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A novel method based on self-sensing motor drive system for misalignment detection

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ABSTRACT

In the diagnosis of electromechanical system, traditional vibration analysis methods are affected by the positioning of additional sensors. To overcome this problem, we propose a virtual phase torque (VPT) diagram method based on self-sensing motor drive system. Firstly, the q-axis current is obtained from field oriented control (FOC) process of permanent magnet synchronous motor (PMSM) drive system and used for load torque sensing. Then, fault components extracted from q-axis current and the phase angle from motor encoder are combined together to form the VPT diagram to detect the offset angle of misalignment. Therefore, misalignments in different directions can be classified. Simulations and experiments using a ball screw platform are implemented to validate the proposed method.

1. Introduction

Misalignment is one of the most common reasons that generate vibration in rotating machinery [1]. In mechanical system, flexible couplings are usually used to overcome slight misalignment between the shafts. However, thermal deformation, load imbalance and other factors can increase the level of misaligned faults and affect the precision of manufacturing. Therefore, a feasible method for misaligned fault diagnosis is required.

In recent years, fault diagnosis methods of electromechanical system follow the processes of signal acquisition, data processing and fault classification [2–6]. Vibration analysis is the most common technique for monitoring and diagnosis of mechanical systems [7–9]. The signal acquisition for certain mechanical faults is accomplished by installing accelerometer or proximity probe. However, the additional sensors mounted on mechanism can cause a series of problems such as signals acquired vary according to the positioning of sensors [10,11], onefold information acquisition [12] and additional cost.

In order to overcome these problems, the self-sensing property of motor drive system is revealed to detect faults in mechanical system. For periodic faults related to the shaft rotation, spectrum analysis of stator current is used to classify faults with different characteristic frequencies which is known as motor current signature analysis (MCSA). MCSA has been proposed to detect faults in induction motors including broke bars, eccentricity and short circuit, etc. [13–16]. In addition, the states of motor-driven machinery can also be monitored through MCSA. In paper [17], gear tooth faults in gearboxes were diagnosed by current signal from induction motor. Permanent magnet synchronous motors (PMSMs) are used in most modern feed drive systems. Therefore, information extracted from the control process of PMSM can be used to monitor the working condition of mechanical system.

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In the field of misalignment in rotating machinery, Verucchi et al. [18] have provided a method which estimated the load torque to identify mechanical faults. Harmonic components in estimated torque at once and twice rotational frequencies are reported to increase when misaligned faults occurs. In misaligned fault, vibration signal varies according to the directions of sensors and misalignments [10]. In a recent paper [11], a method based on coordinate transformation is proposed to simulate vibration signals from any arbitrary directions. In this method, only a pair of proximity sensors is used. Although the influence made by the positioning of sensors has been lightened, diagnosis without additional sensors still has not been achieved.

The self-sensing motor drive system can be considered as a multivariable sensing system at the drive-side of mechanical system, which samples not only current but also torque [18], speed, position, and power [19] information. In this paper, the position information is compounded with fault component in q-axis current to classify angular misalignments with different offset angles. The substance of the self-sensing property is the propagation of faulty information which starts from mechanical defects, transfers through shaft, gearbox, couplings, and ends with motor shaft. Therefore, the method is less sensitive to mechanical defect which occurs at the opposite side of the driving chain, because it brings signal attenuation during fault propagation. Meanwhile, restricted by the structure of motor and flexible coupling, axial vibration is hard to detect by motor current [20]. Thus, the proposed self-sensing method mainly aims at the detection of radial vibration that induces periodic torque ripple.

In this paper, we focus on the diagnosis of ball screws with short stroke length which are the most common feed drives in machine tool. These ball screws are more sensitive to misalignment, and the defect will affect precision of manufacturing. Thus, the virtual phase torque (VPT) diagram method is proposed to deal with misalignment. In the stage of data processing, q-axis current is obtained from field oriented control (FOC) process of PMSM, and its fault component is combined with the phase angle from motor encoder signal to establish the VPT diagram. It can detect the direction of misalignment in electromechanical systems. Therefore, the location of mechanical defect can be confirmed.

The paper is organized as follow. In Section 2, the misalignment model is briefly stated. In Section 3, the self-sensing property of motor drive system is derived. In Section 4, the proposed VPT diagram method for diagnosis is explained. In Section 5, experimental setup, simulation and experimental results are provided. A summary of this research is provided in Section 6.

2. Misalignment modeling

In machine tool, rotational motion of motor is converted into linear motion of table by ball screw. The working condition of feed drive system directly affects the precision of manufacturing [21]. Once a misalignment caused by improper machine assembly, thermal deformation [22] or load imbalance occurs, mechanical system suffers heavy loss.

Fig. 1 shows three major types of misalignment: angular misalignment, parallel misalignment and the combined misalignment. For angular misalignment, there is an angle between the centerlines of motor shaft and ball screw shaft. Parallel misalignment occurs when the shafts are parallel to each other, but not on the same line [18]. In a motor-driven feed drive system, when misalignment occurs, the equation of motion can be described in a uniform way:

$$M\ddot{\boldsymbol{q}}(t) + C\dot{\boldsymbol{q}}(t) + K\boldsymbol{q}(t) = Q(\beta, t) + F \quad (1)$$

where $\boldsymbol{q}(t)$ is the displacement vector of the mechanical structure node, M, C and K are mass, damping and stiffness matrices of the feed drive system. $\boldsymbol{F}$ is the reaction force by the load. $Q(\beta, t)$ is the imbalance force caused by fault. $Q(\beta, t)$ varies with time t and descriptive parameter β, which indicates the type, direction and level of fault.

To analyze the misalignment, a coupling coordinate system is shown in Fig. 2. Based on the misalignment model built by Gibbons [23] and Jalan [9], when we focus on angular misalignment, the centerline of motor shaft (Z2 axis) is coincide with Z3 axis and the reaction torque vector ***MZ2*** can be obtained as:

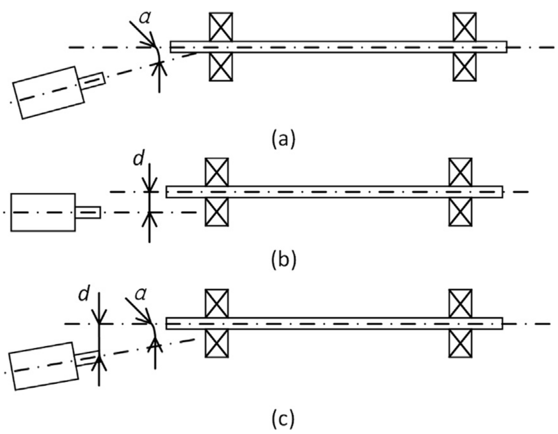

Fig. 1. Types of misalignment; (a) angular misalignment, (b) parallel misalignment, (c) combined misalignment.