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Nonlinear dynamic analysis and chaos control of multi-freedom semi-direct gear drive system in coal cutters

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A B S T R A C T

Under the nonlinear influence, the nonlinear oscillation of the semi-direct gear drive system (SDGDS) in coal cutters will happen, which will cause the system unstable. To solve this unstable problem, a multiple degrees of freedom (MDOF) nonlinear dynamic model of a gear pair is set up using mass centralized method, with both gear meshing features including time-varying mesh stiffness, mesh damping, backlash and dynamic transmission errors and nonlinear coupling effect such as radial clearance of ball bearing being taken into account. After the application of dimensionless treatment, the system is calculated using Runge-Kutta method. Meanwhile, the main parameters which may cause chaos and bifurcation are studied, for example, exciting frequency, radial clearance of ball bearing and mesh stiffness ratio. Then, the kinematic phase diagram, the Poincare map, the largest Lyapunov exponent chart as well as the bifurcation diagram are presented with different parameters. Furthermore, a chaos control method by means of proportion integral (PI) is proposed within a selected reasonable range. The results demonstrate that different parameters can lead to the occurrence of different chaotic behavior. It is also found that the chaotic control method suggested in this paper may not only reduce the area of chaos sufficiently but also suppress the chaotic phenomenon effectively. Besides, as there exists many nonlinear parameters, the study of parameters will lay a profound theoretical basis and practical significance for the improvement of the system stability and the optimization of the system parameters.

1. Introduction

Coal cutters are serves as one of the most important equipment of the mechanization and modernization for the coal production. At the time of coal rock cutting, due to the uneven strength of the coal seam, brittle breakage of the coal rock mass, hard parcels and rock interlayers, the loads on the shearer drum is projected to exhibit the characteristics of randomness, great fluctuation and strong shock [1–3]. The gear pair occupies an essential component of the SDGDS in the coal cutters. However, compared with other electromechanical equipment, it operates in much worse circumstances. Thus, frequent failures may appear during working process which will exert an influence on the working efficiency or even generate other safety troubles. At the same time, the vibration characteristics of the gear pair form a direct affect on the reliability, performance and service life of this system. Therefore, it is extremely necessary to further study the dynamics of the gear pair.

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To achieve lower noise and improve stability of the transmission of the gear pair, dynamic properties of the gear have become a hot issue that a large number of scholars have conducted studies currently, with a higher frequent use of the mass centralized model method [4,5] and the finite element method [6,7]. Johnson [8] is the first person who introduces the concept of the coupling stiffness, and establishes the frequency equation including dynamic influence coefficients and coupling stiffness, which is employed to solve angular natural frequencies. Fukuma et al. [9] present a 3-DOF extended model for the gear pair with the lateral and torsional vibration being taken into consideration. The gear pair is simplified into the spring model which possesses time-varying mesh stiffness. Kahraman and Singh [10,11] investigate response features of nonlinear frequencies of the spur gear pair which is equipped with clearance under internal and external excitation. The impact of the time-varying stiffness on the system is also studied. Cho et al. [12] conduct an analysis on the system dynamic characteristics influenced by the dynamic transmission errors of the gear. As presented by Wang et al. [13], a kinetic model for the hypoid gear is established based on the consideration of the time-varying mesh stiffness as well as the gear backlash. According to the latest studies, the dynamic response of the gear system may also be affected by lubrication, friction and coupling of the ball bearing [14–16]. However, there are limited researches done the analysis of SDGDS for coal cutters with full account of the factors like gear meshing features and coupling effects of the ball bearing. The SDGDS of coal cutters may perform periodic motions while the coal mining is being done. And the temperature of the gear system may go up along with the continuous meshing, bringing out a change in meshing stiffness and meshing damping between the spur gear pairs [17]. At the same time, the gear tooth may be subjected to wear, causing the occurrence of backlash changes among the spur gear pairs [18]. As a result, the factors including dynamic transmission errors among gears, meshing stiffness, meshing damping and backlash should not be neglected when the kinetic models of the gear pair is built. On the one hand, the nonlinear dynamic model experiences the influence of meshed gear. On the other hand, it is susceptible to the radial clearance of ball bearing, which is proposed similar influence as that of the gear backlash [19,20]. From the Ref. [21], it is well known that the backlash and bearing clearance are the main ways to produce noise and vibration of the system. And since that the main vibration modes of the SDGDS can be classified into torsional vibration and radial vibration, the vibration characters involving the spur gear pair cannot be fully reflected by the single-degree-of-freedom spur gear pair model. In view of the situations mentioned above, the MDOF nonlinear model is found to be highly desirable with both gear engagement and coupling being fully understood.

As a peculiar phenomenon to the nonlinear system, the chaotic motion shares a highly frequent presence in the meshing process of SDGDS of coal cutters [22]. The irregular vibration may appear accordingly, then discontinuing the normal functioning of the coal cutters, even bringing about safety accident [23]. In a word, it is of great significance to determine a reasonable parameter interval of gear design for chaotic control by adequate understanding of the influence concerning the MDOF nonlinear dynamic model. At present, the primary control method adopted to the chaos includes OGY method [24], adaptive control method [25], parameter perturbation method [26], periodic excitation method [27] and so on. As predicted by Farshidianfar et al. [28], global homoclinic bifurcation and chaotic behaviors may exist in the nonlinear practical model of gears, and a non-feedback control method is offered to eliminate chaos by exerting additional control excitation. By analyzing hybrid squeeze film damper mounted turbulent journal bearing-gear system, Chang-Jian [29] found that the quantity of chaotic behaviors can be put in control by increasing the proportional gains. However, up till now, literature devoted to chaotic control of the spur gear pair in the SDGDS for coal cutters are comparatively much less extensive.

Over the past years, excellent contributions have been achieved to verify the significance of the gear dynamics. And the time-varying mesh stiffness, backlash and static transmission errors have also been a focus by some scholars. Nevertheless, there has been a lack of researches aiming at analyzing the dynamics and chaotic control of the spur gear pair with the emphasis on both gear mesh features and bearing coupling in the SDGDS of coal cutter. Furthermore, these nonlinear factors have been turned into linear factors in many researches, giving rise to the potential system failures. Therefore, the main attention drawn in this paper is related to the factors, consisting of the time-varying mesh stiffness, damping, backlash, dynamic transmission errors and bearing coupling. The nonlinear dynamic model of the first-stage spur gear pair in the SDGDS is established for the purpose of thorough analysis of excitation frequency, bearing clearance and mesh stiffness ratio, which are responsible for the chaotic system and bifurcation. What's more, time series response chart, the phase diagrams, the Poincare map, the largest Lyapunov exponent chart as well as the bifurcation diagram are obtained by given different parameters. And a chaos control method of PI for a selected reasonable range is presented. The results provide a reference for the spur gear pair design of the SDGDS and chaotic control for coal cutters.

2. MDOF nonlinear dynamic model of first-stage reduction gear

The SDGDS in coal cutter consists of permanent magnet synchronous motor, gear reducer and cutting drum, as shown in Fig. 1. The gear reducer consists of several parts. Each component has several parameters. Each parameter change will cause the change of the system dynamic characteristics. Therefore, it is necessary to establish a system dynamic model that can fully reflect the system dynamic characteristics. The influencing factors need to be fully considered.

In this paper, considering the meshing characteristics of gear teeth and the coupling effect of bearing radial clearance on the dynamics of the SDGDS in coal cutter, the MDOF nonlinear dynamics model of the first-stage reduction gear pair in the SDGDS is established. The schematic diagram of the nonlinear model is shown in Fig. 2. The meshing characteristics of gear teeth include time-varying meshing stiffness, meshing damping, backlash, static transmission error, dynamic transmission