Mechanical Systems and Signal Processing 101 (2018) 535–548

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Evaluating transient performance of servo mechanisms by analysing stator current of PMSM

Qing Zhang [a,b,*], Luyao Tan [a], Guanghua Xu [c]

[a] School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] Key Laboratory of Education Ministry for Modern Design and Rotor-Bearing System, Xi'an Jiaotong University, Xi'an 710049, China
[c] State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an 710049, China

ARTICLE INFO

Article history:
Received 20 April 2017
Received in revised form 10 July 2017
Accepted 8 September 2017

Keywords:
Performance evaluation
Transient motion
Servo mechanisms
Stator current
PMSM

ABSTRACT

Smooth running and rapid response are the desired performance goals for the transient motions of servo mechanisms. Because of the uncertain and unobservable transient behaviour of servo mechanisms, it is difficult to evaluate their transient performance. Under the effects of electromechanical coupling, the stator current signals of a permanent-magnet synchronous motor (PMSM) potentially contain the performance information regarding servo mechanisms in use. In this paper, a novel method based on analysing the stator current of the PMSM is proposed for quantifying the transient performance. First, a vector control model is constructed to simulate the stator current behaviour in the transient processes of consecutive speed changes, consecutive load changes, and intermittent start-stops. It is discovered that the amplitude and frequency of the stator current are modulated by the transient load torque and motor speed, respectively. The stator currents under different performance conditions are also simulated and compared. Then, the stator current is processed using a local means decomposition (LMD) algorithm to extract the instantaneous amplitude and instantaneous frequency. The sample entropy of the instantaneous amplitude, which reflects the complexity of the load torque variation, is calculated as a performance indicator of smooth running. The peak-to-peak value of the instantaneous frequency, which defines the range of the motor speed variation, is set as a performance indicator of rapid response. The proposed method is applied to both simulated data in an intermittent start-stops process and experimental data measured for a batch of servo turrets for turning lathes. The results show that the performance evaluations agree with the actual performance.

1. Introduction

Servo mechanisms play an important role in motion control and coordinated manipulation in industrial manufacturing processes. The main function of servo mechanisms is to control the outputs of drive devices, such as the torque, speed, and position, according to the reference and feedback signals. Then, end executors can perform the expected mechanical motion. Owing to the increasing demands for flexible manufacturing and versatile functions in the field of industry automation, most servo applications require more than continuous, steady, and single-direction motion. A growing proportion of

* Corresponding author at: School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, China.
E-mail address: zhangq@mail.xjtu.edu.cn (Q. Zhang).

http://dx.doi.org/10.1016/j.ymssp.2017.09.011
0888-3270/

servo applications involve transient motion, such as start-up, braking, reversing, acceleration and deceleration. The abilities of smooth running and rapid response in transient motion are the primary concerns for enhancing the accuracy and efficiency of servo machining. However, for pursuing good transient motion, a practical transient performance evaluation method for servo mechanisms is necessary.

Generally, a mechatronic servo system consists of a controller, a power driver, a servo motor, a feedback device and a mechanical executor. The corresponding block diagram is shown in Fig. 1. The power driver converts the control signal into electrical energy depending on the current or voltage, and this energy is input to the servo motor for generating mechanical power. The mechanical executor transforms the movement of the servo motor and implements the controlled mechanical motion. With the help of the feedback device, the error between the actual and expected motion is directly or indirectly traced, and the regulating signal is provided to the controller. In the aforementioned servo process, the electrical and mechanical components interact via energy and information exchange. Electromechanical coupling is used to describe this type of interactive phenomena and has become a popular research topic that is investigated with regard to practical application [1,2]. For the mechanical components, the transient motion is accomplished not with a step pattern but with instantaneous oscillation, because of the influence of elastic deformation, frictional damping, transmission clearance, etc. The oscillating behaviour is coupled to the electrical components and makes the output of the power driver more complicated and uncertain than that in the case of steady motion. Although it brings great difficulty to the analysis and control of the transient motion, a new methodology for evaluating the mechanical transient performance by utilising electrical signals was provided.

The stator current of the motor is the most available signal among the electrical components of servo systems [3]. Compared with other signals indicating servo system behaviour, such as speed, torque, vibration, and acoustic emission, the sensor of current is less expensive and simple to install. Recently, the stator current signal has been widely used to monitor the condition and identify the faults of mechanical components driven by motors. Li et al. developed a method for monitoring tool flute breakage during end milling using the feed-motor current signals [4]. Picot et al. extracted a statistic-based indicator from the current spectrum for detecting the bearing faults of an air conditioning fan [5]. Verucchi et al. identified the misalignment between the motor and load by using the frequency components of the stator current and the estimated electrical torque [6]. Zhang et al. employed the resonance residual technique to analyse the motor current signal for detecting faults in planetary gearboxes [7]. The motor is the source of the whole transmission chain of electrical and mechanical torsion, and its output torsion is usually determined by the stator current. According to the principle of torsion equilibrium, the fluctuation of the load torque is reflected by the current signal. In theory, any operating condition of the mechanical components that changes the load torque can be identified by the current analysis. However, the features related to the mechanical condition are always expressed as illegible modulating components in the current signal [8,9]. For reducing the computational complexity of the demodulation algorithm, most of the existing applications of motor current signal analysis are confined to steady operation.

Over the past years, permanent-magnet synchronous motors (PMSMs) have dominated high-precision and high-performance servo applications because of their high torque-to-weight ratio, high power factor, and ease of control [10]. With the vector control technique, a PMSM can regulate the output torsion by controlling the current, similarly to direct-current motors. As a result, the stator current of the PMSM not only defines the output of the electrical drive but also reflects the reaction of the mechanical components. Because of the advantage of integrating the electrical and mechanical information, the stator current is useful for analysing the overall performance of servo mechanisms driven by a PMSM. When servo mechanisms execute transient motions, the stator current exhibits non-stationary amplitude modulation and frequency modulation, which indicates the evolution of the torsion, speed, and load. In the field of signal processing, novel algorithms such as local mean decomposition (LMD) [11] and empirical mode decomposition (EMD) [12] have been proposed for demodulating transient signals, providing a foundation for extracting the transient performance features from the stator current signal.

In this article, we present a method for evaluating the transient performance of servo mechanisms. A simulation model is first constructed to analyse the behaviour of the stator current of the PMSM in transient motion. According to the simulation results, the current signals are demodulated via LMD to determine the instantaneous frequency and instantaneous amplitude. Then, the complexity of the instantaneous amplitude is measured according to the sample entropy and used to evaluate the smooth running performance. The peak to peak value of the instantaneous frequency is calculated to evaluate the rapid response performance. Finally, the proposed method is successfully applied to evaluate the transient performance of a batch of servo turrets driven by a PMSM.

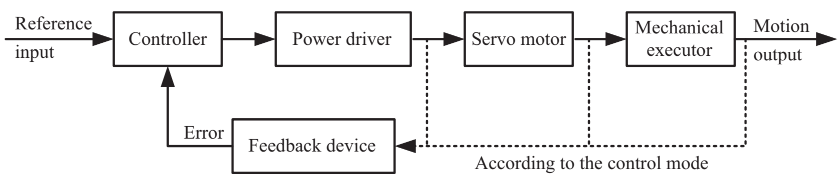

Fig. 1. Block diagram of the mechatronic servo system.