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Research paper

Frictional power losses on spur gears with tip reliefs. The load sharing role

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ABSTRACT

The load sharing impact on the efficiency of spur gears with modified profile was assessed in this work. The aim was to analyse the influence of the profile modifications on the load sharing, which also considers the effect of the torque level on the system deflections, and how these load sharing variations affected the system efficiency. Due to the frictional effect importance on power losses, in the operating conditions considered, sliding friction between teeth in presence of lubricant was studied in this proposal. The results established that tip relief improves the efficiency of the system due to the reduction of effective contact ratio. Moreover, there is a tip relief which makes optimal the efficiency in specific operating conditions, corresponding to the unit value of the effective contact ratio. Thus, the main conclusion of this work is that the tip relief which makes optimal the efficiency coincides with the theoretical dynamic optimum of the transmission.

1. Introduction

Mechanical transmissions are widely used in every kind of industrial applications as the mechanism which transfers the power from the input element, which generates the energy, to the receiver. One of the most utilised transmissions is the one that uses gears as transmitter of energy. This kind of transmission is very common due to its robustness, reliability and compactness. However, a characteristic that defines them and has made them prevail over other kinds of transmissions, it is their high efficiency in the most adverse operating conditions.

The analysis of efficiency in gear transmissions, as a fundamental element of powertrains, is an interesting aspect on which the research community has focused their efforts [1,17,23,26,31,33]. In this regard, there is a need to use increasingly efficient transmissions, not only because of the inherent reduction of energy consumption and therefore of operating costs, but also to meet the more and more restrictive environmental requirements, for instance in vehicles [28]. Environmental policies have made it mandatory to reduce the level of emissions as well as the adjustment of the fuel economy. Although these two reasons are sufficient for researching in this field, there are other reasons to improve this aspect in parallel. It is logical to think that the more efficient a transmission is, the less heat it will dissipate, and therefore, the lower its operating temperature will be. All of this will turn into a lower probability of causing superficial fatigue and wear in teeth or a

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premature failure of the gear. Hence, increasing the system efficiency will not only result in a reduction of operating and maintenance costs in the short term, but also in the medium and long term, by means of reducing associated breakdowns.

Although in these transmissions there are more elements than the gears themselves, such us bearings, seals and other auxiliary elements, this work is only focused on gears, being the most influential element of the system in terms of power losses in the considered operating conditions (considerable loads) [1,8,31]. The power losses in gear elements are usually distinguished into two types; those that depend on the load and those that do not. Load-dependent power losses are usually divided into those due to sliding friction and those corresponding to the rolling friction, depending on the relative movement between the surfaces of the teeth. Non-load-dependent power losses are those due to fluid motion in the transmission surroundings, which could be lubricating fluid, air or both of them. In the work operating conditions, sliding friction is the dissipative effect that causes the most of power losses, as it can produce up to 95% of the system power losses under adverse conditions of load [1,31]. Thus, it is generally assumed that sliding friction is the only dissipative effect of the system [2,13,29,32,33].

The main goal of the present study is to determine the influence of the load sharing on the efficiency of spur gear transmissions when different tip reliefs are considered. Tip relief is widely used in the Industry in order to improve the dynamic behaviour of the transmission by softening the transition between the double and the single contact regions. To consider its behaviour in the numerical model of gear transmissions, it is necessary to take into account the deflections produced by the adjacent teeth to the one in contact, in other words, the effect of the torque level. In this framework, the strength of the present proposal lies in the use of an enhanced load sharing formulation, which considers the profile modifications and the torque level, in the efficiency calculation. There are several works which analyse the tip relief influence on the dynamic properties of gear transmissions [5,12,14,15,18–20] and on the tooth stress produced [16,22,30]. Nevertheless, in the efficiency field, it only exists few works [4,6,21,33]. Some of them are based on the experimental calculation of the power losses in gear transmissions with short and long tip reliefs [6,21], other works use numerical models which do not generally take into account the torque effect in order to calculate the system power losses [4] and others which propose analytical solutions of the efficiency considering the tip relief effect, comparing the results with numerical simulations [33]. Hence, with this proposal, it is intended to contribute to improve the knowledge in this regard, using a load contact model which does take into account the torque level and allows for calculating efficiency values with a high level of accuracy.

In Section 2, the fundamentals that were required to develop the efficiency study are shown. Section 3 provides the analysed transmission properties and the structure of the results presented in Sections 4 and 5. To end this work, the conclusions are summarized in Section 6.

2. Fundamentals applied to this study

Two aspects are necessary to be defined in order to comprehend the scope of this study. Since the assessment of the efficiency of gear transmissions with tip relief was performed, the efficiency calculation methodology and the model to include tip reliefs are presented next.

2.1. Efficiency calculation

The methodology to calculate the efficiency has been presented in previous works [7]. Accordingly, in this section, only a few details, which are necessary for the understanding of the work, are presented for the sake of simplicity.

As the Coulomb's model approach was followed to calculate the sliding friction, hereinafter referred as friction, power losses (P_{loss}) along the mesh cycle are dependent of the sliding velocity ($V_s(\theta)$), the friction coefficient ($\mu(\theta)$) and the contact force ($F_N(\theta)$):

$$P_{loss} = \int_{\theta_A}^{\theta_E} \mu(\theta) F_N(\theta) V_s(\theta) d\theta = P_{in} \int_{\theta_A}^{\theta_E} IPL d\theta$$
$$\Rightarrow IPL = \frac{\mu(\theta) F_N(\theta) V_s(\theta)}{F_{Nmax} V} \tag{1}$$

Where F_{Nmax} is the maximum normal force, V the pitch line velocity along the mesh cycle and IPL the Instantaneous Power Loss factor. Moreover, θ_A and θ_E correspond to the angular positions at the mesh cycle beginning and end.

In this proposal, in order to calculate the friction coefficient, a constant average formulation was implemented (μ_m). The reason why this assumption was included is to isolate the effect of the load sharing in the efficiency from the impact of the friction coefficient. Moreover, Niemann's proposal (Eq. (1)) is the chosen formulation since it is widely used in the scientific literature [2,8,13,24,25,29]. This formulation depends on the contact force, the speed, the geometry of the transmission and the rheological parameters.

$$\mu_m = 0.048 \left(\frac{\frac{F_{Nmax}}{b}}{V_{\Sigma C} \rho_c} \right)^{0.2} \eta_{oil}^{-0.05} R_a^{0.25} X_L$$
$$\Rightarrow V_{\Sigma C} = 2 V_t sin(\varphi) \quad \text{and} \quad X_L = \frac{1}{\left(\frac{F_{Nmax}}{b}\right)^{0.0651}} \tag{2}$$