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On the prediction of power loss in helical gearbox via simulation approach

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ABSTRACT

Frictional loss, load variation, viscosity and speed are major causes of power loss in helical gears under normal operating conditions. The study presents the major theoretical findings to predict the possible power loss in a helical gear box. First, an analytical technique was employed to model the frictional loss and coefficient of friction resulting from the heat generated for a pair of helical gear in mesh. Then, a finite element method and Comsol Multiphysics was applied to model the helical gear structure as well as the surface displacements under static and moving conditions of the pinion. It was observed that the highest amplitude in surface displacement was 14×10^{-6} (m) against when the pinion was stationary which is 20×10^{-6} (m). This can cause a significance wear depth and tooth surface pressure which eventually will lead to increase in fatigue. More so, As the frictional loss increase, there is an increase in the corresponding power loss factor with the highest being 180 for a frictional loss of 270. This shows that friction between a pair of meshing helical gear teeth influences power loss in a gearbox under normal operating condition. Thus, the results are an indication that good predictions during gear design would lead to a better gear transmission efficiency.

1. Introduction

Helical gears are cylindrical in shape with slanted tooth face. They have high contact ratio and excellent quietness with reduced vibration as well as capable of transmitting power efficiently compared to spur gears. They are mostly employed in areas of high-load applications owing to their number of teeth and its ability to distribute load effectively with less wear on the component parts (Diez-Ibarbia et al., 2017). However, despite its transmission efficiency, there are obvious failure problems associated with helical gears such as the resultant thrust distributed on the axes of the gear due to the sliding frictional forces of the meshing gear teeth (Diez-Ibarbia et al., 2018). This often make the gears susceptible to increase heat and subsequent power loss (Salawu et al., 2019). More so causing wear and downtime on the gear teeth (Salawu et al., 2019). Although several efforts have been made by studies on how to reduce frictional losses in helical gears. For instance, Changenet and Pasquier (2002) established that the natural convection and the heat exchange rates are major factors responsible for power loss in a pair of meshing gears. Thus, it is possible to calculate the power loss knowing the coefficient of friction for a pair of meshing gears (Fernandes et al., 2015). Zhan and Fard (2018) studied the effect of helix angle, coefficient of friction, varying root stresses and mechanical errors on helical gear pairs and was able to show that the coefficient of friction and helix angle had noticeable effects on tensile stress. Power loss in gear mating might be dependent on load or not. The meshing of gear teeth and friction in bearings are responsible for load dependent losses while viscous friction and losses due to lubricant are related to no-load losses (Miler, 2019). However, gears are susceptible to failure and power loss due to several adverse factors. The two common types of failure in gear systems include tooth breakage at the root of gears and pitting (due to heat) on the surface of gears (Ziegltrum, 2018). The incessant increase in temperature would not only reduce power loss in the gear system, but also induces failure modes on the system (Marques, 2016). It has been established that the analyses of friction and lubrication of a pair of helical gears in mesh is difficult because of the complex nature of the tooth surface (Deng, 2020). Based on this, several approach have been developed by different studies to reduce these power losses in gears. For instance, Cao et al. (2018) investigated the influence of contact path on the mixed lubrication behaviour of a bevel gear considering the friction and contact fatigue as well as tooth surface roughness. It was observed that the contact path exhibited slight wear due to a reduced film thickness, higher coefficient of friction and increased flash temperature. More so, there is bound to be power loss due to increased temperature and dynamic viscosity of the lubricant (Hu et al., 2019). Furthermore, it

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is important to understand that under unsteady state temperature flash, there could be variation in the power loss of gears due to the different base oil and additives associated with the lubricating oil (Liu et al., 2020). Hammami et al. (2017) reported that the frictional behaviour of gears under mixed lubrication depends largely on the additives blended in the lubricating oil. With a view to understanding the frictional loss in helical gears due to lubricants used and preventing the premature failure of gears, Fernandes et al. (2013) suggested that power loss can be reduced if the lubricant is capable of generating an effective oil film thickness that will flow through the path of contact of a pair of meshing gears. Thus, making it possible to maintain steady state temperature during application (Roda-Casanova, 2019). Prediction of the mechanical efficiency of helical gears is a crucial factor considered during design, in order to achieve reliability and overall productivity of the machine during operation (Simon, 2019). In order to investigate and determine the power losses in spur gears, Miler et al. (2018) performed a mult-objective optimisation of spur gears with focus on volume and efficiency. The result revealed that increasing the module and the profile shift of the gear resulted to reduction in power loss. Meshing helical gears in gearboxes are susceptible to heat due to friction. This results in power loss. Although several authors have analysed the effects of friction and heat on meshing gears, this study not only analyses the effects of friction on power loss but also proffer solution in terms of the optimisation of the lubricant used in such gearboxes to solve gear design frictional problems. Thus, the focus of the study is to use numerical method/simulation to analyse relationship between the power losses that occurs due to friction between two meshing helical gears, the input speed, torque, helix angle and vary the properties of lubricant in order to minimise power loss in a helical gear box.

2. Methodology

2.1. Numerical analyses

Consider a pair of helical gear in mesh (Fig. 1), the heat generated per unit time due to the sliding of the gear tooth can be obtained from the equ. (1) Changenet and Pasquier (2002)

$$P_{fl} = P_1 G \cdot f \tag{1}$$

P_{fl} = *friction losses in the tooth*
P_1 = *input power*

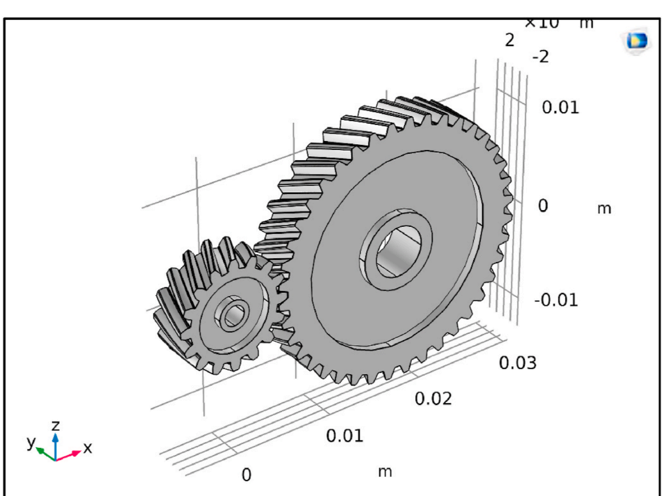

Fig. 1. Structural steel helical gear pair model.

$$G = \frac{\pi}{\cos\alpha} \cdot \left[\frac{1}{N_1} + \frac{1}{N_2}\right] \cdot \left(1 - \varepsilon_d + \varepsilon_1^2 + \varepsilon_2^2\right) \tag{2}$$

Where,

G = *power loss factor*
α = *helix angle*
N_1 *and* N_2 = *number of teeth on pinon and gear*

And

$$\varepsilon_d = \frac{h_f + h_a}{\rho_0} = \varepsilon_1 + \varepsilon_2 \tag{3}$$

h_f = *length of approach path (m)*
h_a = *length of recess path (m)*
p_0 = *base pitch (m)*

The coefficient of friction is determined by Kelley's equation:

$$f = 0.0127 \log_{10}\left[\frac{291205.8}{\rho u \cdot v_b V^2 / N_a}\right] \tag{4}$$

ρ = *density of oil* $\left(\frac{kg}{m^3}\right)$
u = *oil viscosity (cntistokes)*
V = *sum of rolling velocities*
vb = *sliding speed* $\left(\frac{m}{s}\right)$
Na = *normal tooth per load per length*

2.2. Simulation procedure

The geometry for this simulation was generated from customised library helical gear parts on the COMSOL Multiphysics software. These parts were created one after the other and then assembled as shown in Fig. 1. The equations were inputted into MATLAB and Microsoft Excel and the frictional loss factor results were obtained. Power factor equations were computed using MATLAB. To quicken computational time in COMSOL Multiphysics and avoid errors, a local region of the gears was focused on and given a finer meshing. In addition, the gear and lubricant boundaries were represented in one dimension for obtaining the temperature results.

2.3. Finite element analyses

The Finite element approach was applied to the model by employing a second order tetrahedral element method on COMSOL Multiphysics. The assembly of the two gears comprises of 532 boundaries, 1560 edges, and 1040 vertices. The finite element meshed model was computed three times; once on normal size, the other fine mesh size and finally finer mesh size. The normal mesh consisted of 54,227 domain elements, 23,026 boundary elements, and 6732 edge elements as displayed in Fig. 2. The fine sized mesh model comprised of 97,754 domain elements, 32,092 boundary elements, and 8560 edge elements as displayed in Fig. 3. The finer sized mesh model comprised of 3,64,625 domain elements, 78,814 boundary elements, and 16,696 edge elements and is shown in Fig. 4.

3. Results and discussion

Fig. 1, presents the geometry of the helical gear pair model which described a hypothetical situation of the gear system in service environment, while Figures (2–4) show the geometries of the helical gear after the finite element modelling using variable parameters such as

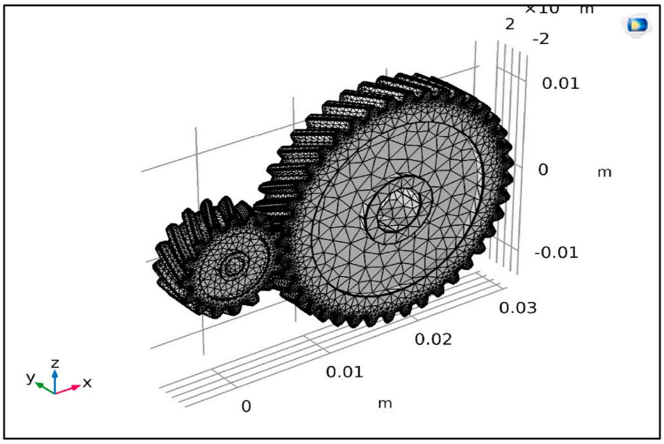

Fig. 2. FE model for normal mesh of helical gear pair.

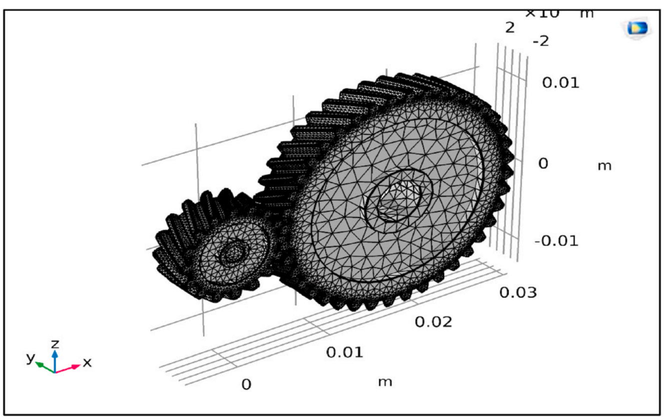

Fig. 3. FE model for fine mesh of helical gear pair.

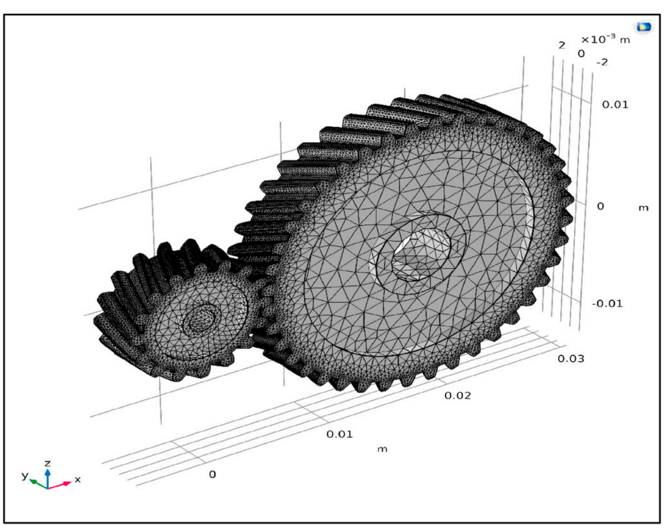

Fig. 4. FE model for finer mesh of helical gear pair model.

domain, boundary and edge elements in other to obtain accuracy and quality of mesh. The comparison between the normal, fine and the finer FE models of the helical gear teeth demonstrates the efficiency of this method for predicting the power loss as well as reducing wear.

Also, Figs. 5 and 6 revealed the surface displacement behaviour of a pair of helical gear in mesh with the pinion being stationary as shown in Fig. 5 and pinion in motion as presented in Fig. 6. There was slight variation in the amplitude of surface displacement for the moving pinion helical gear (Fig. 6) due to meshing of the gear teeth. It was observed that the highest amplitude was 14×10^{-6} (m) against when the pinion was stationary which is 20×10^{-6} (m) (Fig. 5). Thus, wear set in as the gears mesh. More so, the depth of wear will cause significant increase in tooth surface pressure which eventually will lead to increase in fatigue and subsequent power loss in the gearbox (Zhang et al., 2019). Thus, the simulation result helps in predicting the various transmission error that could result into lower transmission efficiency of the helical gear system.

Furthermore, Fig. 7 presents the effects of speed on the temperature of the gear under two different lubricating conditions. The results show that the gear system experienced significant rise in temperature using two different lubricants. However, lubricant number one (1) show a temperature of 550 K even at higher speed of 243 revolutions per minute (RPM) compared to the lubricant number two (2) which maintained the same temperature at a lower speed of 200 (RPM). Thus, the variations in the performances of these lubricants suggests the possible performance efficiency of the gear system and this technique can be adopted extensively in choosing lubricant suitable for improve efficiency as seen in the study by (Liu et al., 2020). Further to this, Fig. 8 presents the effects of viscosity on the frictional resistance of the gear system. It was observed that, the frictional resistance reduced gradually as the viscosity increase which is probably due to the decrease in temperature when lubricant number two (2) was used. However, it is worthy of note to say that, not all lubricants respond to change in temperature because of some unique kinematic viscosity index which is common to most lubricant. Thus, the effect of reduced friction owing to increase in viscosity suggests the necessity of predicting the choice of lubricants with additives that are capable of reducing friction.

More so, Fig. 9, presents the result of varying the number of teeth with the cosine of the helix angle (α). It can be deduced that the number of teeth for each gear depends on the helix angle. Thus, increasing the helix angle, will cause an increase in the contact ratio of the gear and subsequent reduction in bending and contact stress. Also, the nature of the graph depicts the change over time as series of gear teeth engage which invariably helps to establish the relationship between the number of teeth and helix angle. More so, the effects of temperature and torque variation is presented in Fig. 10. It was observed that the temperature increased with significant increase in the torque under the two lubricating conditions. Based on this, it would be difficult to get the approximate value for the torque due to heat and energy loss. Thus, the simulation result would guide gear manufacturers on the need to recommend suitable lubricant to be employed for the helical gears during application.

Fig. 11 show the comparison of frictional loss with power loss for a pair of helical gear in mesh. From the result, it was observed that a linear relationship existed between the frictional loss and power loss. As the frictional loss increase, there is an increase in the corresponding power loss factor with the highest being 180 for a frictional loss of 270. This shows that friction between a pair of meshing helical gear teeth influences power loss in a gearbox under normal operating condition. Although, applied load, speed and coefficient of friction resulted into excessive loss in friction of gears. Thus, the simulation result demonstrates that the power loss in a pair of helical gear in mesh dramatically increases with an increment in the frictional loss.

Fig. 12 represent the relationship between the cosine of helix angle of the gear teeth and the power loss factor. From the results, power loss factor increases insignificantly at the initial value of helix angle, that is between the range of values of cos α being (0.008–0.007). Interestingly, change in helix angle will cause a change in centre distance of the gear pair, however, the centre distance is an important factor for the helix angle modification during the gear design. Thus, studying the relationship between the helix angle and the power loss via this simulation approach would help in understanding the vibration effects which could

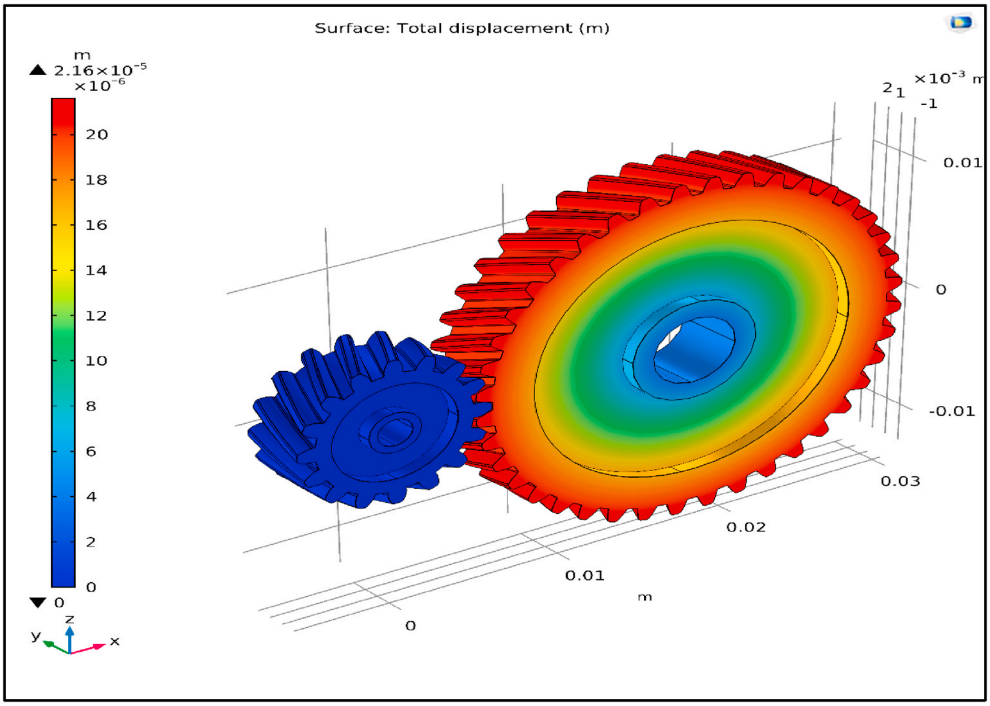

Fig. 5. Surface displacement plot with the pinion as a stationary reference.

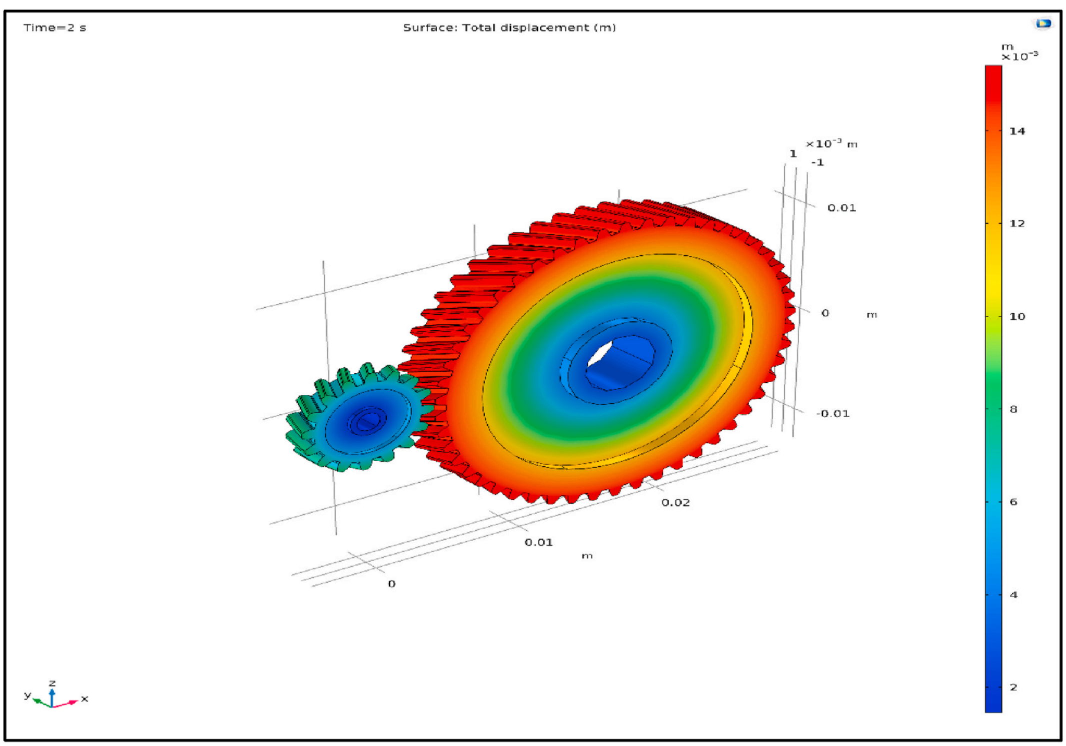

Fig. 6. Surface displacement plot with the pinion moving.

cause power loss. Hence, it becomes easy to tackle during gear design.

4. Conclusion

In this study, a quasi-analytical model and finite element method were employed to predict power loss in a pair of helical gear in mesh. The variable parameters used in the finite element model demonstrates that accuracy in helical gear mesh could be obtained in real life gear application. Also, it was observed that the amplitude of surface displacement is a critical factor that can cause wear of the tooth surface and subsequent power losses. These findings can help in providing a fundamental guidance during the helical gear transmission design. Furthermore, the variation in the performance efficiencies of the lubricants suggests their importance in predictions of the helical gear

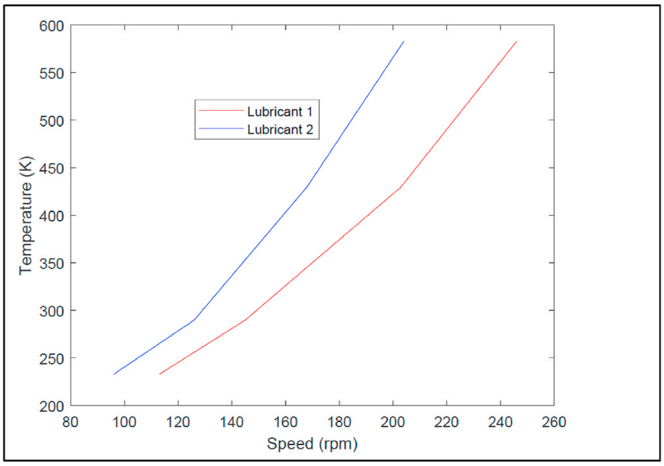

Fig. 7. Variation of temperature with speed.

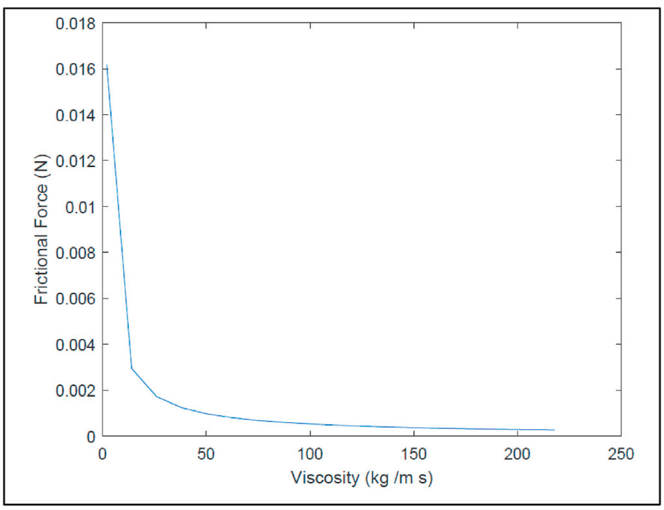

Fig. 8. Variation of frictional force with viscosity.

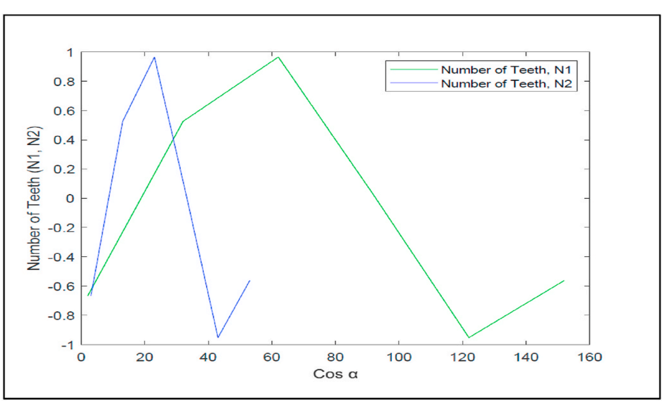

Fig. 9. Variation of number of teeth with cos α

transmission behaviour. More so, the result also established the linear relationship between frictional and power loss factor. Thus, the results are an indication that good predictions during gear design would lead to a better gear transmission efficiency.

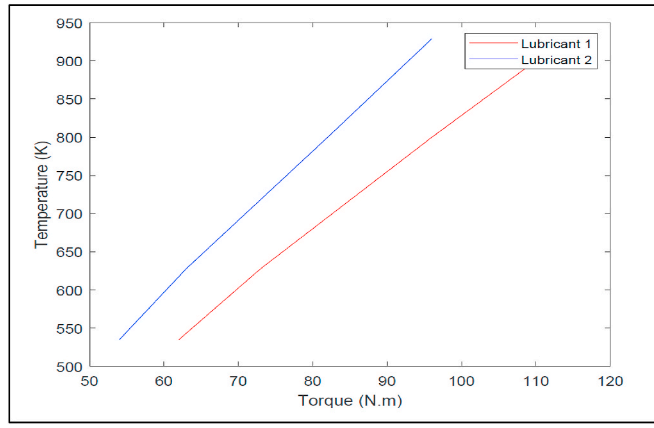

Fig. 10. Variation of temperature with torque.

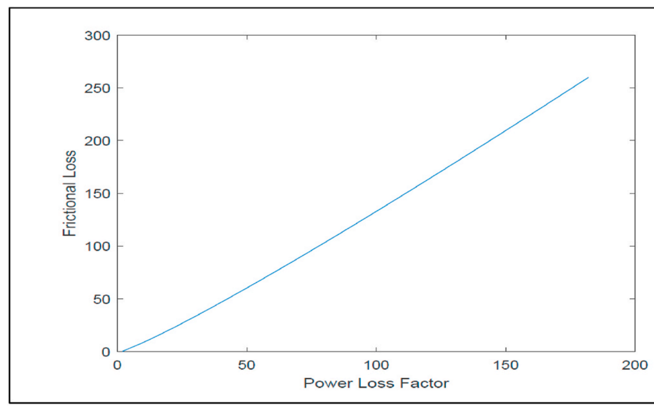

Fig. 11. Frictional loss against Power loss factor.

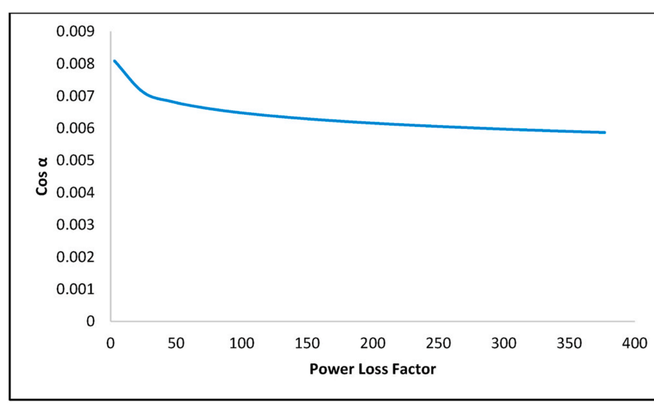

Fig. 12. Graph of cos α against the power loss factor.

Declaration of competing interest

Declaration of no conflict of interest.

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