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Experimental analysis of tooth-root strains in a sun gear of the final drive for an off-highway axle

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Abstract

The force acting on gear teeth can be influenced by several factors such as profile modifications, stiffness variations during meshing, inversion of the sliding direction at the pitch line, tip-to-root interferences, gears and shaft deflections and bearings clearances. Moreover, in planetary gear sets the load can be shared unevenly among the planet gears due to manufacturing inaccuracies of the system. An accurate evaluation of the real load-time history experienced by the teeth is not straightforward and is affected by strong approximations even when advanced simulation software packages are used to create the theoretical model. Therefore, experimental analysis of the behavior of gears under in-service load still constitutes a major step in the development of new transmission systems. In this work, three strain gauges were applied at different positions along the tooth root width of the sun gear mounted in the final drive of an off-highway axle. Strain measurements where then performed during a bench test of the complete axle and the signal was acquired by means of a telemetry system. Finally, the acquired data were used to assess the accuracy of software calculations and to identify the causes of overloads.

Keywords: Strain gauges, Gear, Planetary gear set

1. Introduction

The actual pressure distribution along the face of a tooth as well as among different teeth simultaneously in contact during normal operation of spur gears is strongly affected by the manufacturing and assembling accuracy of the shafts, the supports and the gear itself. Moreover, several aspects of the design as well as the operating condition of the system may influence the dynamic behavior of the gear pair. Among these, profile modifications, load, friction properties, speed, and inertia and stiffness of the rotating elements are the most important. Several numerical methods exist to calculate the compliances in gears and shafts and to estimate the amount of misalignment of mating teeth and the meshing stiffness during gears operation. Based on the results of such analysis, the designer may choose an appropriate set of geometry modifications to improve the pressure distribution for the design load and reduce the transmission error. For instance, crowning and helix modification are used to compensate for the effect of bearing clearances and shaft deformations, while tip and root relieves are useful to avoid interferences and abrupt variations of the load due to the passage from single to multiple tooth pair contact during the meshing period. Although calculation software packages are a very useful tool for the determination of an appropriate set of geometry

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modification to ensure the proper functioning of the gear set, numerical results are based upon simplified models which cannot accurately account for all the possible causes of gears overloading. Moreover, the load distribution can be strongly influenced by deviations from the nominal geometry, even when errors are within the prescribed tolerances. Therefore, despite the increasing reliability of computational tools for gear calculation, experimental validation of the numerical models is still fundamental especially in the design of new products. The first experimental works on the dynamics of gear meshing date back to the 50s, when the advent of foil strain gauges and the rapid improvement of signal conditioning systems allowed the first on-line measurements of tooth root strains. Tests were typically conducted in gear boxes appositely developed, and bridge supply and strain signal were transmitted through slip rings (Yeh, 1959; Utagawa and Harada, 1961; Pethick, 1967). The need for experimental data for the validation of calculation models was particularly felt in the aeronautic industry, where weight saving is of primary importance and the consequence of a failure would be catastrophic. Great attention has been drawn by researchers and engineers to planetary gear units, where the simultaneous meshing of the sun gear with three or more planet gears, introduces a high grade of uncertainty in the calculation, since any deviation by the nominal geometry of the system may lead to an uneven distribution of the load among the planet gears, the load sharing being usually worst for higher number of planets. This aspect was investigated experimentally by Hidaka and Terauchi (1976), Oswald (1987), and Krantz (1992), using strain gauges applied at the tooth root of the sun gear and, more recently, by Ligata et al. (2008) by gluing strain gauges in the fixed internal gear. The latter approach is simpler because eliminates the need for current supply to the gauges and for transmitting the signal from a rotating shaft, but on the other hand does not allow to investigate the behavior under load of the sun gear, which often represent the weakest component in the gear set especially regarding pitting failures. The distribution of the load over the width of a single tooth of the sun gear can be analyzed by means of several strain gauges placed along the tooth root (Hidaka and Terauchi, 1976). The same procedure was used also by Handschuh (1997) and Hotait et al. (2011) for hypoid bevel gears and by Baud and Velex (2002) for helical gears.

A crucial aspect in the dynamic measurements of tooth root strain is represented by noise, which may be introduced in the transmission of the un-conditioned signal through the slip rings. In the last years, the availability of multi-channel telemetry systems significantly contribute to improve the quality of measurements on rotating components such as gears (Zhou et al. 2016), by allowing the conditioning of the signal before its wireless transmission.

In this work strain measurements were performed at the tooth root of a sun gear in a planetary gear set of a steering axle used in agricultural vehicles (Figure 1.a). One of the main cause of failures of axles for off-highway vehicles is pitting on the sun gears of planetary gear sets, which the final drive of the transmission consists of (Figure 1.b). The onset of pitting is detrimental causing noise and vibrations.

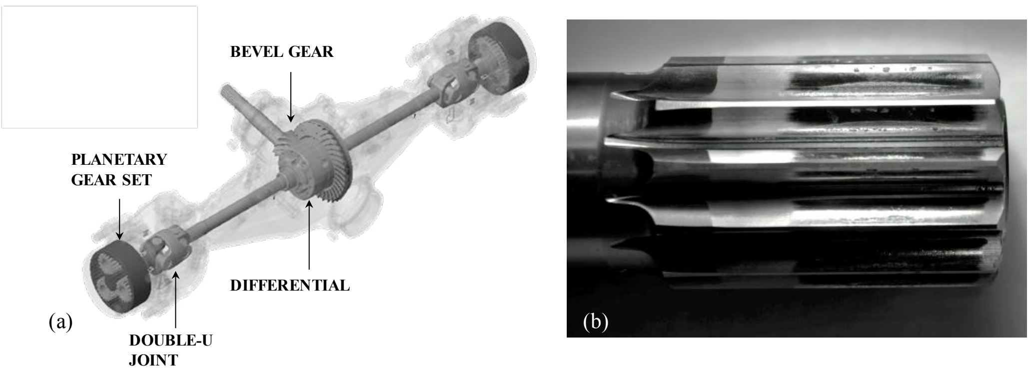

Figure 1. a) Scheme of an off-highway axle. b) sun gear damaged by pitting.

The sun gear is connected to the drive shaft through a double-U joint and meshes with three planets gears mounted on needle bearings and supported by pins fitted by interference to the wheel hub, which forms the planet carrier. The construction quality of the planet carrier, in terms of design and manufacturing accuracy, is perhaps the most important factor to guarantee the structural integrity of the drive. The deflections under load of the carrier and the pins, as well as positioning errors of the pins due to manufacturing or assembling defects may strongly influence the load sharing between the planet gears and the pressure distribution on gears teeth and bearings, considerably reducing the life of the components. Particularly, the assembly of the pins by press fit inevitably implies a certain degree of perpendicularity error. In this work, three strain gauges were placed at the root of the driving flank of a sun gear tooth to analyze the load-time history on the tooth and indirectly evaluate the pressure distribution along the gear width. Signal conditioning and transmission were provided by a multi-channel telemetry system. Data were then compared with the results of a simulation model of the final drive.