Engineering Failure Analysis 39 (2014) 92–107

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Dynamic characteristics of helical gears under sliding friction with spalling defect

Hanjun Jiang [a], Yimin Shao [a,*], Chris K. Mechefske [b]

[a] State Key Laboratory of Mechanical Transmission, Chongqing University, People's Republic of China
[b] Department of Mechanical and Materials Engineering, Queen's University, Canada

ARTICLE INFO

Article history:
Received 21 July 2013
Received in revised form 10 January 2014
Accepted 20 January 2014
Available online 31 January 2014

Keywords:
Dynamic characteristics
Helical gears
Sliding friction
Time-varying contact stiffness
Spalling defect

ABSTRACT

The change of friction force on both sides of the pitch plane and the change of contact stiffness induced by tooth spalling defect cause the change of the dynamic characteristics of helical gears. However, there is no good solution for the modeling and calculation of the internal excitation in helical gears with spalling defect to reveal the change of the dynamic characteristics. In this study, the calculation methods of friction excitations and contact stiffness are proposed based on the time-varying length of contact line in helical gears. By considering the change of the mesh position and the loss of length of contact line induced by tooth spalling defect, the time-varying friction force is obtained by subtracting the length of spalling defect at the mesh position from the length of the normal contact line, and the time-varying contact stiffness is obtained by Hertz contact algorithm. A six-degree-of-freedom analytical helical gear pair model is developed by incorporating the time-varying sliding friction and mesh stiffness based on the changes of friction force and mesh stiffness. Dynamic characteristics are simulated via helical gear pair examples with spalling defects. The results show that the oscillations of the dynamic responses become more significant at both the beginning and the end of the spalling area, especially with the growth of the spalling size. The developed analytical model provides a new method for the study of excitation characteristics in helical gears with tooth spalling defect.

1. Introduction

The gear drive is one of the most important transmission forms in the machinery industry because of their compact structure, high transmission efficiency and strong load capacity. However, vibration and noise generated by gearboxes are annoying problems. Recently, sliding friction has been reported to be an important source of gear vibration and noise. Houser et al. [1,2] experimentally demonstrated that the friction forces play a pivotal role in determining the load transmitted to the bearings and housing in the off-line-of-action (OLOA) direction. Velex et al. [3,4] evaluated the effects of sliding friction, teeth shape deviations and time-varying mesh stiffness in spur and helical gears. They revealed the potentially significant contribution of teeth friction to gear vibration and noise. Kar and Mohanty [5] formulated a time-varying contact length, frictional force and torque for a defect free helical gear system. They declared that the frictional force and torque induce low frequency components along with the gear mesh frequency. He et al. [6,7] incorporated the sliding friction and realistic time-varying

* Corresponding author. Tel.: +86 2365112520.
E-mail address: ymshao@cqu.edu.cn (Y. Shao).

http://dx.doi.org/10.1016/j.engfailanal.2014.01.008
1350-6307/

Nomenclature

L_{CD}	length of line of action
β_b	base helix angle of gear
$L_{\max}$	length of maximum contact line
b	face width of gear
v	velocity of pinion
f, f_1, L_{PA}, L_{PB}, L_{PC}, L_{PD}, L_{AB}	various distances show in Figs. 1 and 2
P_t	base pitch of gear
S_1, S_2	defined variables
L, L_t	length of contact line for single gear pair and total mesh gear pairs
L_i	length of ith contact line
L_{ir}, L_{il}	length of contact line of right and left parts for ith mesh tooth pair
F_{ir}, F_{il}	frictional force of the right and left side of ith contact line
F_{fp}, F_{fg}	total frictional force on pinion and gear
F_{fpi}, F_{fgi}	frictional force of ith mesh tooth pair for pinion and gear, respectively
F_m	mesh force of gear pair
μ	friction coefficient of gear pair
X_{pri}, X_{pli}	moment arm on the right and left side of ith contact line
X_{pr}, X_{pl}	moment arm on the right and left side contact line
T_{fpi}, T_{fgi}	frictional torque of each contact line on pinion and gear
T_{fp}, T_{fg}	frictional torque on pinion and gear
l_s, l_{s1}, l_{s2}	length of the spalling
w_s	width of the spalling
d_{ov}, d_{oh}, d_v, d_h, R_1, R_2, R_3, R_4	various distances show in Fig. 7
$\Delta L(t)$, $\Delta L_r(t)$	loss of contact line
R_{bp}, R_{bg}	base radius of pinion and gear
k_m	mesh stiffness of gear pair
k_o	mesh stiffness density per unit length
k_b,	combined bending, shear and axial compressive stiffness
k_h, k_{sh}	Hertzian contact stiffness
u	Poisson's ratio
ε	contact ratio
θ_i, $\dot{\theta}_i$, $\ddot{\theta}_i$	angular position, angular velocity and angular acceleration
I_p, I_g	inertia of pinion and gear
T_p, T_g	input torque and brake torque
F_{mi}	dynamic mesh forces of ith meshing tooth
e	static transmission error
ζ_{mi}	damping ratio of ith meshing tooth
I_e	equivalent moment of inertia
m_p, m_g	mass of pinion and gear
x_p, x_g, y_p, y_g	displacement of pinion and gear along LOA direction and OLOA direction
$\dot{x}_p, \dot{x}_g, \dot{y}_p, \dot{y}_g$	velocity of pinion and gear along LOA direction and OLOA direction
$\ddot{x}_p, \ddot{x}_g, \ddot{y}_p, \ddot{y}_g$	acceleration of pinion and gear along LOA direction and OLOA direction
C_{iBj}, K_{iBj}	damping and stiffness of bearing along LOA direction and OLOA direction
δ	composite dynamic transmission error
F_{iBJ}	dynamic bearing forces
$L_s(t)$	contact line of single tooth pair for spalling defect gear
$L_{sr}(t)$, $L_{sl}(t)$	contact line at the right side and left side of the pitch plane for spalling defect gear
$\Delta(t)$, $O(t)$, $P(t)$	shape, size and location function of spalling defect
t_c	time of one mesh circle

stiffness into an analytical spur and helical gear model. This work revealed that sliding friction is indeed the source of the OLOA motions, and that sliding friction has marginal effects on the dynamic transmission error for helical gears, as compared with spur gears.

Many dynamic models have been presented in order to calculate the influence of friction [8–12]. Meanwhile, friction between meshing teeth accelerates the occurrence of failure modes such as pitting or spalling damage and surface wear