

Effect of Lubricant on the Stiffness and Damping Characteristics in a Single-Stage Gearbox: A Theoretical Analysis



Vikas Sharma and Anand Parey

Abstract Gearbox is the most used mechanism to transmit the energy positively. Ignorance of any localized faults like crack, pitting, spalling, scuffing and wear could be responsible for the occurrence of any catastrophe. The odd operating conditions of a gearbox result in the initiation of the aforementioned faults. Such faults and operating conditions influence both noise and vibration levels. This article describes the role of lubricant in the gearbox. In this article, a theoretical model and a finite element method (FEM) have been presented to exhibit the characteristics of lubricant. The variation in the stiffness between the gears with and without lubricant has been evaluated using FEM. The results of simulation studies discussed and it has been found that the thickness of lubricant film affects both stress distribution and the mesh stiffness of the gear pair.

Keywords Finite element method · Gearbox faults · Lubricant · Stiffness · Vibrations

1 Introduction

Ignorance of the incipient fault and the possible reason for its cause could lead to the failure of a gearbox of a machine. Literature reports that such failures could be as dreadful as a catastrophe [1, 2]. A lubricant film plays a vital role in between the contact surfaces of any rotating machine elements such as bearings and gearboxes. No, or inadequate, lubrication causes high amount of wear which leads to degradation of components and the entire system could fail. It has been reported that failures in heavy machineries were due to lubrication problems [3]. Monitoring of lubricating

V. Sharma (✉)

Department of Mechanical Mechatronics Engineering, The LNM Institute of Information Technology, Jaipur, India
e-mail: s.vikasiiti@gmail.com

A. Parey

Department of Mechanical Engineering, Indian Institute of Technology Indore, Indore, India
e-mail: anandp@iiti.ac.in

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systems and lubricants in a gearbox could prevent breakdown/failures of machines and preventive measures could be suggested timely [4].

Lubricant in a gearbox is essential in maintaining efficient and effective operations under harsh speed and load conditions [5]. Lubricant damps the noise generated by the gear mesh. Harsh operating conditions due to variation in speed and load provoke gear tooth failures such as pitting, scuffing and wear. Gearbox vibration signals are dependent on gear mesh stiffness and if a fault in gear tooth initiates the mesh stiffness changes. As a result of change in gear mesh stiffness due to gear fault, the vibration signals of the gearbox change. This change in gearbox vibration signal highlights the fault occurred. In other words, reduction in gear mesh stiffness and severity of damage can be assessed by evaluating the same using vibration-based signals. Lubricating oils reduce wear and friction at these contact surfaces and separate them by maintaining proper lubrication and ensuring wear-less operation to avoid failures. Lube oil also affects gearbox behaviour in terms of vibration generated, heat absorbed and power characteristics [6]. Therefore, continuous monitoring of changes in lubricant properties could prove to be vital in avoiding propagation of defects within machines [7] and by preventing unexpected breakdowns.

Studies show that churning and splashing of lubricant in between the mating surfaces considerably affect the behaviour and performance of gearbox [8]. Churning of oil causes significant power losses in the gearbox and the losses due to churning increase with increasing viscosity at low speeds; however, these losses decrease at higher speeds [9, 10]. Further, due to internal friction in the lube oil, losses decrease with rise in temperature [11]. Further, an increase in temperature increases chemical activities, formation of tribological layers and decrease in oil film thickness.

Gear mesh stiffness is one of the fundamental parameters in the physics of gear. It further helps in determination and load-carrying capacity of gears, dynamic tooth loads and vibration characteristics of geared systems. If the meshing surfaces of gear and pinion tooth contain a surface fault, then there will be a loss in tooth contact. Due to the loss of contact, stiffness will reduce gradually, and as a result, vibration signal will change. Particularly, due to the absence/minimal thickness of lubricating film, surface faults/error appears in the original involute profile of gear. Due to gear tooth faults, a change in gear mesh stiffness and occurrence of impulses have been observed in between meshing gears, which have lost the original involute profile, thus leading to change the vibration levels of the system [12].

For gearbox vibration analysis, most of the researchers have discussed that time-varying gear mesh stiffness is one of the important parameters that affect the vibration response of the gearbox [13–15]. A reduction in gear tooth stiffness with an increase in teeth wear shows a linear relationship with wear severity. Further, increase in the vibration levels occurs due to reduction in oil film thickness between the meshing surfaces due to reduced damping effect [16].

The literature presents the studies considering gears under static conditions only; thus, the stiffness has been evaluated without considering the lubrication. However, in the present manuscript, this gap has been attempted to address. Further, the effect of no or less lubrication on the gear vibration can be understood from the results obtained. In the above-mentioned literature, the gear mesh stiffness

is calculated without considering the characteristics of lubricant. However, in the practical environment, there is always a lubricating film in between a gear mesh pair and its role cannot be neglected while deriving the equivalent gear mesh stiffness of a gear pair. An attempt to exhibit the effect of lubricating film on the gear mesh stiffness has been addressed in the present manuscript. In this study, the theoretical model for evaluating gear mesh stiffness is presented. A simulation study has been performed to illustrate the effect of lubrication on gear mesh stiffness.

2 Gear Mesh Stiffness of a Single-Stage Spur Gear Pair

In the present study, single-tooth contact pair of gear system is investigated. In a single pair, two teeth are meshed and share equal force. In case of single-tooth contact pair, the gear mesh stiffness consists of the tooth stiffness of gear 1 (gear) and gear 2 (pinion). The gear mesh stiffness expression is considered by many researchers to study the gear defects such as crack, pitting and spall is given by [13, 17–19]:

$$\frac{1}{K_m} = \frac{1}{k_p} + \frac{1}{k_g} \tag{1}$$

where k_p is the tooth stiffness of pinion, k_g is the tooth stiffness of gear and K_m is gear mesh stiffness.

But, for the real circumstances, a stiffness component of lubricant film will also be added to Eq. (1) as suggested by Yuan et al. [20]. Figure 1 presents the model of an actual gear pair. The equivalent gear mesh stiffness of the gear pair in mesh with lubrication can be denoted by K_e which can be express as:

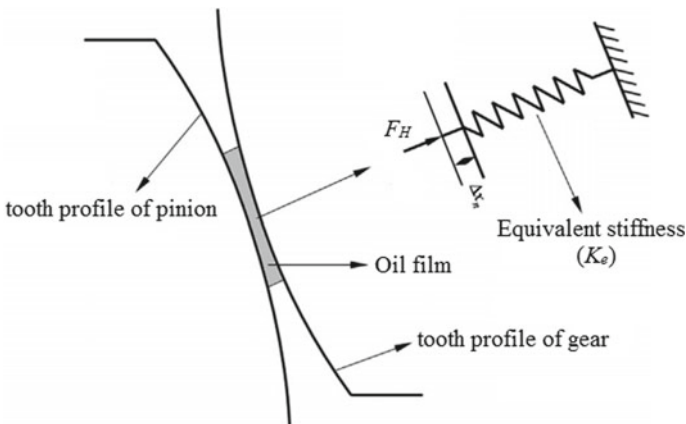


Fig. 1 Model of spring stiffness of a gear pair

$$\frac{1}{K_e} = \frac{1}{K_m} + \frac{1}{K_1} \quad (2)$$

where K_1 is lubricant film stiffness, described as $K_1 = \partial F_H / \partial h_c$, where F_H is the hydrodynamic force or the contact mesh force and h_c is the thickness of the lubricating film between the two meshing surfaces. K_m is the gear mesh stiffness of gear pair without lubrication, which is evaluated as $K_m = k_p k_g / (k_p + k_g)$.

Further, the damping of lubricant film plays a crucial role in gear dynamics. The critical viscous damping ratio ζ is inversely proportional to gear mesh stiffness and can be expressed as [21]:

$$\zeta = \frac{c}{2\sqrt{K_m m_e}} \quad (3)$$

where c is the damping coefficient of viscous lubricant and m_e is the gear pair's equivalent mass. It can be observed from Eq. (3) that the damping ratio is inversely proportional to the stiffness. Also, the damping ratio is dependent on the excitation frequency ω . Nevertheless, viscous damping also depends on the physical parameters of the gear-lubricant system, viz. tooth profile and geometry, sliding velocity of teeth as well as the tooth meshing force. The contact mesh force F_H will act on a gear pair as [21]:

$$F_H = F_k + F_c \quad (4)$$

where F_k is the amount of force disbursed to stiffness components and F_c towards the damping effect.

In a gear mesh during teeth contact, the oil squeeze action between the gear teeth controls the damping behaviour of lubricant [21]; parameters such as the viscosity of lubricant, temperature of lubricant as well as the velocity of the gear pair play a significant role. It has been observed that for a given temperature, the damping ratio (lubricant viscous damping capacity) increases with higher operating speed. A decrease in the minimum film thickness leads to augmentation of the dissipative energy and severe teeth vibro-impacts.

3 Discussion of Simulation Studies of a Single-Stage Gear Pair

The major parameters of gear pair and lubricant used in the simulation studies are given in Table 1. In the present article, two simulation studies have been carried out to study the behaviour of lubricant. First one is the finite element method-based simulation study that has been performed to highlight the stress distribution under the effect of lubricated film. The second one is the MATLAB simulation of numerical expressions to exhibit the behaviour of mesh stiffness under the effect of lubrication.

Table 1 Gear geometry and lubricant parameters

Parameters related to gear pair		Parameters related to lubrication	
Young’s Modulus (E)	206.8 GPa	Damping ratio (ζ)	0.17
Poisson’s ratio (ν)	0.3	Viscosity at ambient pressure (η_0)	0.08 Pa s
Pressure angle (φ)	20°	Density at ambient pressure (ρ_0)	870 kg/m ³
Face width (B)	16 mm	Pressure–viscosity component (α_0)	2.2×10^{-8} Pa ⁻¹
Tooth number (Z_p/Z_g)	32/81	Ambient temperature (T_0)	30 °C
Module (m)	2 mm		
Material density (ρ)	7800 kg/m ³		

3.1 Finite Element Method

A three-dimensional model of spur gears with involute tooth profile has been adopted to analyze the effect of stress distribution with and without lubrication. The film of lubrication in between the gear tooth meshing surfaces has been treated as mass-less spring-damper link. The finite element modelling of gear pair with lubricating film has been performed in Ansys. The FEM-based model of spur gear has been analyzed from engagement to disengagement point. The main parameters of spur gears used for finite element modelling are shown in Table 1. Figure 2 shows the FEM-based model of gear and pinion. The contact regions of pinion and gear wheel are fine meshed than the remaining body of the gears. The internal diameter of gear wheel is fixed and internal diameter of pinion is supported by frictionless support. The moment of 19.8 Nm is applied on pinion. The deflections along the y -axis and x -axis are obtained using FEM. In Fig. 2, only mesh position is shown; however, the other mesh positions from engagement to disengagement are modelled and applied same procedure at each position.

Figure 3 shows the Von-Mises stresses developed at the contact of the gear mesh for both the conditions, i.e. with lubrication and without lubrication. For the case of without lubrication, the maximum value of stress is 1.229 GPa, whereas for the case of with lubrication, the value of maximum stress 1.18 GPa. On comparing the stress distribution at the gear mesh point, it has been observed that the lubricant bears 49 MPa of stress. It is worth noting that the distribution of the stresses for both the cases remains more or less same. A possible reason behind this behaviour could be because of the simulation conditions. To analyze the effect of lubrication in between the gears, MATLAB simulation has also been performed and presented subsequently. It can also be observed that the applied moment of 19.8 Nm exerts the force at the tooth root of gear.

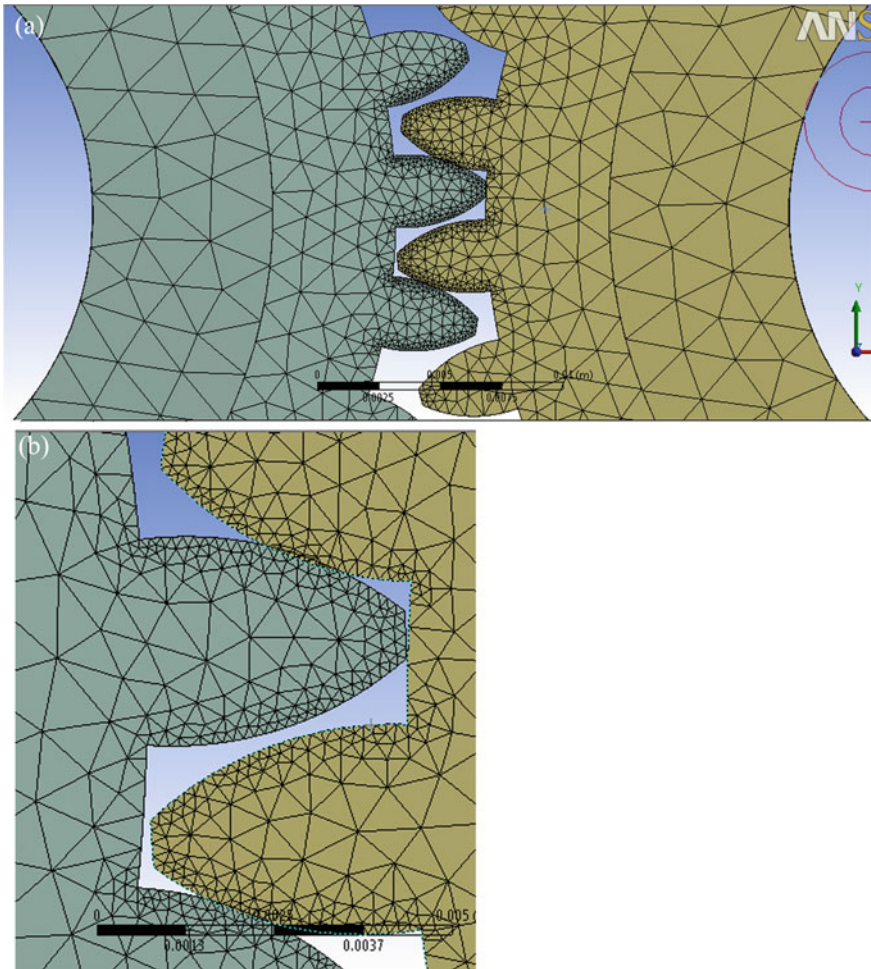


Fig. 2 Finite element method of pinion gear pair. **a** Full model, **b** zoomed view

3.2 *MATLAB Simulation of Numerical Expressions*

The main parameters of the pinion and the gear used to evaluate the gear mesh stiffness are listed in Table 1. Figure 4 shows the mesh stiffness values for healthy gear pair for both the cases, viz. without lubrication and with lubrication. A change in stiffness value has been observed when there is lubrication between the meshing surfaces, as compared to the stiffness value without lubrication. Due to lubrication, the friction coefficient in between the meshing surfaces varies. It has been observed that for the case of without lubrication, the stiffness increases linearly for the double contact region of gear meshing. Whereas for the case of with lubrication, the mesh stiffness increases for the approach part of double tooth contact and then decreases

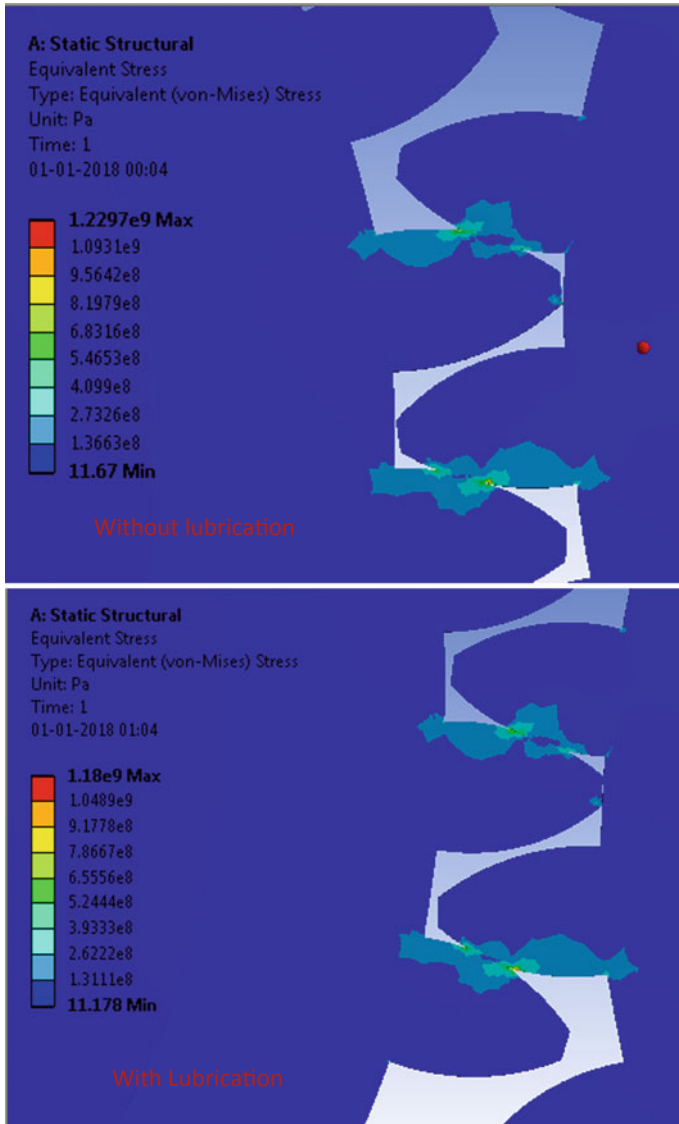


Fig. 3 Stress distribution at contact point of mesh

for the recess part of double tooth contact. The variation in mesh stiffness is due to the nonlinear characteristics of lubricant, i.e. damping and stiffness. The gear mesh stiffness has been plotted for three mesh cycles and is shown in Fig. 4. An increase in the gear mesh stiffness has been observed for both approach and recess for the duration of single point tooth contact with lubrication. On the other hand, the

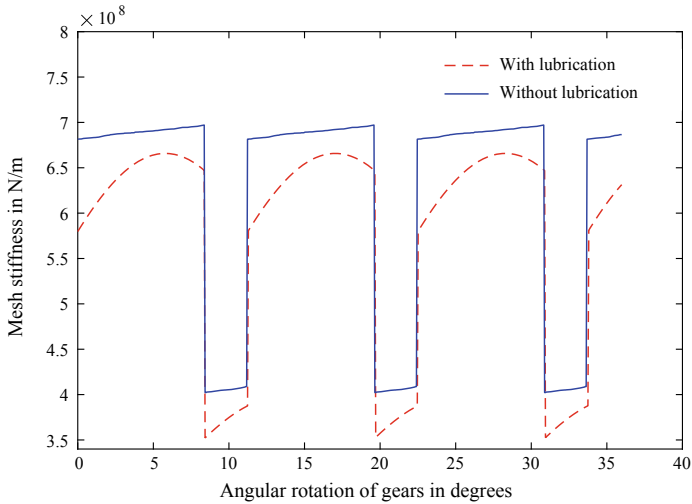


Fig. 4 Effect of lubricant on mesh stiffness for healthy gear tooth

mesh stiffness without lubrication is reflected by a very steep curve, which is due to increased friction in between the meshing surfaces.

4 Conclusion

The lubricant film in between the gear tooth meshing surface plays a pivotal role. Simulation studies highlight that lubrication affects the application of force on the gear mesh surfaces, contact teeth and minimizes the level of stress. The distribution of the stress at the contact point of teeth in gear mesh remains nearly same. Further, lubrication also affects the mesh stiffness of the gear pairs. The mesh stiffness increases with decrease in the lubricant film thickness. In the presence of lubrication, the variation in equivalent gear mesh stiffness occurs from single-to-double and double-to-single-tooth contact nonlinearly. Further, experimental evaluations need to perform to prove the effect of lubrication on the vibration characteristics. A relationship exhibiting connection between gear vibration and lubrication can be further addressed mathematically.

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