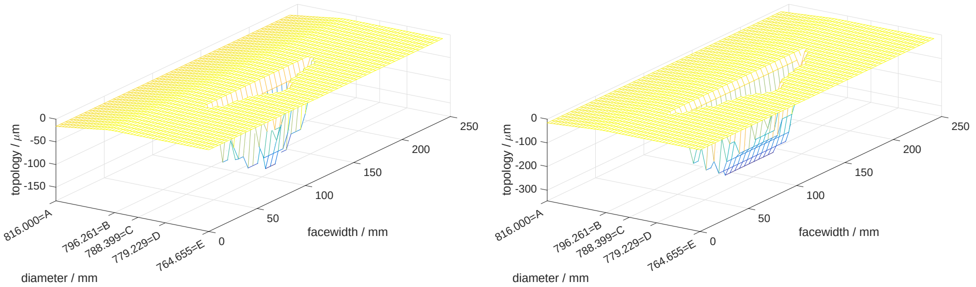
Figure 4: Flank modifications of the planetary gear stage

different sizes of pitting are applied to the sun wheel, as it is the pinion in our planetary gear stage example. Fig. 6 shows the different pitting sizes that were applied to one planet gear as an overlay to the flank modification. The same pitting sizes as described in [2] are used here.



(a) Pitting Size 1, corresponds to 1.11 % area of active tooth flank (b) Pitting Size 2, corresponds to 2.64 % area of active tooth flank

Figure 5: Pitting Sizes 1 and 2 with their partial pitting size

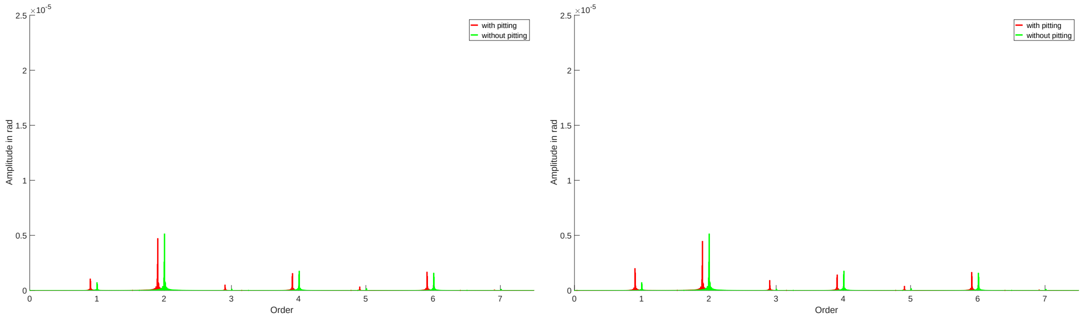


(a) Pitting Size 3, corresponds to 4.72 % area of active tooth flank (b) Pitting Size 4, corresponds to 8.04 % area of active tooth flank

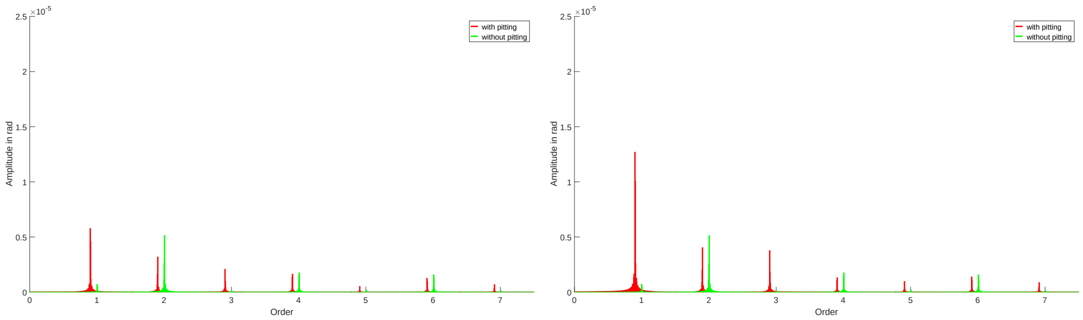
Figure 6: Pitting Sizes 3 and 4 with their partial pitting size

5. Description of Simulation Results

As described in [2] a deteriorating effect on the total transmission error clearly existed for the symmetric mesh phasing. To investigate this effect for sequential mesh phasing, the spectrum of the total transmission error was investigated. Fig. 7 shows the spectrum of the total transmission error of the four different pitting sizes compared to the spectrum without pitting from order 1 until 7.



(a) Pitting Size 1 (1.11 %) (b) Pitting Size 2 (2.64 %)



(c) Pitting Size 3 (4.72 %) (d) Pitting Size 4 (8.04 %)

Figure 7: Spectrum of the total transmission error with Pitting compared to the Spectrum without Pitting (Partial Size of the Tooth Flank)

Fig. 7 clearly shows a deteriorating effect and a change in the amount of the total transmission error for the first order, which is leading back to the application of the pitting to one planet. Fig. 8 shows the level of the total transmission error, which was calculated according to the calculation of a vibration level in [22]. There is only a slight change in the Level of total transmission error for the smaller two pitting sizes. Furthermore, the amplitude of the total transmission error is reduced compared to the symmetric mesh phasing of a similar gear box in [2]. Since the range of the total transmission error in [2] was only slightly above the minimal measurable value, it will be difficult or even impossible to

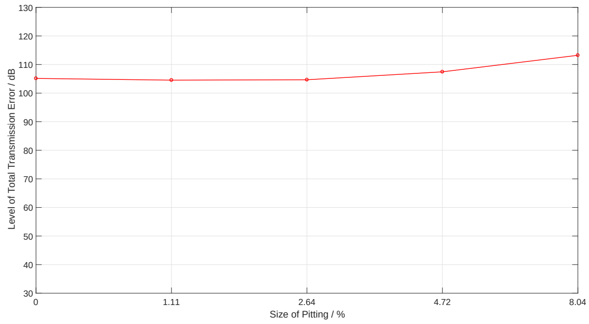


Figure 8: Level of total transmission error according to Size of Pitting

detect pitting at an early stage of its appearance with state-of-the-art rotary sensors.

As described in section 3.3, planetary gear stages with sequential mesh phasing have a higher excitation in radial direction. Hence it is also feasible to investigate the influence of pitting on the orbit of the sun shaft. Fig. 9 shows the absolute value of the sun eccentricity for the different pitting sizes and without pitting for several base pitches. Since distance sensors are able to measure down to

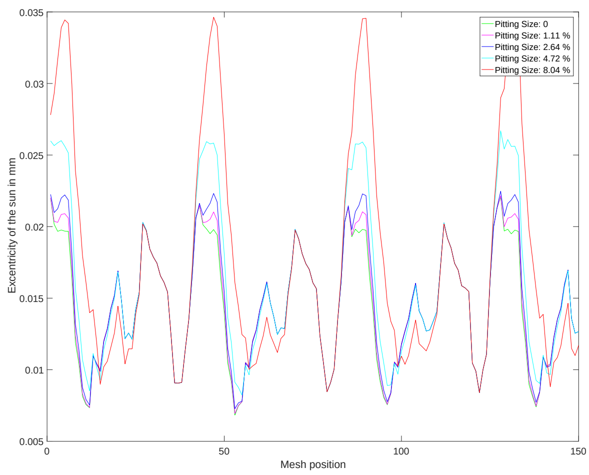


Figure 9: Absolute value of sun eccentricity for several base pitches

$1\mu\mathrm{m}$ or even below and the deterioration of the sun eccentricity is already some $\mu\mathrm{m}$ for the smaller pitting sizes, it could also be feasible to perform condition monitoring by measuring and evaluating the radial position of the sun shaft.

6. Conclusion

Pitting is a gear failure mechanism that does not lead to an instant malfunction of the gearbox but progresses during running time. This leads to a deterioration in excitation behaviour. It is possible to use this deterioration to perform condition monitoring. Evaluating the total transmission error or the orbit of the sun gear are two possibilities of condition monitoring. These two possibilities were investigated by simulation in this paper. The model of the gearbox used to conduct the quasi-static simulations was shortly described in section 3.4.

Section 5 shows the differences in the spectra of the total transmission error between the calculations with and without pitting. For the bigger pitting sizes the deterioration is also visible in the level of the total transmission error.

Since the amplitudes for a sequential mesh phasing are quite small, it is difficult to do the measurements with state of the art absolute rotary sensors. Hence the movement of the sun was additionally analysed for the planetary gear stage to check if condition monitoring could be performed by evaluating the movement of the sun. For this reason, the absolute value of the sun eccentricity was shown in section 5. The movement of the sun shows that there is a deterioration for the smaller pitting sizes as well.

The results described show that it is difficult to monitor wehther pitting occurs in a planetary gear stage with sequential mesh phasing by measuring the total transmission error with state-of-the-art rotary sensors. The results show that a monitoring of the radial excitation or rather the orbit of the sun could instead be more promising, depending on the bearing support of the sun gear.

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