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Friction torque in rolling bearings lubricated with axle gear oils

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ABSTRACT

As a part of the main research project within the aim of increasing significantly drive axle efficiency, this work focuses on rolling bearing friction torque lubricated with five fully formulated axle gear oils with different viscosity and different formulations. The lubricant tribological behaviour in different rolling bearings was analyzed. A modified Four-Ball Machine was used to test the rolling bearings. The effect of speed, temperature and axial load on rolling bearing friction torque was assessed. Experimental results for the internal friction torque were validated with an SKF model. Direct comparisons in terms of friction torque between axle gear oils when they are lubricating different rolling bearing types are presented and discussed.

1. Introduction

Power losses in automotive drive trains have become an important field of investigation in automotive industry [1–5]. So far, the federal standards and the state government regulations in vehicle fuel economy combined with limits imposed by Environmental Protection Agency (EPA) rules on CO_2 emissions into the atmosphere have traditionally been the main reason for this focus in drive train power losses [6–9]. The looming energy crisis and increasing fuel prices have also added to the motivation to reduce such losses.

It has been well settled that the automotive axle-differential is considered as a significant contributor to power loss in the drive line [10]. Axle efficiency values were reported to be as low as 90–95% depending on the type of vehicle and on the applied torque and speed [2,11,12]. Therefore, any tangible improvement to the axle efficiency has a significant impact on the carbon emissions and the energy consumption [3,11].

The axle transmission is a key component of the vehicle powertrain. It is a very compact mechanical system, consisting generally of a hypoid bevel geared transmission, tapered roller bearings, seals, shafts and an axle gear oil [13]. The axle transmission requires a very high reliability, since failures are not accepted by consumers [14–16].

As any power transmission system, axle power losses are divided into several energy loss mechanisms as proposed in a number of papers by Hohn et al. [17–19]. The sources of the major axle power losses were dissipated mainly in friction loss between the meshing teeth of hypoid gears [12,20–23], friction loss in the bearings [24–26], friction loss in the seals [27] and spin losses due to lubricant pumping and churning, and windage [5,28].

Axle power losses mainly originated in two type of losses. No-load losses or churning losses generated by gears, rolling bearings and seals that are related to the input speed, the operating conditions and mainly related to the lubricant properties such as viscosity and density of the oil [6–8,15] as well as immersion depth of the components in a sump lubricated axle [29]. Rolling bearing losses depend on its type and size, bearing arrangement, lubricant viscosity and supply [19]. These losses are relevant but they are outside the scope of this research.

Load dependent losses generated by gears and rolling bearings are related to the transmitted torque, coefficient of friction and sliding velocity in the contact area of the components. Load dependent rolling bearing losses also dependent on type and size, rolling and sliding conditions and lubricant type [30]. In order to have a good prediction of the power losses of the system, each component should be tested separately.

The rolling bearings are a major contributor to axle system power loss [25] and their main function in axles is to support the pinion and the differential gear under high load carrying capacity and high stiffness.

To achieve high efficiency in axle differentials, the reduction of internal friction torque in rolling bearings is of major concern. Thus, the importance of understanding internal friction in rolling bearings becomes relevant. The energy saving and bearings performance

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optimization are required [31].

The energy consumption due to rolling bearing power loss is becoming more and more important when taking into account the focus of science and industry on this issue.

Recently, automotive manufacturers and the rolling bearings manufacturers are trying to improve rolling bearing designs in order to reduce the power loss generated, the energy consumption and the operating temperatures and improve the lubrication conditions. At the same time, they ask the lubricant manufacturers to provide new products that increase rolling bearing life, while reducing the energy dissipated [25,26].

Only a limited number of studies focused on developing the axle rolling bearings friction torque.

Spindler and von Petery (2003) [24] reported that INA (Industrie-NAdellager) has developed a new bearing design, where the tapered roller bearings on the pinion shaft are replaced by double row angular-contact ball bearing and the tapered roller bearings of the ring gear shafts are replaced by single-row angular ball bearings. The benefits of the rolling bearing substitution are no preload loss during operation with 50% reduction of friction torque meeting the requirements for high rigidity and long life.

Matsuyama et al. (2004) [25] published results when the super-low friction torque tapered roller bearing supporting the pinion was used in rear axle differentials. This study achieved a friction torque reduction of 80% compared to standard bearings.

Petery et al. (2004) [32] reported that INA and FAG in collaboration with BMW conducted power loss measurements of the original bearing design of a BMW axle with cross-locating taper roller bearing arrangement and an alternative design with crosslocating double- and single-row angular ball bearing arrangement. For medium load and speed and low temperatures, relevant in the New European Driving Cycle (NEDC), the bearing loss reduction for the alternative design was over 50 per cent [19].

Hoshokawa et al. (2009) [26] proposed a new bearing concept which is the double row angular contact ball bearing-so-called Tandem Ball Bearings for rear axle drives. Through a comparative testing between a new bearing design and standard bearing used in axles a relevant reduction of 50% in friction torque can be achieved. This bearing concept not only increases the service life but also make significant contribution to lower fuel consumption by up 1.5% in every driving.

The motivation behind this study is conducting an accurate

Table 1
Axle gear oils properties.

Parameter	Unit	75W85-B	75W90-A	75W90-B	80W90-A	75W140-A
		candidate	reference	candidate	reference	reference
Base oil	[−]	PAO	PAO	PAO	Mineral	PAO
API/standard	[−]	–	GL-4/GL-5/MT-1	–	GL-4/GL-5/MT-1	GL-5
Chemical composition						
Boron (B)	[ppm]	0	–	81	–	–
Calcium (Ca)	[ppm]	1795	18	2891	97	33
Magnesium (Mg)	[ppm]	6	1087	17	936	1093
Phosphorus (P)	[ppm]	783	1622	958	1436	1686
Sulphur (S)	[ppm]	2954	23262	3271	26947	22784
Zinc (Zn)	[ppm]	899	7	1120	23	12
Physical properties						
Density @ 15 °C	[g/cm^3]	0.853	0.87	0.861	0.886	0.885
Thermal expansion coefficient ($\alpha_t \times 10^{-4}$)	[/]	−8.1	−7.3	−7.6	−7.7	−6.8
Viscosity @ 40 °C	[cSt]	68.95	112.35	114.42	123.3	200.7
Viscosity @ 70 °C	[cSt]	23.86	36.7	38.14	34.86	61.86
Viscosity @ 100 °C	[cSt]	11.44	16.37	17.18	14.38	26.21
a_A	[/]	0.7				
n_A	[/]	7.6655	7.5833	7.407	8.5027	7.1537
m_A	[/]	2.9663	2.9133	2.842	3.2783	2.7211
Thermoviscosity @ 40 °C ($\beta \times 10^3$)	[K^{-1}]	40.2	44.3	43.3	50.7	46.3
Thermoviscosity @ 70 °C ($\beta \times 10^3$)	[K^{-1}]	28.5	31.3	30.9	34.8	33.2
Thermoviscosity @ 100 °C ($\beta \times 10^3$)	[K^{-1}]	21.1	23.1	22.9	25	24.7
s @ 0.2 GPa [35]	[/]	0.7382	0.7382	0.7382	0.9904	0.7382
t @ 0.2 GPa [35]	[/]	0.1335	0.1335	0.1335	0.139	0.1335
Piezoviscosity @ 40 °C ($\alpha_{Gold} \times 10^{-8}$) [35]	[Pa^{-1}]	1.291	1.387	1.39	1.934	1.498
Piezoviscosity @ 70 °C ($\alpha_{Gold} \times 10^{-8}$) [35]	[Pa^{-1}]	1.128	1.194	1.2	1.623	1.28
Piezoviscosity @ 100 °C ($\alpha_{Gold} \times 10^{-8}$) [35]	[Pa^{-1}]	1.022	1.072	1.079	1.435	1.142
VI	[/]	162	147	163	118	169
Tribofilm characterization						
C 1s	[At %]	38.87	48.83	35.01	39.11	53.79
Fe 2p	[At %]	0.83	0.52	1.29	0.39	–
O 1s	[At %]	40.37	40.47	44.24	47.41	37.07
Ca 2p	[At %]	7.68	–	10.23	0.39	–
Mg 1s	[At %]	–	2.58	–	3.88	2.24
P 2p	[At %]	8.75	7.15	5.91	7.58	6.38
S 2p	[At %]	1.21	0.45	2.01	0.6	0.5
Zn 2p3	[At %]	2.3	–	1.32	0.07	–