Tribology International 101 (2016) 383–394

Contents lists available at ScienceDirect

Tribology International

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

Investigation on coupling effects between surface wear and dynamics in a spur gear system

Xianzeng Liu [a], Yuhu Yang [a], Jun Zhang [b,*]

[a] School of Mechanical Engineering, Tianjin University, Tianjin 300072, PR China
[b] School of Mechanical Engineering and Automation, Fuzhou University, Fuzhou 350116, PR China

ARTICLE INFO

Article history:
Received 19 March 2016
Received in revised form
3 May 2016
Accepted 5 May 2016
Available online 7 May 2016

Keywords:
Gear dynamics
Gear wear
Mesh stiffness
Transmission error

ABSTRACT

A dynamic wear prediction methodology is proposed to investigate the coupling effects between surface wear and dynamics of spur gear systems. The overall computational scheme combines a quasi-static wear model and a translational-rotational-coupled nonlinear dynamic model. The worn surfaces are represented by modulated mesh excitations and introduced into the dynamic model to investigate the effects of surface wear on system's dynamic characteristics. The dynamic gear mesh forces are converted into an equivalent load by using the Miner rule to reveal the effects of dynamics on wear behaviors. A spur gear transmission is taken as an example system to demonstrate the interactions between surface wear and dynamic behaviors. The simulations indicate that surface wear and gear dynamics are highly interacted.

1. Introduction

Gear systems are widely used in various power transmission applications due to their distinguished merits of accurate transmission ratio, large power range, high transmission efficiency and stable operation quality. For a gear system worked in dirty environments with heavy duties, the surface wear and the vibration are considered two major causes of operational failure. To improve the transmission accuracy and avoid premature fatigue, numerous efforts have been carried out to investigate the vibration mechanism of gear systems [1–7] and the wear mechanism of gear teeth [8–32].

As addressed in previous studies, surface wear and gear vibration are mutually affected by each other [8–17]. As a long-term material removal behavior, surface wear results in a deviation from the intended tooth profile and alters the gear mesh excitations, which makes the dynamic behaviors of a gear system with worn surfaces quite different from their counterparts without wear. Surface wear not only alters the stress and load distributions but also aggravates system's characteristics of vibration and noise. On the other hand, the dynamic loads caused by system vibration are different from the static loads, which increases the contact pressures between the mating surfaces and fasten the wear process. From this point of view, the gear system dynamics also affects the surface wear characteristics significantly.

Although the investigations on surface wear and gear dynamics are abundant, the studies focused on the their coupling effects are quite few. Among these few studies, most of the them are concentrated on the effects of surface wear on the dynamics of a gear system [8–14]. For example, Choy et al. [8] studied how the surface pitting and wear affect the vibrations of a gear system. The effect of surface wear was represented by the change of gear mesh stiffness which was then introduced into a gear-shaft model. Wojnarowski and Onishchenko [9] established a two degrees-of-freedom elastic dynamic model with worn teeth to study the impacts of surface wear on spur gear dynamics. Yesilyurt et al. [10] investigated the influence of surface wear on the change of gear mesh stiffness from the durability and diagnostic points of view. Their study manifested that the effect of surface wear on the system's dynamics was primarily caused by the deviations in tooth shape from the idea involute profile. Kuang and Lin [11] investigated the effect of surface wear on the variation of vibration spectrum of a spur gear system by combining a single degree-of-freedom dynamic model with a wear prediction model developed by Flodin et al. [18,19]. The simulation results showed that the surface wear may change the dynamic load histogram of an engaging spur gear pair greatly. Later, they carried out a similar investigation for an engaged plastic gear pair [12]. However, in their studies only the dynamics at one rotational speed were investigated. Yuksel and Kahraman [13] combined a wear prediction model proposed by Bajpai et al. [23] and a deformable-body dynamic model [33] to study the influence of quasi-static wear profiles on the dynamics of a planetary gear set. The worn surfaces were introduced into the dynamic model to quantify the effect of

* Corresponding author.
E-mail address: zhang_jun@tju.edu.cn (J. Zhang).

http://dx.doi.org/10.1016/j.triboint.2016.05.006
0301-679X/

Nomenclature

A_e, B_e	Magnitudes of AM and FM for STE
m_p, m_g	Mass of pinion and gear
A_k, B_k	Magnitudes of AM and FM for mesh stiffness
n	Number of harmonic terms
F_{aT}	Fluctuating force
n_1	Speed of pinion
F_{aTr}	Harmonic amplitude of fluctuating force
p	Contact pressure
F_m	Average mesh force
q	Number of pressure update
F_p, F_g	External radial preloads of bearings
s	Sliding distance
I_p, I_g	Mass moments of inertia for pinion and gear
t	Time
R_p, R_g	Radii of base circles for pinion and gear
u	Relative displacement along the line of action
T_{eq}	Equivalent load
y_p, y_g	Transverse displacements of pinion and gear
T_j	Torque at each discrete time instant
δ	Displacement in the direction of the path of action
T_p, T_g	Input torque and output torque
$\delta_{H1,2}$	Hertz flattening
$2b$	Backlash value of gear pair
δ_{RK}	Gear body deformation
c_m	Mesh damping
δ_Z	Gear tooth bending
c_{py}, c_{gy}	Damping of bearings for pinion and gear
ε^q	Predetermined wear threshold
e	STE
ε^t	Maximum allowable wear threshold
e_r	R-th harmonic amplitudes for STE
ζ	Number of wear cycles
h	Wear depth
θ_p, θ_g	Torsional displacements of pinion and gear
k	Wear coefficient
ϕ_{aTr}	Harmonic phase angle input torque excitation
k_{ar}	R-th harmonic amplitudes for mesh stiffness
ϕ_{ea}, ϕ_{eb}	Initial phases of AM and FM for STE
k_m	Time-varying stiffness
ϕ_{er}	Harmonic phase angles of STE
k_{mm}	Average mesh stiffness
ϕ_{ka}, ϕ_{kb}	Initial phases of AM and FM for mesh stiffness
$k_{t1,t2}$	Total stiffness of one tooth pair
ϕ_{mr}	Harmonic phase angle of mesh stiffness
$k_{p,g}$	Individual stiffness of one tooth
ω_{aT}	Fundamental frequency of input excitation
k_{py}, k_{gy}	Bearing stiffness of pinion and gear
ω_e	Fundamental frequency of STE
l	Slope of the Wöhler-damage line
ω_m	Fundamental frequency of mesh stiffness
m_c	Equivalent mass of gear pair

surface wear on the dynamic gear meshing forces. Nevertheless, the surface wear behaviors under dynamic conditions were not discussed in this study. Osman and Velex [14] combined a dynamic model with a wear model based on Archard's law to investigate the effect of surface wear on the dynamic responses of a wide-faced gear.

Compared with the studies of the effects of surface wear on gear dynamics, the investigationes on the effect of gear dynamics on the surface wear behaviors were even less [16,17]. Ding and Kahraman [16] combined a one degree-of-freedom dynamic model with Bajpai's wear prediction model [23] to study the interactions between the surface wear and the dynamics in a spur gear system. In this study, the effects of wear profiles were represented by a periodically time-varying mesh stiffness function and an external displacement excitation. More recently, they extended the methodology to a planetary gear system to investigate the interactions between the surface wear and the system's dynamic behaviors [17].

From the above reviews, it can be found that there is common thread in the efforts of investigating the coupling effects between the surface wear and gear dynamics in that the worn surfaces are treated as internal excitations (time-varying meshing stiffness and/or transmission error) incorporated with certain kind of dynamic model of a gear system. Based on these dynamic models, the effects of surface wear on the dynamic behaviors of gear are investigated and vice versa. However, it needs to point out that an accurate prediction for the gear dynamics relies on a comprehensive dynamic model. Unfortunately, the dynamic models used in the above studies only included the torsional deflections in gear-shaft systems. The translational effects coming from the shaft bending and bearing radial deflections were not considered in these dynamic models, which may degenerate the prediction accuracy of the dynamic analysis. To guarantee the prediction accuracy, a comprehensive translational-rotational-coupled nonlinear dynamic model with three degree-of-freedom for a spur gear system is proposed and then combined with a quasi-static wear model proposed earlier by the authors [32]. Based on this combined dynamic surface wear prediction methodology, the effects of surface wear on the dynamic behaviors of the spur gear system are investigated. Meanwhile, the influences of the dynamic loads on the surface wear behaviors are studied by converting the steady-state dynamic gear forces into an equivalent load with the Miner rule. The converted equivalent load is introduced into the quasi-static wear model to reveal the surface wear process under dynamic load conditions.

A thorough understanding of the coupling effects between the gear wear and the gear dynamics helps to prolong the service life and improve the performance of gear sets. Motivated by this thought, the main contents of this paper are arranged as the follows. In Section 2, a translational-rotational-coupled nonlinear dynamic model for a spur gear system is developed which incorporates the effect of worn surfaces of the mating gear pair. The profile deviations from surface wear are represented in the forms of gear mesh excitation and transmission error functions with amplitude and frequency modulations. In Section 3, a dynamic wear prediction methodology is proposed by combining the proposed dynamic model with the aforementioned quasi-static wear model [32]. In Section 4, a spur gear system is taken as an example to demonstrate the coupling effects between the surface wear and the dynamic responses. Finally, some conclusions are drawn in Section 5.

2. Dynamic modeling for a spur gear system

In this section, an analytical nonlinear dynamic model for a spur gear system with surface wear is established, with which the dynamic behaviors of the system can be predicted.

By simplifying the real-world gear system into a mass-spring-damping system, a lumped parameter nonlinear dynamic model