ARTICLE IN PRESS

Mechatronics xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Mechatronics

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

Noise analysis and efficiency improvement of a pulse-width modulated permanent magnet synchronous motor by dynamic error budgeting☆

Thomas Riel*, Rudolf Saathof, Andelko Katalenic, Shingo Ito, Georg Schitter

Automation and Control Institute (ACIN), TU Wien, Gußhausstraße 27-29, Vienna, 1040, Austria

ARTICLE INFO

Keywords:
Dynamic error budgeting
Pulse-width modulation
Performance analysis
Error estimation
Servo systems
Permanent magnet motors

ABSTRACT

This paper presents the mechatronic analysis and performance estimation of a pulse-width modulated permanent magnet synchronous motor (PMSM), which is part of a direct-drive rotational servo system. Physical modeling together with dynamic error budgeting are applied to identify the minimal required switching frequency that maximizes the energy efficiency of the system while maintaining the required precision. The analysis is carried out for a wide velocity range and considers various friction phenomena. The disturbances induced by the switched amplifier are also considered and compared to a linear amplifier. The accuracy of the derived model and analysis is experimentally verified over the entire velocity range as well as for the considered range of switching frequencies.

1. Introduction

Direct-drive PMSMs are widely used in precision positioning applications, such as robots [1] or optical measurement platforms [2]. Their high accuracy is achieved by eliminating or reducing the negative effects of gear boxes such as backlash and friction. They also have the advantage of high power density and high dynamic performance due to decreased inertia [3], also making them good candidates for electric vehicle [4]. However, to achieve a precise motion with errors in the sub-μrad range, a detailed analysis of present noise sources and a good mechatronic design of the system are necessary [5].

One of the most precise ways of controlling a PMSM is with vector based control, such as field-oriented control (FOC) [6]. The analysis and compensation of systematic error sources, such as current measurement errors or torque ripples, have attracted quite some attention [7–9]. For precision positioning applications it is important to understand in detail and to minimize all of these systematic disturbances. However, the influence of stochastic disturbances acting in the drive system also needs to be investigated. If not considered in the system design, these disturbances fundamentally limit the achievable precision.

Recently, the analysis of stochastic disturbances acting on the FOC system of a PMSM has been presented [10,11]. The analysis is based on dynamic error budgeting (DEB), using power spectral densities (PSDs) of the known noise sources. However, the analysis is performed for a linear power amplifier, considering only two different angular velocities.

Linear power amplifiers are regularly used in precision positioning applications due to their low noise. However, they suffer from high energy dissipation and therefore have low efficiency. This is problematic, especially in space constrained or highly integrated applications, as the additional heat intake requires a larger heat sink and leads to unwanted thermal effects. Mitigating these thermal issues requires additional cooling effort, which may induce additional disturbances, such as vibrations caused by the cooling system. Switched power amplifiers relax these thermal issues due to their high efficiency. In contrast to linear amplifiers, which show a typical efficiency below 50%, switched amplifiers reach efficiencies of more than 90% [12]. Switched amplifiers using (pulse-width modulation) are commonly employed in current controlled power amplifiers for PMSM. However, they suffer from higher noise, which may degrade the system accuracy in precision positioning applications. To design an energy efficient precision servo system it is therefore important to identify, analyze, and reduce the disturbances induced by switched amplifiers.

Switched amplifiers also show substantial noise at frequencies below the fundamental switching frequency [12,13]. As most mechatronic systems are more susceptible to noise below practical PWM switching frequencies, special emphasis has to be put on this frequency region. The primary sources of this low frequency noise are power supply noise [14], inter-modulation distortions [15], and sampling and quantization effects [12,16,17]. Considering these effects in the analysis of a drive system with switched amplifier is necessary to provide an accurate description. A simplified analysis of the induced

☆ This paper was recommended for publication by Associate Editor Roger Goodall.

* Corresponding author.
E-mail address: riel@acin.tuwien.ac.at (T. Riel).

http://dx.doi.org/10.1016/j.mechatronics.2017.10.006
Received 18 November 2016; Received in revised form 17 August 2017; Accepted 15 October 2017

Please cite this article as: Riel, T., Mechatronics (2017), http://dx.doi.org/10.1016/j.mechatronics.2017.10.006

disturbances is possible by only considering the fundamental switching frequency of the PWM [18]. However, this kind of analysis does not include the entire PWM signal spectrum, which includes a variety of spectral components [19], and neglects the adverse low frequency effects.

This contribution therefore aims to analyzes all relevant, stochastic disturbances acting in the FOC system of a PMSM with switched power amplifiers. In addition, the analysis is performed for a continuous velocity range, including friction effects and torque distortions of the ball bearings. The analysis is used to investigate the tradeoff between the system precision and amplifier efficiency, in order to identify the ideal switching frequency. The analysis is performed using DEB for a continuous operation range from standstill to several degrees per second and includes important friction phenomena, which is required for low velocity, high precision positioning [11]. To our best knowledge this is the first time such an analysis of a switched system using DEB is presented.

The remainder of this paper is organized as follows. Section 2 starts by reviewing the theoretical foundation and necessary assumptions for DEB. Section 3 gives a short description of the analyzed system, which is mathematically modeled in Section 4. The derived models are utilized in Section 5 to analyze the influences of the stochastic disturbances by DEB. In Section 6 the performance analysis with corresponding experimental validations is presented. Finally, the conclusion is given in Section 7.

2. Review of the theoretical foundation of dynamic error budgeting

DEB is a method for estimating the performance of a mechatronic system, by modeling the stochastic disturbances acting on the system by their corresponding PSD [20]. DEB has been applied to disk drives [21], magnetically suspended rotating platform [22] and rotational servo systems [10,11]. Before applying DEB, it is important to know its necessary assumptions and limitations. Therefore, the theoretical foundation of DEB is reviewed in this section. Based on this review, the necessary assumptions for the application of DEB are derived.

2.1. Linking the time domain to the frequency domain

In contrast to previous work [20,22], this paper uses the Wiener–-Khintchin theorem to link the time domain and the frequency domain, instead of Parseval's theorem [23]. This is necessary because the Fourier transform of a random variable does not exist as a random variable, in general, has infinite energy, and therefore Parseval's theorem can only be applied to a truncated version of a stochastic process [23]. In engineering practice, the use of a truncated version of a stochastic process may be the preferred choice, however, for modeling purposes a precise definition may be required.

Assume $x(t)$ is a complex, wide-sense stationary, random process, then the PSD of the random process, $PSD_x(\omega)$, is defined by [24]

$$R_x(\tau) = \int_{-\infty}^{\infty} e^{i\omega\tau}\, PSD_x(\omega)\, d\omega, \tag{1}$$

where $R_x(\tau)$ is the auto-correlation function of the random process. Hereby, Eq. (1) is known as the Wiener–Khintchin relation [23].

If the inverse Fourier transform of $R_x(\tau)$ exists, the PSD can directly be calculated from [24]

$$PSD_x(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-i\omega\tau}\, R_x(\tau)\, d\tau. \tag{2}$$

This means the auto-correlation function $R_x(\tau)$ and the PSD of the random process $PSD_x(\omega)$ form a Fourier pair.

If it is further assumed that $x(t)$ is an *ergodic process*, then $R_x(\tau)$ can be calculated from measurements in the time domain, by forming the long-time average of the auto-correlation function [24]

$$R_x(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} x(t)x(t+\tau)dt. \tag{3}$$

Eqs. (2) and (3) and the assumption of an ergodic, wide-sense stationary, random process are therefore sufficient to link the time domain and the frequency domain for the application of DEB.

For practical issues it may be favorable to redefine the random process $x(t)$ as sum of its random varying part $x_1(t)$ and its mean value μ [24]

$$x(t) = \mu + x_1(t), \tag{4}$$

thereby avoiding that the PSD has spectral content at $\omega = 0$.

2.2. Power spectral density conversion of linear systems

For linear-time invariant (LTI) systems the PSD of the output y of the system $PSD_{y,x}(s)$, induced by a disturbance x at its input is given by [23]

$$PSD_{y,x}(s) = |T_{y,x}(s)|^2\, PSD_x(s), \tag{5}$$

where $PSD_x(s)$ is the PSD of the input and $T_{y,x}(s)$ is the transfer function from x to the output y.

By assuming independence between the different disturbances acting on a system, the overall PSD of the output y can be found by summation of the effect of all disturbances [23]

$$PSD_y(s) = \sum_i |T_{y,x_i}(s)|^2\, PSD_{x_i}(s). \tag{6}$$

If the independence is not given, then the covariance between the different disturbances has to be taken into account [23]

$$PSD_y(s) = \sum_i \left| T_{y,x_i}(s)|^2\, PSD_{x_i}(s) + \sum\sum_{i\neq j} \right| T_{y,x_i}(s)|\,|T_{y,x_j}(s)|\;\; CSD_{x_i,x_j}(s), \tag{7}$$

where $CSD_{x_i,x_j}(s)$ is the cross-spectral density (CSD) between the two inputs x_i and x_j.

3. System description

The system to be investigated consists of two individual rotational axis with direct-drive PMSM, as shown in Fig. 1. The custom build PMSMs have eleven pole pairs and a rated torque of 6.44 Nm. The servo system is used to position an optical imaging system with high precision. Two ball bearings are used to accommodate the load of the imaging system. To minimize the influence of the positioning error on the optical measurement result, a low positioning error is required. For

Fig. 1. Laboratory prototype of the two axis rotational servo system with direct-drive PMSMs.