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An experimental investigation of spin power losses of a planetary gear set

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ABSTRACT

This experimental study investigates the contributions of the key components of load-independent (spin) power losses of planetary (epicyclic) gear sets. A dedicated test set-up is developed to operate a planetary gear set under unloaded conditions in various hardware configurations within a wide range of speed. Torque provided to the gear set is measured as the spin torque loss. A test matrix is executed specifically to measure total spin loss of the gear set as well as the contributions of its main components, namely drag loss of the sun gear, drag loss of the carrier assembly, pocketing losses at the sun–planet and ring–planet meshes, viscous planet bearing losses, and planet bearing losses due to centrifugal forces caused by the rotation of the carrier. Variations of the same gear set are tested and results from these tests are compared to estimate and rank order the contributions of these components of power loss. Impact of the rotational speed and oil temperature levels on each component is also quantified.

1. Introduction

Powertrain efficiency has become a major topic in recent years within the transportation, aerospace, and energy industries due to continuously increasing fuel prices and growing concern over sustainability and the environmental impact of fossil fuels. As part of this focus, power losses from transmissions have become one of the major concerns of drive train engineers. On the automotive side, automatic transmissions employ co-axial designs where multiple stages of planetary (also called epicyclic) gear sets and wet clutches are used to obtain different gear ratios. As such, the efficiency of the planetary gear sets dictates the overall efficiency of these transmissions. Furthermore, the push towards having transmissions with larger number of forward ratios often results in kinematic configurations that might operate planetary gear sets at higher speeds, presenting additional challenges in terms of drivetrain efficiency.

Power losses of any gear system can be classified in two major groups. One group of losses, often referred to as *mechanical* (load-dependent) power losses, are induced by friction at the lubricated gear and bearing contacts and increases with the torque transmitted by the gear system. The second group of losses is formed by load-independent mechanisms, often referred to as spin power losses. The term *spin* loss is used loosely to define losses taking place due to rotation of the system without transmitting any torque. In gearboxes that operate in dip lubrication conditions, spin losses represent losses associated with the churning (drag and pocketing) of oil surrounding the gears and bearings. In planetary gear systems, oil is typically delivered to gear and bearing contact interfaces through lubrication paths, designed to spread oil from the rotational center outwards. Under such conditions, gears and bearings are often subject to a certain mixture of oil and air.

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The major sources of spin loss within a planetary gear set comprise (i) viscous drag loss associated with spinning components, namely gears, bearings and the carrier assembly (carrier with planet gears mounted on it), (ii) pumping of lubricant and air from the spaces between meshing gear teeth, and (iii) friction-induced losses occurring at planet gear bearings due to centrifugal forces while the gear set free spinning. The drag power losses (P_d) are those associated with the interactions of each individual gear and the carrier assembly with the surrounding medium, where windage refers to drag on a component spinning in air, and churning refers to drag associated with lubricant interaction for a component that is fully or partially immersed in oil. The three main sources of drag power loss of a planetary system are sun gear drag (P_{ds}), planet carrier assembly drag (P_{dc}), and ring gear drag (P_{dr}). Any of these components that are stationary would result in zero drag. Each drag power loss term represents the sum of (i) power loss due to oil/air drag on the periphery (circumference) of the gear or carrier, and (ii) power loss due to oil/air drag on the faces (sides) of the gear or carrier [1–3]. The total drag power loss of the planetary gear set is given as the sum of each source as follows:

$$P_d = P_{ds} + P_{dc} + P_{dr}. \tag{1}$$

The pumping power losses (P_p) are caused by gears squeezing (or pumping) oil (or oil–air mixture) out of the space between the teeth contracts as they roll into mesh [1,4]. These losses occur at each sun gear mesh with planets (P_{ps}) as well as at the meshes of the ring gear with planets (P_{pr}) such that

$$P_p = N\left(P_{ps} + P_{pr}\right) \tag{2}$$

where N is the number of planet gears in the gear set.

The planet bearing spin losses (P_b) can be described in terms of (i) load-dependent (mechanical) losses and (ii) viscous (load-independent) power losses. Each planet bearing and washer is subject to viscous power loss P_{vb}. In addition, the rotation of the carrier causes centrifugal forces $F_b = mr\omega_c^2$ acting on each planet radially. Here, m is the mass of a planet including its bearing, r is the radius of the circle defined by planet centers (sun–planet center distance), and ω_c is the carrier rotational speed. These centrifugal forces induce load-dependent friction drag at each planet bearing in spite of the fact that no mechanical power is transmitted by the gear set. These radial forces result in certain power losses denoted here as P_{bg}. In its simplified form, power loss of a cylindrical roller bearings is given as [5,6]

$$P_{gb} = C_{gb} m. \tag{3}$$

Here $C_{gb} = f_1 d_m r \omega_c^2 \omega_b$ where d_m being the bearing pitch diameter, ω_b being the bearing speed (relative speed of the planet gear with respect to the carrier) and f_1 being an application constant determined through testing. For $\alpha = \omega_b/\omega_c,\ C_{gb} = f_1 \alpha d_m r \omega_c^3$. With this, total power loss associated with all of the planet bearings of the planetary gear set is given as

$$P_b = N\left(P_{vb} + C_{gb} m\right). \tag{4}$$

Summing these three main sources of power losses, the overall spin power loss of an N-planet planetary gear set can be written as

$$P = P_d + P_p + P_b. \tag{5}$$

The majority of literature concerning power losses in gears pertains to mechanical efficiency of counter-shaft (fixed center) gearing applications. Mechanical efficiency models based on elastohydrodynamic lubrication formulations have been proposed in recent years to investigate the impact of lubricant parameters, surface conditions (magnitude and lay of the surface roughness), gear geometry and operating conditions on contact friction and mechanical power losses (e.g. ref. [7–10]). Likewise, there have been a limited number of detailed experimental investigations of spur and helical gear mechanical power losses to provide much needed experimental databases [11]. Furthermore, some of these models [7,8] were compared to these experiments to demonstrate their accuracy. These studies, while significant to describe load dependent power losses of gears, are of limited relevance to this study, which focuses on spin power losses.

Some studies were conducted to investigate spin power losses of fixed-center spur and helical gears. These studies exclude bearing losses as fixed-center gear systems can be studied separately from bearing losses. Studies such as references [12–15] presented empirical or computational fluid mechanics based models of windage power losses for single gears in air. Some others [16–18] empirically studied churning effects of a single disk or a gear rotating while partially and fully immersed in oil, thus capturing drag effects caused by dip lubrication. Meanwhile, others [10,11,19–21] aimed at determining spin losses of counter-shaft spur or helical gear pairs in mesh with viscous drag and pocketing losses lumped together. Further studies by Perchesky and Whidtbrott [22] and Diab et al. [23] presented models describing pocketing behavior, and Ariura et al. [24], Seetherman and Kahraman [1–3], Talbot et al. [4], and Changenet and Velex [25], presented models capable of separately characterizing pocketing and drag losses for fixed-center gear pairs in mesh. These single gear or gear pair spin loss studies form a solid foundation for characterizing spin power losses present in fixed-center gearing applications. Their applicability to planetary gear systems, however, is yet to be demonstrated as a planetary gear set possesses unique kinematic and mechanical features including planet bearings, rotating planet carrier, more complex lubrication schemes, and multi-mesh external and internal gearing interactions.