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Multivariable extremum seeking control of preload controllable rotary ultrasonic motor

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1. Introduction

Ultrasonic motors (USM) possess superior features including their compact structure, high energy density, lightweight, and high torque at low speed[1]. However, the current driving control schemes result in suboptimum driving efficiencies and limitations of the output power range. To approach these issues, dynamic preload control was proposed to expand the output range and increase driving efficieny[2]. Besides preload control, an automatic optimum frequency tracking scheme was proposed in Ref. [3] where the induced current was minimized to realize maximum efficiency.

Proposed work in Ref. [2] & [3] was based on decoupling the relation between the driving frequency and preload on the motor state. However, simultaneous control of both frequency and preload can further improve the USM performance. Thus, a multivariable control scheme is proposed for better exploration of the solution space.

2. Experimental Setup

This study was conducted using a FUKOKU USR60-B4 USM coupled to a “Mechano-Transform MTKK12S400F140” Piezo linear actuator (PLA) to apply the dynamic preload. Controlling the applied voltage to the PLA terminals can effectively change the preload. The USM driving signal was generated using a Direct Digital Synthesis (DDS) board. The measurements were collected through a HIOKI 3332 power meter for current and input power measurements, and an ONNO SOKKI SS-050 torque detector for speed and torque measurements. The load torque was applied using a MITSUBISHI ZKB-1.2XN power brake. The overall system was controlled using a digital signal processor (DSP) and the control scheme was implemented in MATLAB Simulink environment.

3. Control Principle

Extremum seeking control (ESC) was chosen to control the USM. ESC is an adaptive, robust, fast converging and model-free control algorithm [4]. ESC is a good match for USM control since it eliminates the need for modeling the USM, and fulfills the optimization requirements. ESC is a local optimized that minimizes or maximizes a loss function by applying a perturbation signal around the control parameter [3]. For a single input single output (SISO) ESC, the driving frequency was chosen as a control parameter, and current feedback served as the loss function.

A sinusoidal perturbation is added to the center control parameter as in Eq. 1. The gradient of the loss function (ξ) is then estimated by multiplying the filter loss function response (J) by a phase ($\emptyset$) shifted sinusoidal as in Eq. 2. The control parameter is then updated towards the extremum using an integrator of gain K as in Eq. 3.

$$\theta = \hat{\theta} + A\sin(\omega t) \qquad (1)$$

$$\xi = \sin(\omega t - \emptyset) \times \frac{s}{s+\omega_c}[J(\theta)] \qquad (2)$$

$$\theta(t) = \theta(t-1) + K \times \xi \qquad (3)$$

Preload can also be integrated within the ESC scheme through a multi-input single-output (MISO) ESC. Controlling the preload can effectively change the driving efficiency and the output power. Fig.1 shows the proposed MISO-ESC control scheme. Besides driving frequency ESC loop, a preload ESC loop is added. The preload perturbation signal has to be shifted by π/2 from frequency perturbation such that their effect on the loss function could be distinguished. Each of the ESC loops will have a different set of parameters (i.e. perturbation amplitude, phase shift, integrator gain) such that the desired response is obtained.

Since the output power needs to be controlled while maintaining high optimum efficiency. The loss function should be changed to be dependent on both the current feedback as well as the speed error. ESC can then minimize the speed error and the induced current concurrently.

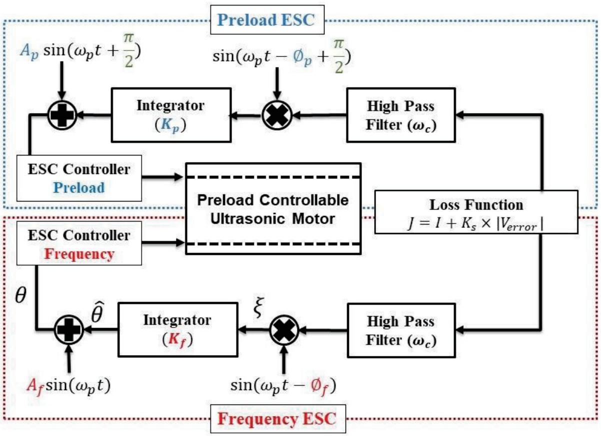

Fig. 1 MISO ESC control scheme

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4. Experimental Results

The USM is driven under a peak to peak voltage of 250 V and a load torque of 0.3 Nm. The initial preload was set to 100 N and the PLA could control the preload within a 70 N range up to 170 N. The driving frequency was initialized at 41 kHz and the PLA voltage was initialized at 90 V. A target speed of 100 rpm was commanded and automatic seeking was started.

Figure 2 shows the control parameters of the ESC. The optimum driving frequency is localized and tracked during the operation time. Under extended operation, the optimum frequency shifts to lower frequencies. The preload was reduced to increase driving efficiency; however, a further reduction might lead to reduced speed. Thus, preload fluctuates around a PLA voltage of 50 V.

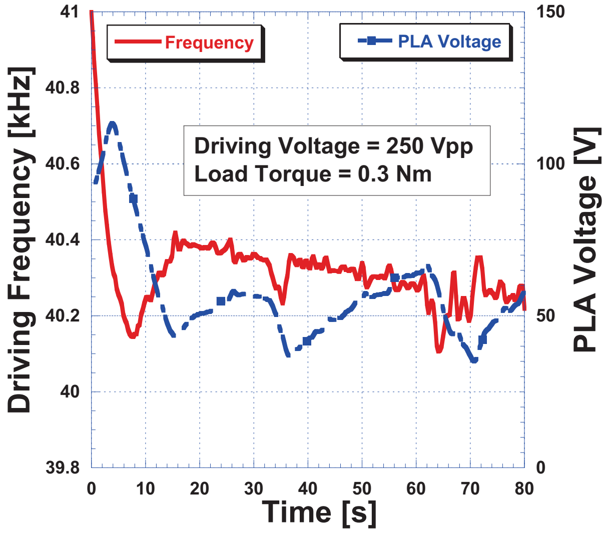

Fig. 2 ESC control variables

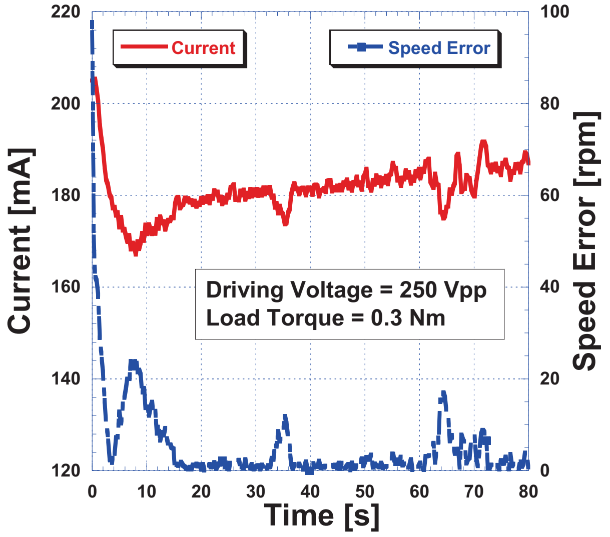

Fig. 3 ESC loss variables

Figure 3 shows the loss function parameters that their sum is to be minimized. Current is minimized initially but it increases slightly with time due to increase in temperature. The speed error is maintained around zero with a few sharp peaks. These peaks might be the result of the instability of the signal generator. Future work will aim at a more stable behavior. Figure 4 illustrates how the rotor speed was maintained around the target speed of 100 rpm. The driving efficiency was also optimized at around 20%.

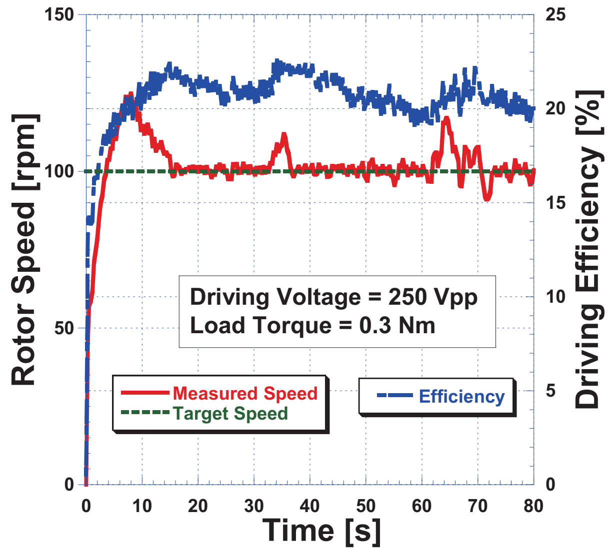

Fig. 4 ESC optimized variables

5. Conclusion

In this research, a multi variable control scheme of USM was proposed. Both driving frequency and preload were integrated in an extremum seeking control scheme that can control the output power while maintaining high driving efficiency. The experimental results show the effectiveness of the control scheme.

Future work will aim at further tuning of architecture parameters to realize a better response. The experimental setup will be improved to overcome any bottlenecks caused by delayed measurements.

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References

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