Applied Acoustics 137 (2018) 33–39

Contents lists available at ScienceDirect

Applied Acoustics

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

Experimental research on structure-borne noise at pulse-width-modulation excitation

Janez Luznar[a], Janko Slavič[b,*], Miha Boltežar[b]

[a] Domel, d.o.o., Otoki 21, 4228 Železniki, Slovenia
[b] Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva 6, 1000 Ljubljana, Slovenia

ARTICLE INFO

Keywords:
Bearing forces
Experiment
PWM carrier frequency
Structural dynamics
Structure–borne noise

ABSTRACT

Pulse-width modulation (PWM) is widely used in motor control and represents a carrier-frequency-dependent structural excitation. The PWM's excitation harmonics are also reflected in an air gap's electromagnetic forces, the transmitted bearing forces and the resulting structure–borne noise. Inappropriate carrier-frequency selection can cause additional electromagnetic noise. The latter can be reduced by a characterization of the coupling between the excitation harmonics and the structural dynamics. To obtain a clear insight into the physical phenomenon, an experiment with original motor parts is proposed, which introduces bearing force measurement and excludes the aerodynamic and mechanical sources of noise. The detailed dependence of the structure-borne noise on the PWM carrier frequency can be obtained by dense carrier-frequency measurements. The experimental results show that even at higher frequencies (above 10 kHz), the carrier-frequency selection can cause a 25 dB(A) difference in the total sound pressure level. The switching noise of PWM controlled machines can be reduced by the appropriate carrier-frequency selection in accordance with the structural dynamics.

1. Introduction

In permanent-magnet synchronous motors (PMSMs) the variable speed can be controlled by pulse-width modulation (PWM), which composes current waveforms of the desired fundamental frequency component together with a number of higher switching harmonics [1]. The latter enriches the Maxwell force spectrum [2]. The general PWM principles are based on a constant carrier frequency, which result in a concentrate unpleasant noise spectrum [3], but still many times indicate lower overall noise than random modulation techniques [4,5]. The latter represent wide frequency domain excitation [6], interacting with many modal modes, where one or two can be simultaneously eliminated, as shown by Chai et al. [7]. However, to avoid any mode excitation, the proposed research focused on constant carrier techniques and selecting an appropriate carrier frequency.

PMSMs contain different sources of acoustic noise: mechanical, aerodynamic and electromagnetic [8]. To anticipate and investigate the electromagnetic noise, analytical models have been developed, which indicate good agreements between computation and experiment by applying the forces on stator only [9]. Further, the strong impact of the supply harmonics on the noise of synchronous machines was shown by coupling the 2D electromagnetic and 3D structural finite element (FE) models [2]. Torregrossa et al. [10] proposed a 3D FE model to evaluate the electromagnetic vibration up to 5 kHz, but the frequency range of the numerical prediction is limited by the structural model's validation with experimental modal analysis [11]. Since the modal parameters only match up to a few kHz [12–16], the electromagnetic noise predictions at higher frequencies have limited credibility.

There are also experimental investigations of the acoustic noise for PWM-controlled motors that show a dependence on different motor types, motor powers, rotor speeds, PWM techniques and the carrier frequency [17]. Binojkumar et al. [3] studied the acoustic noise at different fundamental frequencies and over a range of carrier frequencies, but we believe a denser carrier–frequency arrangement is necessary to obtain a detailed PWM excitation coupling with structural dynamics. Blaabjerg et al. [18] proposed the random PWM excitation and acoustic measurement to identify the transfer function of mechanical structure. The latter was used by Mathe et al. [19] to approximate the force spectrum, based on the input voltage spectrum. However, there is still a lack of experimental investigation, focusing on PWM switching noise reduction at dense PWM carrier frequency excitations.

The electromagnetic forces have been identified as the main cause of noise and vibration in PMSM [9]. There are methods to measure the unbalanced magnetic forces [20–22] and to characterize the force excitation harmonics, e.g., directly by dynamic force measurements [23]

* Corresponding author.
E-mail address: janko.slavic@fs.uni-lj.si (J. Slavič).

https://doi.org/10.1016/j.apacoust.2018.03.005
Received 13 September 2017; Received in revised form 26 January 2018; Accepted 6 March 2018
Available online 13 March 2018
0003-682X/

or indirectly by FEM transfer functions and measured vibration data [24]. Nevertheless, there is still a lack of experimentally identified PWM excitation forces, coupled with structural dynamics.

The aim of our investigation was to experimentally research the influence of the PWM carrier–frequency on the bearing forces and structure–borne noise. An experimental approach is introduced, where the system's complexity is minimized by using only one excitation coil, half of the stator stack and a fixed rotor. The preliminary researched structural dynamics enables a better understanding of the coupling between the PWM excitation harmonics and the response of the bearing forces. Densely spaced carrier–frequency measurements show a strong variation in the structure–borne noise and indicate that the appropriate carrier–frequency selection is important even at higher frequencies (above 10 kHz).

The manuscript is organized as follows. Section 2 shows the PWM excitation, Section 3 shows the structural dynamics, Section 4 shows the experimental setup, Section 5 shows the results and discussion, Section 6 draws the conclusions and Section 7 presents the perspectives.

2. PWM excitation

The acoustic noise in electric motors has many sources due to diverse electromagnetic, mechanical and aerodynamic phenomena [8]. The main source of acoustic noise for low- and medium-speed motors has an electromagnetic origin [17], which is especially broadband in the case of inverter–fed electric motors [25]. The process of structure–borne noise generation at PWM excitation is shown in Fig. 1. The PWM excitation harmonics cause electromagnetic forces, which interact with the structural dynamics. Every frequency component of the force has its own effect upon the structure and therefore contributes to the surface vibration, causing the electromagnetically induced noise.

2.1. PWM excitation harmonics

In applications a sine–triangle PWM is very common [3], where the sinusoidal modulating signal at frequency f_1 and amplitude U_1 is compared with the triangular carrier signal at frequency f_c and amplitude U_c. In the linear modulating region ($m_a \leqslant 1$), the amplitude of the fundamental component varies linearly with the modulation index m_a [26]

$$m_a = U_1/U_c \tag{1}$$

and the frequency contents involve the fundamental component f_1 with additional switching harmonics at the frequencies f_h [10]:

$$f_h = n{\cdot}f_c \pm k{\cdot}f_1 \tag{2}$$

where $n = 1,2,3,\ldots$, and f_c is the carrier frequency. When n is even, $k = \pm 2,\pm 4,\ldots$ and when n is odd, $k = \pm 1,\pm 5,\ldots$. The voltage harmonics for sine-triangle PWM excitation with the parameters $f_1 = 100$ Hz, $m_a = 0.8$ and $f_c = 4000$ Hz are shown in Fig. 2.

The PWM voltage excitation harmonics depend on the carrier type, the carrier frequency f_c, the fundamental frequency f_1 and the

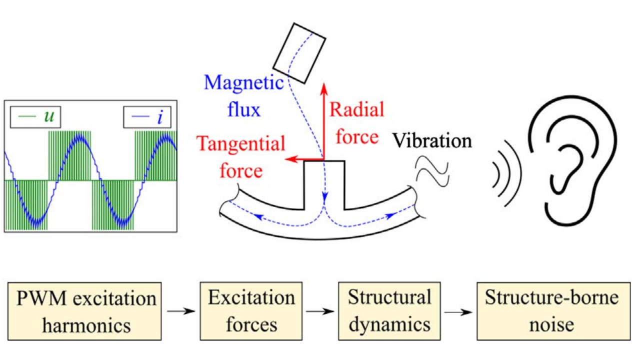

Fig. 1. Structure–borne noise at PWM excitation.

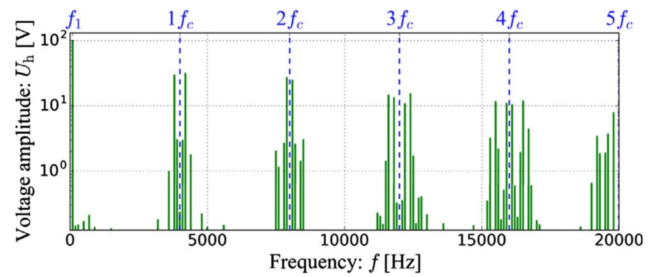

Fig. 2. Frequency contents of the voltage excitation harmonics for a sine–triangle PWM.

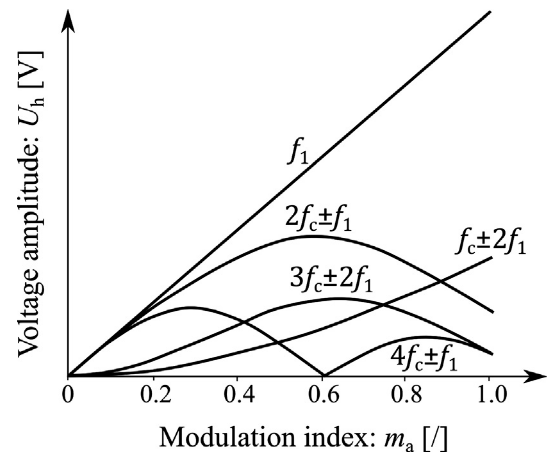

Fig. 3. Evolution of the sine-triangle PWM voltage harmonic amplitudes as a function of the modulation index m_a [28].

modulation index m_a [26]. By increasing the carrier frequency f_c, the frequencies of the switching harmonics f_h increase, whereas by increasing the fundamental frequency f_1, the frequencies of the switching harmonics f_h become more dispersed [27].

Variable speed control is achieved by adjusting the fundamental frequency f_1 and the modulation index m_a. The latter does not affect the frequencies of the PWM excitation harmonics, but varies their amplitudes. Fig. 3 shows the evolution of the sine-triangle PWM voltage harmonics' amplitudes as a function of the modulation index m_a. It is evident that a variable motor load results in different proportions of the switching harmonics in the PWM voltage excitation and therefore the structure–borne noise minimization is a complex task.

2.2. Excitation forces

The PWM voltage harmonics excite the stator coils, which form the magnetic field; consequently, the excitation harmonics also occur in the air-gap magnetic flux B [29] and the air-gap Maxwell pressure distribution σ [30]:

$$\sigma_r = \frac{1}{2\mu_0}(B_r^2 - B_t^2) \tag{3}$$

$$\sigma_t = \frac{1}{\mu_0}B_r B_t \tag{4}$$

where μ_0 is the permeability of free space, r is the radial and t is the tangential direction. The Maxwell pressure distribution over the rotor-stator air-gap surface (S) can be transformed to the Cartesian coordinate system (σ_x,σ_y), resulting in the electromagnetic force components F_x and F_y [21]:

$$F_x = \int_S \sigma_x \mathrm{d}S, \tag{5}$$

$$F_y = \int_S \sigma_y \mathrm{d}S \tag{6}$$