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Research paper

Influence of controllable parameters on load sharing behavior of torque coupling gear set

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ABSTRACT

The multi-motor torque coupling system couples the power of multiple motors by using torque coupling gear sets. The torque coupling gear set is a fixed-axis gear train consisting of multiple input pinions and one output gear. The load carrying capacity and service life of the gear set is affected by the load sharing behavior. A dynamic model of the multi-motor torque coupling system is established. Under the constant load, step load, and variable speed conditions, the influence of the pinion speed synchronization error and drive torque synchronization error on the load sharing behavior of the torque coupling gear set is studied. The results indicate that under these three conditions, the load sharing behavior gets worse with the increase of the pinion speed synchronization error or drive torque synchronization error; the pinion speed synchronization error has a more significant effect on the load sharing behavior. The two synchronization errors can be reduced by controlling multiple inputs of the gear set, and thus, the load sharing behavior can be improved.

1. Introduction

The multi-motor torque coupling system is widely used in high-power equipment such as tunnel boring machines. The system uses multiple small motors; the motor rotor inertia is small, and its response is rapid. The multi-motor torque coupling system couples the power of multiple motors by using torque coupling gear sets. The torque coupling gear set is a fixed-axis gear train consisting of N input pinions and one output gear. In the ideal case, each transmission path carries 1/N of the total torque. This can improve the torque-to-weight ratio of the transmission system. However, the advantage of torque coupling gear sets depends on the condition of equal load sharing between the transmission paths. The phenomenon of asynchronicity between multiple inputs of the torque coupling gear set could occur or there could be manufacturing and assembly errors in the gear set. These factors are likely to result in an unequal load sharing phenomenon, thus affecting the load carrying capacity and service life of the gear set. Therefore, it is necessary to study the load sharing behavior of a torque coupling gear set.

Wei et al. [1,2] established the dynamic model of the torque coupling gear set in a tunnel boring machine. Under constant load conditions, they studied the effect of the drive torque synchronization error, rotational speed, and bending-torsional coupling on the load sharing behavior. Shu et al. [3] studied the influence of drive torque synchronization error on the load sharing behavior of a torque coupling gear set under impact conditions. The above studies demonstrate that under constant load and impact conditions, the drive torque synchronization error causes the load sharing behavior to deteriorate. Under

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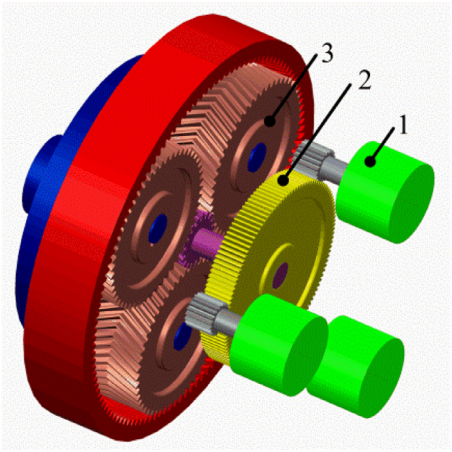

Fig. 1. Multi-motor torque coupling system. (1-motor; 2-torque coupling gear set; 3-planetary gear set.)

constant load conditions, Li et al. [4] studied the influence of motor control characteristics on the pinion speed synchronization error and load sharing behavior of torque coupling gear sets. However, when the pinion speed synchronization error occurs, the motor controller causes a drive torque synchronization error to occur. Thus, these two synchronization errors are coupled to each other and influence the load sharing behavior together. Based on the Floquet coefficient obtained from the dynamic model of a torque coupling gear set, Yu et al. [5] proposed a load-sharing index. They studied the effects of the meshing frequency, pinion bearing stiffness, and pinion mounting location on the load sharing behavior. Bai et al. [6] studied the effect of rotational speed on the load sharing behavior of a torque coupling gear set under constant load conditions. Li et al. [7–10] studied the effects of backlash, static transmission error, inertia, and load torque on gear vibration in a torque coupling gear set. Zhang et al. [11] studied the effects of mesh frequency, stiffness variation amplitude, and mesh phasing on the instability of a torque coupling gear set. Zhang et al. [12] established a finite element model of the tunnel boring machine powertrain system. They studied the translational vibration of the input and output gears of a torque coupling gear set under impact conditions.

At present, existing studies have mainly analyzed the influence of drive torque synchronization error, motor control characteristics, mechanical parameters, rotational speed, and load torque on the load sharing behavior of a torque coupling gear set. However, existing research on the influence of the pinion speed synchronization error on load sharing behavior is inadequate. External disturbances and gear errors can cause fluctuations in the gear speed. In a torque coupling gear set, when the phases of the pinion speeds differ from each other, the pinion speeds become asynchronized. The tooth surface of the gears is elastic, and thus, the pinion speed synchronization error may influence the load sharing behavior of the gear set. Meanwhile, the study on the influence of drive torque synchronization error on the load sharing behavior takes into consideration few conditions. Accordingly, in this study, the influence of the pinion speed synchronization error and drive torque synchronization error on the load sharing behavior of torque coupling gear sets is studied under the constant load, step load, and variable speed conditions.

The multiple drive motors of torque coupling gear sets are independent of each other. The pinion speed synchronization error or drive torque synchronization error can be altered through the synchronization control of the multiple motors [13]. This study can thus lay the foundation for improving load sharing behavior through controlling.

2. Model of multi-motor torque coupling system

A prototype of the multi-motor torque coupling system is illustrated in Fig. 1. It consists of three motors, a torque coupling gear set, and a planetary gear set. The torque coupling gear set consists of three evenly spaced input pinions and one output gear. It has three power transmission paths and couples the power of the three motors.

2.1. Motor model

The motor uses direct torque control (DTC). The schematic of the DTC motor is shown in Fig. 2. It consists of a three-phase rectifier, a three-phase inverter, an induction motor, a DTC unit, and a speed controller.

The speed controller derives the torque reference T_m^* based on the difference between the actual speed n and speed reference n^*. The DTC unit regulates the switch status of the three-phase inverter based on the torque reference T_m^*, flux reference Ψ_s^*, bus voltage U_{bus} and motor stator current i_{ab}. The switch status influences the motor's input voltage and electromagnetic torque. Therefore, the actual speed n varies and follows the speed reference n^* [14]. In this study, the DTC motor model available in the Simulink library was used.