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Research paper

Influences of spline assembly methods on nonlinear characteristics of spline–gear system

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ABSTRACT

As a connector, the spline is widely applied in gear transmission systems. In transmitting torque, the load and deformation of the spline are affected by the applied assembly method, and this effect leads a change in the time-varying meshing stiffness (TVMS) of the gear pair. Consequently, the nonlinear characteristics and vibration performance of the whole system can be affected. In this study, the TVMS of gear systems that use two different spline assembly methods, namely, *the-side-fit* and *the-major-diameter-fit*, is predicted by finite element contact analysis. Subsequently, the nonlinear dynamic model of the spline–gear system is established and its accuracy is verified through a vehicle vibration experiment. The numerical results reveal that the system assembled through *the-side-fit* and *without spline* exhibits a diverse range of periodic, sub-harmonic, and chaotic behaviours at high speed, whereas no bifurcation is observed through *the-major-diameter-fit*. As the magnitude of interference increases in *the-major-diameter-fit*, the dynamic transmission error decreases. Therefore, different assembly methods can affect the nonlinear characteristic. Moreover different magnitudes of interference in *the-major-diameter-fit* also have effects on the nonlinear characteristics and vibration performance of spline–gear systems.

1. Introduction

Spline couplings have greater high torque-transmitting capacity and a self-cantering action under load even when backlash occurs between mating members [1]. Splines are widely used in drivetrains to connect components that carry torque, such as gears, shafts, clutches, and couplings. A system in which the gear is mounted on the shaft to transmit a large torque through the spline is called spline–gear system in this study. Furthermore, the spline, which connects the gear and shaft, affects the mechanical properties of the gear-shaft-bearing system, and the dynamic characteristics of the gear pair. The dynamic characteristics of the gear can influence the stability and vibration performance of the whole drive system. Therefore, the spline is important in the dynamic analysis of the spline–gear system.

To analyze the characteristics of the involute spline and the gear mounted on the shaft through the spline, H.P. Bloch et al. [2] focused on the neutral, lubrication and wear of spline joints. And many other studies focused on the methods of contact force distribution along the axial direction of splines or developing an analytical model to estimate the torque distribution along the face width direction of spline teeth [3–5]. In recent years, Wink and Nakandakar [6] presented an investigation of the influence of spur gear [7–9] loads on the load distribution of spline teeth. Guo et al. [10] purposed a

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Nomenclature

ε	Contact ratio of gear tooth.
F_{ns}, F_{ts}	Normal contact force and tangential force of the spline tooth
u_g	Comprehensive elastic deformation of one single pair of gear teeth.
ϕ	Angel of rotation in one whole meshing cycle of gear tooth
x_1, x_2	Modification coefficient of pinion
Z_H	Coefficient of nodal region for nonstandard gear.
Z_E	Elastic coefficient of material
Z_ε	Coefficient of contact ratio.
Z_β	Helical angular coefficient
ε_α	Transverse contact ratio
ε_β	Vertical contact ratio
σ_H	Contact stress
K_A	Coefficient of performance
K_V	Dynamic factor
$K_{H\beta}$	Longitudinal load distribution coefficient,
$K_{H\alpha}$	Load among tooth distribution coefficient
α	Pressure angle
u	Transmission ratio
m_p, m_g	Masses of pinion and gear
F_n	Normal contact force of the gear pair
T_g, T_p	Input torque and resisting moment
k_{pz}, k_{py}	Axial stiffness coefficients of pinion and gear
k_{gz}, k_{gy}	Axial stiffness coefficients of pinion and gear
I_p, I_g	Masses moment of inertia of pinion and gear
R_{bp}, R_{bg}	Base circle radius of pinion and gear
O_p, O_g	Rotation centres of pinion and gear
c_{py}, c_{gy}	Axial damping coefficient of bearing housings of the driven pulley shaft and intermediate shaft
c_{pz}, c_{gz}	Vertical damping coefficient of the driven pulley shaft and intermediate shaft
θ_p, θ_g	Rotational displacement of pinion and gear

new analytic model which addresses the tooth contact and induced loads of gear coupling that are affected by misalignment, torque, and friction.

Meanwhile, many works focus on tooth stiffness which is a very important dynamic behaviour parameter of spline couplings and gears that are used in power transmission systems to transfer torque by means of tooth engaging each other [11–13]. Wang et al. [14] carried out the dynamic analysis of a hypoid gear pair considering the effects of the time-varying meshing stiffness TVMS parameters and backlash. Raghuwanshi and Parey [15] used photo elasticity to measure the mesh stiffness of gear teeth with cracks. And Cui et al. [16] mentioned that, to achieve the expected purpose monitoring the gearbox condition, it is important to improve the accuracy of the vibration response which is primarily caused by the TVMS is the source of the parametric excitation of the gear pair and plays a fundamental role in its dynamic behaviour [17]. Owing to the high sensitivity of the gear pair to TVMS, tooth profile errors, and overall structural dynamics, the vibration response of the gear pair system can be very complex and not easy to be controlled [18].

Existing studies, either focus only on the characteristics of the spline or the gear or consider only the effects of the gear on the spline. A few works have analysed the influence of the interaction between spline and gear in detail. And in most cases, they neglected the flexibility of the spline joint in torsional dynamic models assuming that the shaft is rigidly connected to the gear [19,20]. The interaction between the spline and the components connected with it should be considered, because it affects their specialty, such as the TVMS [21], which is essential to the noise and vibration of the gear system. Moreover, few researchers have focused on the assembly method on the nonlinear characteristics and vibration performance of the spline–gear system using the dynamic analysis. Additionally, the influence of the magnitude of interference on the dynamic characteristic of the system when *the-major-diameter-fit* is applied has been studied.

This study aims to investigate the effect of spline connection methods on the nonlinear characteristics and vibration performance of the system used in continuously variable transmission (CVT), which consequently enhances the fuel economy and dynamic performance of a vehicle. Two assembly methods are studied, namely, *the-side-fit,* whose tooth sides act as drivers and centralise the mating splines, and *the-major-diameter-fit,* whose flank backlash must always be positive and large enough to prevent over-determination. Firstly, finite element analysis (FEA) is used to calculate the TVMS of the spline–gear system assembled using two different methods and have different magnitudes of interference (in *the-major-diameter-fit*). Then, on the basis of the calculated TVMS, a gear dynamic model with 6 degree of freedom (DOF) is established to analyse its nonlinear performance. Meanwhile, vibration experiments are conducted to verify the correctness of the proposed