Analytical study of frictional power losses in spur geared transmissions

MUSHIRABWOBA Bernard*[1], LAHCEN Belfals[1], NAJJI Brahim[2], LASRI Abdelilah[1]

[1]Affiliation (Laboratory of Quality Security and Maintenance, Ecole Mohammadia d'Ingénieurs (EMI)_Université Mohammed V, Rabat, Maroc)

[2]Affiliation (Laboratory of Mechanics, Thermics and Materials, Ecole Nationale Supérieure de Mines de Rabat (ENSMR), Rabat, Maroc)

*Correspondance author (e-mail : mubefils@yahoo.fr)

Abstract

Power transmitters are highly used in many of our domestic and industrial applications. Due to the rising of the fuel prices and the increase in energy demand, there is a continuous demand for higher efficiency gears. The objective of this work is to present a developed meshing modeling which enables to instantly calculate the power losses due to friction phenomenon between spur gear teeth. The present work gives a better understanding of how to numerically evaluate the friction power losses in spur gears and it is a preliminary study to the future work where the impact of friction and wear phenomena on the material lifetime and energy consumption will be discussed.

Key words: *spur gear, numerical modeling, frictional power losses, gear efficiency*

1. Introduction

Power transmitters are the mechanical systems or mechanisms that are used to accommodate the power according to the needs and they are highly used in many domestic and industrial applications. Although the latter offer better performance, the increase in power to be transmitted at high rotational speeds result in significant power losses in spur geared transmissions then since power losses have direct impact on the lifetime of the power transmitters, they must therefore be taken into account during the different phases especially when designing and choosing the materials of the gears. A well designed mechanical system would enable the user to avoid breakage of the mechanism due to thermal expansion and would allow a better design of the cooling systems.

2. Overview on friction phenomenon between spur gear teeth.

According to Diab [1], Velex P. and Cahouet, V. [2], the friction between teeth is one of the major sources of power dissipation and may also be a source of vibrations and noises. The friction phenomenon related power losses are preponderant at low speeds whereas they are low at high-speed in comparison to the power losses due to the ventilation phenomenon and to the trapping phenomenon which was discussed by the authors in [3]. In order to understand the friction phenomenon resulting from metal-metal in non-lubricated contacts also known as dry friction, many experiments were conducted. The total power losses resulting from this phenomenon is closely linked to the coefficient of friction.

2.1 Empirical laws of friction

Some authors have established the friction laws in order to estimate the friction coefficient as a function of geometric and operating parameters. In table 1 below, the friction laws used in this study are presented.

Author and reference	Friction law
Benedict and Kelley [4]	$\mu = 0.0127\left(\frac{50}{50-S_{rms}}\right)\log_{10}\left(\frac{3.98\times10^{9}P_h^{\,2}R}{\upsilon_0 SR(V_r)^3 E'}\right)$
Misharin [5]	$\mu = 0.3865\left(\frac{1}{\upsilon_k V^2{}_r SR}\right)^{0.25}$
O' Donoghue and Cameron [6]	$\mu = 0.6\left[\frac{S_{cla}+22}{35}\right]\left[\frac{0.756}{\upsilon^{1/8}SR^{1/3}V_r^{\,1/2}R^{1/2}}\right]$
Drozdov and Gavrikov [7]	$\mu = \left[\frac{1/V_r}{0.4Rg\sqrt{\upsilon_k}+\phi+13.4/V_r}\right]$ $\phi = 0.47-0.13(10)^{-4}P_{\max}-0.4(10)^{-4}\upsilon_k$

Table1: Empirical laws of friction used to determine the coefficient of friction.

Where S_{rms} and S_{cla} are the surface roughness parameters in µm defined as $S_{rms}=1.25\ S_{cla}$, υ_0 and υ_k respectively the dynamic viscosity in centipoise (cPo) and cinematic viscosity in centistokes (cSt), Vr and Vs respectively the rolling and sliding velocities in (m/s), P_h the maximum pressure of Hertz in pascal (Pa), R the effective radius of curvature in meters (m) and SR the slide to roll ratio defined as the ratio between the sliding velocity and the rolling velocity.

2.2 Experimental law of friction

To establish a friction law that takes into account several meshing factors including lubrication, material type and surface roughness, the authors H.Xu, A. Kahraman, N. Anderson and D. Maddock [8] considered the contact between teeth as an elastohydrodynamic (EHD) contact because the latter is characterized by low contact areas, significant surface deformation, high contact pressure and the presence of the oil film between the contacting asperities. They came to the following friction law:

$$\mu = e^{f(SR,P_h,\upsilon_0)}P_h^{\,b_2}\left|SR\right|^{b_3}V_e^{\,b_6}\upsilon_0^{\,b7}R^{\,b8}$$

Where:

$$f(SR,P_h,\upsilon_0) = b_1 + b_4\left|SR\right|P_h\log_{10}(\upsilon_0) + b_5 e^{-\left|SR\right|P_h\log_{10}(\upsilon_0)} + b_9 e^{S}$$

Ve is the entraining velocity in m/s and the constants bi are given as:

bi = -8.916465 ; 1.03303 ; 1.036077 ; -0.354068 ; 2.812084 ; -0.100601 ; 0.752755 ; -0.390958 ; 0.620305 for i = 1 to 9.

3. Modeling of meshing and friction power losses calculation

Since the friction power losses depend on the friction coefficient a comparative study of friction laws was carried out in [9] which allowed us to chose the experimental friction law because it takes into account all contact parameters and by using the documentation on spur gears cited in [10], we established a numerical modeling which allows us to know the evolution of different meshing parameters along the line of action. In this present work we used the geometric data given in the table 2 below :

Parameter	Value
Number of teeth (Pinion)	50
Number of teeth (Wheel)	50
Module (mm)	1
Tooth width (mm)	20
Viscosity (cSt)	60
Pressure angle (degrees)	20
Surface roughness parameter S (µm)	0.07
Effective radius of curvature R (mm)	5
Maximum pressure of Hertz $P_{h.}$ (Gpa)	2
Torque (Nm)	16
Rotational speed (rpm)	1500

Table 2. Geometric data

4. Sliding power losses

The instantaneous power losses due to the sliding between spur gear teeth are calculated by the product of the frictional coefficient (µ) by the sliding speed (V_s) and the normal load (F_N).

$$P_s(x) = F_N(x) V_s(x) \mu(x)$$

4.1 Sliding velocity

In spur geared transmissions, the sliding velocity is defined in [11] as follow:

$$V_s(x) = 0.1047\left(1 + \frac{1}{i}\right) N(x - x_p)$$

Where: *i* is the transmission ratio and N the pinion rotational speed.

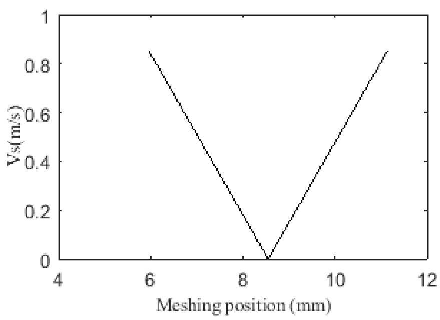

Fig. 1.Variation of the sliding velocity along the line of action.

the maximum value of the sliding velocity is found at the starting and ending points of meshing while its minimum value is obtained at the pitch point.

4.2 Sliding power losses

The calculated instantaneous sliding power losses is plotted on figure 2 below :

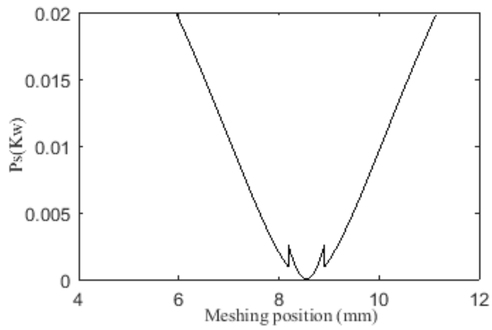

Fig. 2.Variation of the power losses along the line of action

As obtained in [12], the instantaneous power loss curve shows the minimum value of the sliding power losses at the pitch point which results in the increase of the load and the decrease of the coefficient of friction and the sliding velocity in that area.

5. Rolling power losses

The instantaneous power losses due to the rolling between spur gear teeth is obtained by the product the thermal reduction factor ($\varphi_t(x)$) given in [1], by the tooth width (b), by the lubricant film thickness (h(x)) and by the rolling velocity (Vr).

$$P_r(x) = 9 \times 10^7 b h(x) \varphi_t(x) Vr(x)$$

5.1 Rolling velocity

In [13], the rolling velocity is defined as:

$$V_r(x) = 0.1047 N d_p \left[\sin(\theta) - \frac{(i-1)(x - x_p)}{d_p} \right]$$

Where, *i* is the transmission ratio, N the pinion rotational speed (rpm), dp the pitch diameter of the pinion (mm), θ the pressure angle (degree), *x* the meshing position (mm) and x_p the pitch point position (mm).

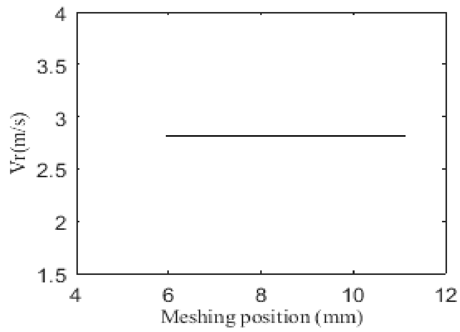

Fig. 3.Variation of the rolling velocity along the line of action.

The rolling velocity has a constant value which is justified by the fact that in this study the transmission ratio is equal to 1 because the pinion has the same number of teeth as the gear.

5.2 Rolling power losses

The calculated instantaneous rolling power losses is plotted in figure 3 below:

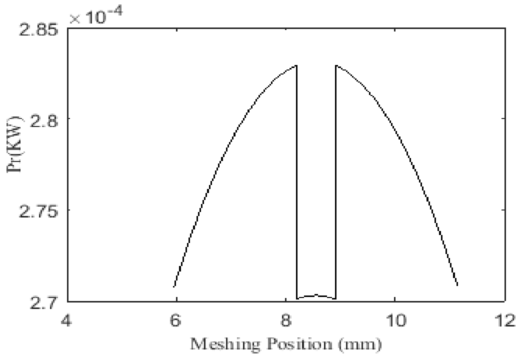

Fig. 4.Variation of the rolling power loss along the line of action

We remark an abrupt drop in the rolling power losses observed around the pitch point due to the increase in the load in that region

6. Total power losses due to friction phenomenon

At any given meshing point, the instantaneous total power losses related to the friction phenomenon between spur gear teeth is obtained by summing the sliding power losses (P_s) and the rolling power losses (P_r) at that point.

$$P_t(x) = P_r(x) + P_s(x)$$

Where: $P_r(x) = 9 \times 10^7 bh(x)\varphi_t(x)Vr(x)$ and

$$P_s(x) = F_N(x)\mu(x)Vs(x)$$

The total power losses will be discussed in our future work and the effect of different operating and geometric parameters on the latter will be taken into consideration.

7. Conclusion

In this study an analytical study on instantaneous sliding power loss in spur geared transmissions was carried out. A numerical model that takes into account different gear parameters in the contact was developed. It allows the user to instantaneously know the sliding and the rolling power losses at every meshing position along the line of action, in order to evaluate the average total power losses; a numerical integration will be used in our future work by aiming to study the impact of the friction and wear phenomena to gear material lifetime and energy consumption.

8. References

[1] Diab, Y. ; Ville, F. ; Houjoh, H. ; Sainsot, P. ; Velex, P. ; 2004 ; '*Experimental and numerical investigations on the air-pumping phenomenon in high speed spur and helical gears'*, Proc. IMechE vol. 219 Part c:, Journal of Mechanical Engineering Sciences,2005.

[2] Velex P. and Cahouet, V. « *Experimental and numerical investigations on the influence of tooth friction in spur and helical gear* dynamics » ASME, J. Mech. Des., 2000, Vol. 122, pp 515-522.

[3] Abdelilah Lasri, Lahcen Belfals, Brahim Najji and Mushirabwoba Bernard, "*Pressure estimation of the Trapped and Squeezed oil between Teeth Spaces of Spur Gears"*, Applied Mathematical Sciences, Vol. 8, 2014, no.107,5317 – 5328, HIKARI Ltd , http://dx.doi.org/10.12988/ams.2014.47542.

[4] Benedict G. H. and Kelley, B. W. « *Instantaneous coefficients of gear tooth friction* ». Tribology Transactions, 1961, Vol. 4, pp. 59-70.

[5] Misharin, Y. A.," Influence of the friction condition on the magnitude of the friction coefficient in the case of rollers with sliding", Proc. Int. Conf. On Gearing, 1958, inst. Mech. Eng., London, pp. 159-164, 1958.

[6] O'Donoghue, J. P., Cameron, A., "Friction and temperature in rolling sliding contacts", ASLE Transactions 9, pp. 186-194, 1966.

[7] Drozdov, Y. N., Gavrikov, Y. A., "Friction and Scoring under the conditions of simultaneous Rolling and sliding of bodies", Wear, pp. 291-302, 1967.

[8] H.Xu, A. Kahraman, N. Anderson, and D. Maddock, "*Prediction of mechanical efficiency of parallel-axis gear pairs*," ASME, Journal of Mechanical design, Vol, 129, no. 1, p, 58-68, 2007.

[9] Mushirabwoba Bernard, Lahcen Belfls,Brahim Najji and Abdelilah Lasri, "A comparative study of friction laws used in spur gear power losses estimation", Contemporary Engineering Sciences, Vol. 9, 2016, no. 6, 279 – 288, HIKARI Ltd, http://dx.doi.org/10.12988/ces.2016.512329.

[10] Shigley, Nisbeth J.K, Budynas R.G. (2015). Mechanical Engineering Design. Tenth Edition., pp 666-706 ,McGraw-Hill Companies Inc. New York.

[11] Gitin M. Maitra: "*Handbook of Gear Design*". Second edition, 1994.

[12] Mushirabwoba Bernard, Lahcen Belfls,Brahim Najji and Abdelilah Lasri, "Contribution to the study of power losses due to friction phenomenon between spur gear teeth" ,Materials Research Proceedings 1 (2016) 63-66, doi: http://dx.doi.org/10.21741/2474-395X/1/16.

[13] N. Anderson and S. Loewenthal, "*Spur gear system efficiency at part and full load, NASA tp-1622*," AVRADCOM TR-79-46, February, Tech, Rep., 1980.