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Moving towards the maximum speed in stepping motors by means of enlarging the bandwidth of the current controller

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ABSTRACT

This paper pursues to maximise the mechanical speed when using stepping motors (SM) without position sensors in order to achieve a rapid-response manufacturing whenever any equipment based on such electrical machines is involved.

The novelty of this paper is the fact that not only the bandwidth of the current controllers is improved for such maximization of the SM mechanical speed, as traditionally done in previous works, but also a comprehensive approach has been addressed. Such global approach starts justifying why the traditional PI controller is not sufficient and it includes the analytical tuning of the current controllers, considering implementation tiny issues (but of paramount importance) such as the delays caused by the processor and the sample and hold current measurements. It is proved and justified that this previously mentioned issues, which are often omitted, play a crucial role when trying to maximise the speed of the SM, since the electrical fundamental frequencies of the SM move close to the sampling frequency. Therefore, the analytical process to tune and implement the current controllers will have to be done in discrete-time domain, i.e. using the Z transform and treating the SM drive as a sampled data system.

Experimental waveforms and results based on real prototypes will prove the validity of the entire research.

Finally, a real case-study based on Printed Circuit Board (PCB) prototyping machine which is composed by two stepper machines, is fully reported. Such PCB prototype is the fruitful collaboration between the University (research institution) and a private company (industry).

1. Introduction

Stepping or stepper motors (SMs) are extensively used in position controlled drives in a wide range of applications, from traditional drives [1,2], up to state of the art applications [3–6]. In [3], an automatic ultrasound scanning system uses an SM to accurately position the planar piston transducer and the needle-type hydro-phone in the tank. In [4], the authors point out that the SM is a satisfactory choice for driving the control rods in a modular high temperature gas-cooled reactor. The state of the art Π-joint lab prototype presented in [5] uses a miniature hybrid SM as a linear actuator, while in [6] a new type of a linear stepper drive for sensorless positioning tasks in hydraulics is reported.

Despite some Field Oriented Controllers [7] with position feedback are reported [8,9], the SM major advantage is the capability to perform control position without the need of any electromechanical sensor to measure the position. Such inherent open-loop control position capability is based on the fact that this electrical machine is able to be driven in a step-by-step algorithm. Furthermore, the micro stepping technique, which divides each step in many incremental parts surpasses the discretization of the steps and allows an almost continuous position control [1,2]. Such stepping open-loop position control is reliable as long as the machine does not lose synchronisation and does not miss any step. Research efforts are driven in [10] and [11] to detect step-outs and compensate for them to keep the accuracy in the position control. Also, more traditional sensorless control approaches have been carried out based on extended Kalman filters [12,13] and passive nonlinear [14–16] as well as disturbance [17] observers.

Still, SMs have torque and speed ripples problems which have driven the research attention [18–20] sometimes even using artificial intelligent techniques such as neural networks [21,22].

This paper pursues to maximise the SM mechanical speed in order to achieve a rapid-response manufacturing. Many high-precision motion systems [23] are designed in the continuous s

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domain, which is a handicap when facing high speeds. The three highest maximum speeds reported in the previously cited works are 288 rpm for [11], 380 rpm for [12] and 450 rpm for [22], whereas in this paper 1320 rpm is the highest maximum speed reported. To achieve such goal, firstly, the need of surpassing the widely used traditional proportional and integral (PI) controller [24,25] is justified and secondly, a new second-order controller is designed and tuned in z domain, which brings the possibility to properly compensate the processing delays as well as the pulse width modulation (PWM) of the power electronics actuator. Such proposed high bandwidth (BW) controller has envisaged, from the very beginning, the industrial feasibility for further commercialization. Therefore, the proposed algorithm not only has the possibility to be implemented in cheap microcontrollers but also it is fully understandable attending the classic control theory, likewise the well-known PI controller, which is always a plus when dealing with industry and practical engineers.

Lastly, a real prototype designed for such research is fully described and high speed results are reported.

Considering that the proposed controller is somehow competing with the well-known and widely used PIs, an extensive experimental comparison with the mentioned PIs controllers is illustrated.

To conclude the work, a 2 axis rapid prototyping Printed Circuit Boards (PCBs) machine [26], which has two stepper motors axis, is fully reported. Such PCB machine is the fruitful collaboration between the University and a private company and it is a tangible example of how increasing the SM speed reduces the time employed for rapid prototyping applications. The PCB manufacturing is an emblematic example of the nowadays electronics industry [27,28].

2. Stepper motor model

SMs have two phases (labelled α and β) in quadrature, whose electrical equations are represented in (1) and (2).

$$\frac{di_\alpha}{dt} = \frac{1}{L}\left(v_\alpha - Ri_\alpha + \omega_m \psi_{PM} N_r \sin\left(N_r \omega_m t\right)\right) \tag{1}$$

$$\frac{di_\beta}{dt} = \frac{1}{L}\left(v_\beta - Ri_\beta + \omega_m \psi_{PM} N_r \sin\left(N_r \omega_m t - \pi/2\right)\right) \tag{2}$$

The torque production, whose mathematical expression is given in (3), is achieved, as in the majority of electrical machines, by the interaction (or vector product) between the magnetic flux and the current.

$$T_e = N_r \psi_{PM} \sin\left(N_r \omega_m t + \pi/2\right) i_\beta - N_r \psi_{PM} \sin\left(N_r \omega_m t\right) i_\alpha \tag{3}$$

Finally the mechanical speed is given in (4), which models a first order mechanical system with an external load torque

$$\frac{d\omega_m}{dt} = \frac{1}{J}\left(T_e - T_L - F\omega_m\right) \tag{4}$$

In order to guarantee the proper micro stepping functionality, a closed-loop current controller (with current sensors) must be performed. Despite the only references are the alpha and beta currents, the position set point is indirectly given within the angle included by the mentioned current references, which are sinusoidal. Therefore, the success of the position control depends entirely on the sinusoidal current tracking capability and, consequently, on the current controller performance.

From (1) and (2) it is concluded that the plant dynamics can be simplified to a first order system composed by the resistance and the inductance. The third term corresponds to back electromotive force (*EMF*) and it can be modelled as a disturbance. Fig. 1 shows the general block diagram.

Due to the nature of the SM, the typical number of rotor slots is 50, which implies that the electrical angular speed is 50 times

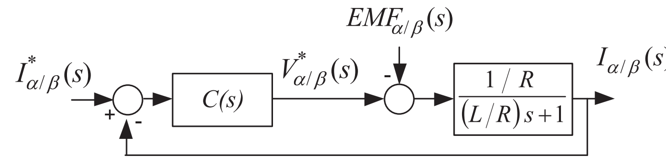

Fig. 1. Control scheme with the controller C(s), plant transfer function and the current, voltage and back EMF signals for the alpha and beta phases.

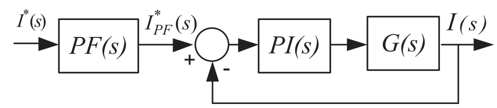

Fig. 2. Current control loop with a PI controller and a PF. System_1.

larger than the mechanical one. This multiplying factor is the main challenge when maximising the mechanical speed. For instance, for achieving an angular speed of 500 rpm (≈57,36 rad/s, 8,33 Hz) a sinusoidal current waveform of 25.000 rpm (≈2618 rad/s, 416 Hz) is needed, which clearly compromises the BW of the current controller.

Research efforts have been made to design the controller (*C(s)*) not only to guarantee the stability but also to maximise the tracking capability of this current closed-loop control at such high angular speeds [29].

3. Traditional PI control approach. System_1 and System_2

Traditionally the current controllers for electric machines are addressed tuning a proportional and integral (PI) controller in Laplace (s) domain, as it is shown in Fig. 2, to fulfil the desired specifications. The pre filter (PF), PI and the plant transfer function (G(s)) are given in Eqs. (5), (6) and (7) respectively.

$$PF(s) = \frac{1}{(K_P/K_I)\,s + 1} \tag{5}$$

$$PI(s) = K_P + \frac{K_I}{s} = K_I\frac{(K_P/K_I)\,s + 1}{s} \tag{6}$$

$$G(s) = \frac{1/R}{(L/R)\,s + 1} \tag{7}$$

The closed-loop system transfer function can be expressed as indicated in (8)

$$\frac{I(s)}{I^*_{PF}(s)} = (K_I/L)\frac{(K_P/K_I)s + 1}{s^2 + s(R + K_P)/L + K_I/L} \tag{8}$$

By means of the unity-gain PF given in (5) and provided that $(K_P/K_I) > 0$, the unwanted zero is cancelled and therefore Eq. (8) is reduced to a second-order system, whose generic transfer function is equal to:

$$\frac{\omega_n^2}{s^2 + 2\xi\omega_n \cdot s + \omega_n^2} \tag{9}$$

The PI will be tuned using Eqs. (10) and (11), to fulfil the specifications of settling time at 2% ($Ts_{2\%}$), given in Eq. (12) and damping factor (ζ), which will be fixed to $\zeta = 0.7071$ in order to keep the overshoot to less than 4.3% and therefore to avoid the resonance peak in the gain of the closed-loop frequency response. On the other hand, the $Ts_{2\%}$ will be minimised in order to increase the current closed-loop BW and, therefore, maximise the maximum mechanical speed.

$$K_I = \frac{4.22^2 \cdot L}{\zeta^2 \cdot Ts_{2\%}^2} \tag{10}$$