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Losses of power in the gear systems

This paper provides a review of experimental investigations and available models of gear load-independent power losses for spur, helical, and bevel gears. The aim of the review is to provide a comprehensive compilation of published information on gear load-independent power losses to assist gearbox designers in identifying relevant experimental and modeling information.

Environmental awareness is pushing mechanical engineers to develop mechanical systems, and in particular gear units, that have lower environmental impact. Such objective can be reached through different perspectives: reduce gear power loss and improve efficiency, reduce gear operating temperature, reduce friction between gear teeth, reduce gear load-independent power losses. The losses associated with meshing gears are important in the design of many industrial, marine, and gas turbine situations. Gearbox efficiency varies from 98% to 99% for the best designed high power applications. The highest rated gearboxes now exceed 100 MW [1], so for such a gearbox a 1 per cent power loss equates to 1 MW and this is not insignificant.

Power losses of a gearbox containing several gear pairs that are supported by shafts and rolling element bearings can be classified into two groups. The first group is comprised of load-dependent (friction-induced) power losses caused primarily due to contacting surfaces of gears and the bearings. The losses in the second group are independent of load and are often referred to as spin power losses. There are many sources of such losses, the primary ones being oil churning and windage that are present as a result of oil/air drag on the periphery and faces of the gears, pocketing/squeezing of lubricant from the cavities of the gear mesh, and viscous dissipation of bearings. While losses from these two groups are often comparable under high-load, low-speed conditions, the spin losses were shown to dominate over the load-dependent power losses at higher operating speed conditions. Of the total losses, for a typical gearbox, 40 per cent come from meshing, 50 per cent from bearings, and 10 per cent from windage and churning [2]. Windage power loss (WPL) is defined as the power loss due to the fluid drag experienced by the gear when it is running in air or an air-oil mist. Churning power loss (CHPL) is defined as the power loss when a gear is running in an oil bath or is dipping into oil “slugs.” During the meshing of high-speed spur or helical gears, the mixture of air and lubricant is successively compressed and expanded in the intertooth spaces giving rise to significant heating and power loss named as air-oil pocketing power losses.

Windage Power Losses. Estimates on the percentage effect of windage vary as the value is dependent on a number of different parameters. One of the critical parameters is the pitch line velocity; obviously, high velocities ([3] suggests 51 m/ s, and [4] suggests tangential speeds greater than 90–120 m/ s) produce greater stirred motion, so large gears rotated at high rotational rates are particularly vulnerable. Additionally, the lubrication flow rate and scavenge design are critical as these directly affect the properties of the fluid surrounding the gear [3], [5]. So, in a case where you have a high level of lubricant suspended around a gear with high pitch velocity, as is the case of an aero-engine, windage becomes a significant contributor to the power loss. It may only account for a few percent, but this can be critical. Traditionally, there have been two approaches to reducing WPL; the first is to use a shroud or baffle to enclose gears and the second is to positively pump the oil and air from the gearbox casing. Pumping from the gearbox casing is known as evacuating the gearbox [1], and allows a reduction of fluid density within the casing. This can result in up to 1% improvement in efficiency but can only be used in a limited number of situations.

Published gear windage power losses experiments, which have been few and far, can be grouped based on their primary focus. One group of studies focused on the measurement of air windage losses [6] by measuring the deceleration of a single gear or disk rotating in air, and then applying the kinetic energy theorem to obtain power loss from air drag. [7] used the tool of dimensional analysis to define an empirical windage moment coefficient in terms of speed, oil properties, Reynolds number, gear size, tooth parameters, and the geometry of nearby fluid flow obstructions such as close-fitting gear case walls. While applicable to a single disk or gear rotating in air, these models did not consider the effects of a meshing gear or impinging oil jet, and so cannot be validated using geared transmissions.

As an alternative, [8] and [9], [10] developed empirical models for meshed spur gears based on pitch radius, face width, rotational speed, and viscosity of the ambient fluid. Likewise, [11], based on measurements of high-speed, long addendum spur gears, reported that windage power loss was proportional to the 2.8th power of the rotational speed and also that the inertial losses resulting from the impinging oil jet were linearly proportional to the rotational speed. Here, the inertial losses from the impinging oil jet were shown to increase with oil jet pressure, and composed a significant portion of load-independent power loss.

Oil churning power losses.Most of experimental studies considered a single gear, disk, or bladed rotor immersed in oil [12], [13], [14]. These oil churning studies were also devoted to developing empirical equations to obtain a dimensionless churning moment coefficient. [12] proposed four different flow regimes around a rotating disk fully submerged in fluid and correlated these flow regimes to Reynolds number and enclosure effects based on experimental results. Mann and Marston [13] studied friction drag of bladed and unbladed disks and related experimental results to a moment coefficient based on Reynolds number and axial clearance with the chamber, etc.

However, in the case of gears, there are fewer empirical models and, because of experimental difficulties, measurements of thermal performance and power losses have been limited. The first in situ temperature measurements date back to the classic works by [15], [16], while the specific studies on churning losses comprise those of [17], [18] and, more recently, [19] and [20].

[17] developed empirical relations for a dimensionless moment coefficient from numerous experiments on gears rotating partially submerged in a fluid and identified separate power loss equations for meshed gears rotating upward or downward in an oil bath. [19] conducted friction torque tests with a simple bench setup using smooth disks of various diameters and face widths, which were partially submerged in high-viscosity oil, and compared these results to experimental observations with a gear.

More recent efforts using similar methods include that by [21], [22], and [20].

[22] performed a number of experiments to determine churning loss in single and meshed spur gear pairs. They compared their experimental observations on spin power losses with the empirical formulations of [19] and [17] and found that contrary to what Bones had predicted, the spin power losses were not strongly affected by the viscosity of the lubricant. Furthermore, their observations called into question the attempt used to characterize spin power loss based on a Reynolds number dependent on lubricant viscosity.

[8] measured losses from jet-lubricated spur gear systems experimentally. They proposed an analysis of the power required to pump the oil trapped between mating gears.

[5], [23] analyzed the effect of rotationally induced windage on the lubricating oil distribution in the space between adjacent gear teeth in spur gears. The purpose of their study was to provide formulations to study lubricant fling-off cooling. They proposed that impingement depth of the oil into the space between adjacent gear teeth and the point of initial contact was an important aspect in determining cooling effectiveness.

[24] analyzed fluid flow in the meshing zone between spur gear pairs to assess the magnitude of the fluid velocity, temperature, and pressures that result from meshing gear teeth.

A more recent study by [20] investigated the influence of meshing gear on oil churning power losses by performing a number of gear oil churning experiments to come up with empirical formula for power losses. Parameters included were gear module, diameter and face width, speed, and lubricant viscosity. Their empirical formula suggested that the influence of viscosity on oil churning loses is insignificant with regard to viscosity at high speeds of rotation for single gears, corroborating similar findings from the experimental observations of [22].

Another relevant work by [21] also stresses this apparent lack of dependence of oil type on load-independent losses. In their experiments, measured gear and bearing power losses, and forged a balance between generated heat in the gearbox due to gears and bearings and the dissipated heat in the form of free and forced convection and through radiation as well, from housing and rotating parts, to calculate mean lubricant temperature.

Conclusions. This review describes a number of studies that have investigated gear windage and churning power loss. While it is clear from all of these investigations that the rotational speed, gear geometrical parameters, degree of confinement, and density of the fluid surrounding the gear are important, the degree of effect and general solutions for reducing power loss are less clear. The majority of the modeling methodologies are experimental correlations derived from specific experiments that have unique elements, making a general conclusion regarding the best methodology difficult. The methodologies do allow a general assessment of the expected levels of gear windage and churning present in a specific design and possible routes to reducing gear windage and churning power loss. It is clear from this review that a modeling methodology capable of being used for all gear types and configurations is required, which allows analysis of the fluid dynamics phenomena.

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