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Analysis of dynamic excitation behavior of a two-stage spur gearbox

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Abstract

In times of engine downsizing and lightweight design, the dynamic and acoustic behavior of multi-stage gearboxes is becoming increasingly important. One parameter is the manufacturing quality of the gears which can be expressed by DIN standard and is influenced among other things by the production process.
The presented objective is the analyzation of the dynamic behavior with focusing dynamic interactions of two-stage gearboxes. To achieve this goal, gears with different micro geometries and the interactions between the meshes are investigated mathematically. Therefore, a dynamic multi body simulation model is presented in which gear meshes will be described as force coupling elements.

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1. Introduction

Multi-stage cylindrical gearboxes are used in the entire drive technology. In addition to a sufficient load capacity and a high efficiency of the gearbox, the acoustic behavior has to be taken into account. The increasing demands on the acoustic behavior appear in customer requirements and amended law restrictions, e.g. in car or wind industry [6, 16]. For this reason, it is not sufficient to evaluate the physical characteristic values of noise and, hence, psychoacoustic metrics have to be considered. For a single-stage gearbox, several research projects have been carried out [3, 4, 12, 13, 14]. Because of the mutual interactions between the gear meshes at a two-stage gearbox, the knowledge cannot be transferred directly without restrictions. Throughout scientific research, the minority of the reports focuses on the acoustic behavior of two-stage gearboxes and evaluating the emitted noise with psychoacoustic metrics.

The excitation behavior of gearboxes is determined by the gear mesh excitation. A selection of influence factors is shown in Fig. 1. In order to reduce the parametric excitation, an integer contact ratio is recommended by changing for example the helix angle or the face width [18]. On the one hand, flank modifications reduce the path-dependent excitation. On the other hand, they are often used to reduce the impact excitation. The consideration of parametric, path-dependent and impact excitation in the acoustic-oriented design of single-stage gearboxes is state of the art especially under quasistatic and partly under dynamic conditions [10, 14, 20].

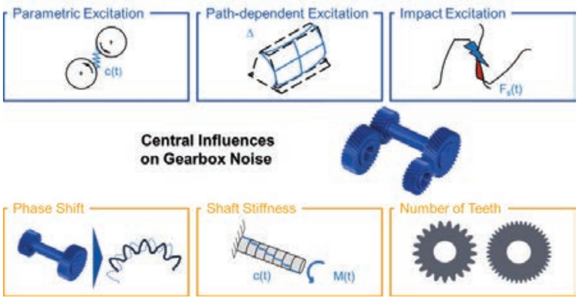

Fig. 1. Excitation and Noise Behavior of Two-stage Gearboxes

For multi-stage gearboxes, further parameters have to been taken into account. Firstly, the begin of the gear meshes is

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temporally displaced. This phenomenon is called phase shift. Furthermore, the stiffness of the connecting shaft between the gear meshes influences the excitation. Due to a differing number of teeth, the noise behavior of gearboxes changes. In this report, the influence of the stiffness of the connecting shaft and the number of teeth are investigated by means of calculations.

Nomenclature

α_n	Pressure angle
$A_{25.Ord\text{-}2st}$	Output value
β	Helix angle
b	Face width
$E_{25.Ord\text{-}2st}$	Input value
f	Frequency
$G(j\omega)$	Absolut value of the transfer function
i	Ratio
M_i	Torque
m_n	Module
n_i	Rotational speed
Ord_{ist}	Order of the i. stage
z_i	Number of teeth

2. State of the Art: Excitation behavior of Two-Stage Gearboxes

The excitation behavior of single-stage gearboxes is topic of many research activities [3, 4, 12, 13, 14]. Based on these researches, there is some scientific work dealing with mutli-stage gearboxes. Mostly, it is discussed by means of calculated theoretical models and rarely compared with empiric investigations.

GOLD conducts numerical and experimental investigations with three-stage gearboxes. GOLD develops a vibration model using only the torsional degree of freedom. Furthermore, this model is extended to a spatial system using all six degrees of freedom to perform dynamic analysis. His work indicates the necessity of spatial simulation models to identify the eigenfrequencies of multi-stage gearboxes. Only in special cases the lowest eigenfrequencies can be calculated by using torsional vibration models. [7]

VINAYAK ET AL. describe the equation of motion of single-stage gearboxes including all six spatial degrees of freedom. The simulation model is expanded to analyze a gear chain using three gears and a two-stage gearbox. There is an investigation of the model using temporal variable (LTV=Linear time variant) and temporal constant parameters (LTI=Linear time invariant). The numerical results show the existence of an in interaction between the gear meshes. [16]

SATTELBERGER investigates the dynamic behavior of single- and two-stage cylindrical gearboxes through experimental and mathematical results. The focus of his analysis is put on the coupling stiffness and phase shift between both gear meshes. Concerning the coupling stiffness, he discovers that the gear meshes are not affected by each other for a low coupling stiffness. In contrast, for a high stiffness, the stiffness between the gear meshes can be relevant. In case of identical or similar tooth contact frequencies of the gear meshes, the adaption of the phase shift of a half pitch is usable for excitation reduction. This result can be confirmed by a parallel connection of two cylindrical gears which are distorted a half pitch against each other. [14]

KUBUR ET AL. also use a model with six degrees of freedom for theoretical analysis of multi-stage gearboxes, which can contain any number of gears. The model is validated through experimental results of a one-stage gearbox. Subsequently, several parameters are varied on the basis of a two-stage gearbox. The effect of the change of the length of the intermediate shaft, the bearing stiffness, the phase shift and the orientation of the helix angle on the tooth and bearing force courses is evaluated. [10]

ZHOU ET AL. conduct acoustical researches on two-stage gearboxes by theoretical and experimental results. The comparison between measurement and simulation shows good conformity. Additional to gear mesh frequency, there are also modulation frequencies which indicate an interaction between the gear meshes. The analysis of the appearing orders allows conclusions on the gear mesh which is responsible for the modulation. [17]

HESSE investigates the excitation behavior through variation of gear mesh excitation experimentally. The gear mesh excitation is varied by changing tooth surface topography. The analyzed test setup consists of a manual gearbox. Together with the gear stage on the countershaft, the setup matches a two-stage gearbox. The gearbox is connected by a constant velocity joint shaft to the hypoid gear stage. Because of the large distances and the influence of the drive train stiffness, there are little interactions between the gear meshes. According to this, the behavior of the elements between the gear sets has significant influence. [8]

3. Research Objective

As the state of the art shows, the minority of the reports focuses on the acoustic behavior of two-stage gearboxes and evaluating the emitted noise with psychoacoustic metrics. Furthermore, there are less reports which regard the dynamic interactions between the different influences on noise behavior of two-stage gearboxes mathematically as well as experimentally.

For this reason, a research project funded by the DFG (BR 2905/66-1) was initiated with the objective to develop a method for noise optimization of multi-stage gearboxes considering dynamic interactions and psychoacoustic metrics. This report focuses on the first work package of the project, in which the excitation behavior of a two-stage gearbox is to be analyzed mathematically. Therefore, the method that was developed in the preceding project DFG BR 2905/32 is enhanced regarding a second gear mesh. As a demonstrator, a test gearbox has been developed for measuring the excitation of gear meshes with torsional acceleration measurement systems. With a multi body simulation model and a force coupling element, which has been developed at WZL, the dynamic calculations are performed [1, 4, 7]. The influence parameters on the excitation behavior are the modifications of the tooth flank, the stiffness of the intermediate shaft and the number of teeth. The influence of the modifications will be taken into account by measured flank topographies.