SELF-TUNING ALGORITHM AGAINST MAGNETIC ACTUATOR WIND-UP FOR MILLING SPINDLE POSITION REGULATION

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Abstract: An Anti-Windup (AW) compensator is applied to the Embedded Cylindrical-Array Magnetic Actuator (ECAMA) to sustain the performance of spindle position regulation under actuator saturation. Since ECAMA is a type of Active Magnetic Bearing (AMB), the maximum supplied coil current and the induced magnetic force are both limited by their extrema. In this work, an AW compensator is proposed and employed to compensate the output of PID controller to prevent saturation of ECAMA. By employing commercial software *MATLAB/Simulink* and signal processing interface, Module DS1104 by *dSPACE*, the efficacy of the AW compensation is practically verified by intensive experiments.

1 INTRODUCTION

Windup is generally referred to the saturation phenomenon of actuators, i.e., the magnitude or rate of actuator output is limited by an upper bound. Consequently, the required control input cannot be realized by the actuator as long as the magnitude of control input exceeds the saturation level of the associated actuator (Astrom and Rundqwist, 1989. Tarbouriech, Queinnec and Garcia, 2007).

In this work, an Anti-Windup (AW) compensator is applied to the Embedded Cylindrical-Array Magnetic Actuator (ECAMA) for milling machines (Tsai and Lee, 2010) to sustain the performance of spindle position regulation under actuator windup. Since the maximum supplied coil current and the induced magnetic force are both limited by the extrema of ECAMA, the saturation phenomenon takes place, once the required control input exceeds the upper limit of the power amplifier. That is, if the induced magnetic force reaches its upper limit, the control law will not be applicable any more and hence the tremble of spindle becomes drastic.

In this work, an AW compensator is employed to compensate the output of a PID controller to prevent windup of ECAMA caused by the electric current saturation at power amplifier.

2 ANTI-WINDUP (AW) COMPENSATOR

Generally speaking, there are two approaches which can be adopted to avoid actuator saturation. The first approach is to take the actuator limit into the consideration of controller design directly. However, the design of controller becomes complicated or cannot be realized for practical applications. The alternative approach is to separate the prevention of windup from the controller design. The controller, without any constrains on actuator, is firstly designed to meet the performance requirements. After the controller has been designed, the AW compensator is developed to ensure closed-loop system stability.

The concept of AW compensation is depicted in Fig. 1 (Tarbouriech and Turner, 2009). The “Unconstrained Controller” is referred to the controller with no actuator limit has been designed. The AW compensator output is either the constrained or unconstrained control input and defined as follows:

$$u_s = \begin{cases} u_{\max} & \text{for } u > u_{\max} \\ u & \text{for } u_{\min} \le u \le u_{\max} \\ u_{\min} & \text{for } u < u_{\min} \end{cases} \tag{1}$$

where $u_{\max}$ and $u_{\min}$ are the upper limit and lower

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limit of control input respectively. Once the required control input is beyond the upper or lower thresholds, the AW compensator gets engaged. The compensation command can be joined to the feedback signal (y_{aw1}) or to the output of controller directly (y_{aw2}). Such an approach is attractive in practice because no restriction is imposed upon the controller design.

3 EMBEDDED CYLINDRICAL-ARRAY MAGNETIC ACTUATOR (ECAMA)

ECAMA is a type of Active Magnetic Bearing (AMB) and designed for high-speed milling applications. The proposed ECAMA and the spindle are depicted in Fig. 2. In addition, a high-speed motor (>20000 RPM) and a self-sensing module for spindle position deviation measurement are equipped at the two ends of spindle. The configuration of the ECAMA is shown in Fig. 3. It is mainly composed by the modified concave-type yokes (Tsai and Hsu, 2007) and the I-shape electromagnets. The prototype of the I-shape electromagnets are shown in Fig. 4. Totally 1200 turns of coils are wound around each individual I-shape silicon steel core.

4 CONTROL STRATEGY FOR ACTUATOR WINDUP

The unconstrained controller employed in this work is the PID controller. Owing to the integral action, the output of controller tends to exceed the upper limit of power amplifier once a large error exists. The block diagram of spindle position control system is shown in Fig. 5. The output of controller is applied to the coils at ECAMA *via* power amplifiers. By tuning the supplied coil current, the spindle position can be regulated by the induced magnetic forces. In fact, the AW compensator in Fig. 5 is a gain. By compensating the input of integral term, the controller output can be suppressed to be within unsaturated region. Since the magnetic saturation against ECAMA is determined by both the supplied coil current and the area of I-shape silicon steel core, the actual upper limit of the supplied coil current for the AW compensator design in this work is evaluated by experiments. According to the experimental results (Tsai and Lee, 2010), the upper and lower ampere-turns limits of coil are found to be 2000 and 0 ampere-turns respectively. Since the coil wound on each I-shape electromagnet is 1200 turns, the upper and lower limits of supplied coil current are 1.67 A and 0 A respectively.

5 EXPERIMENTAL RESULTS

The test rig in our work, including the milling machine (by How-mau Mchinery CO., LTD, Model CNC-K3), is depicted in Fig. 6. The original milling spindle of CNC-K3 is replaced by the proposed ECAMA. Prior to the experiments, a set of PID gains which can operate stably under low rotating speed, *i.e.,* 1000RPM is given. The follow-up experiments are performed under spindle speed of 6000 RPM. The experimental results in X-axis are shown in Fig. 7~Fig. 10. Fig. 7 and Fig. 8 are the outputs of the controller without and with AW compensation respectively. It is obvious that the windup phenomenon induces large control outputs, no matter in positive or negative side. On the contrary, all the controller outputs are within ± 200, which is referred to the supplied coil voltage of ± 20 V, under AW compensation. The spindle position deviations in X-axis without and with AW compensation are shown in Fig. 9 and Fig. 10. The dotted lines in Fig. 9 and Fig. 10 are referred to the maximum spindle position deviation which is limited by the Auxiliary Bearing (AB) (Tsai, Shih and Lee, 2010) to avoid collision in case malfunction of ECAMA occurs. The spindle position deviation under actuator saturation is shown in Fig. 9. Drastic tremble of spindle and collision is observed. However, the spindle position deviation, shown in Fig. 10, is much improved under AW compensation and no collision between spindle and ECAMA/AB bearing takes place. In other words, the efficacy of the AW compensator for actuator saturation is verified.

6 CONCLUSIONS

The AW (Anti-Windup) compensator is proposed and applied to ECAMA (Embedded Cylindrical-Array Magnetic Actuator) to retain the performance of spindle position regulation under actuator windup. According to the experimental results, without any modification of the PID controller, the controller by aid of AW compensator can still operate well under actuator saturation. However, ECAMA is designed for high-speed milling. Since the cutting force between the cutter and workpiece sometimes alters drastically in a very short period of time during the practical milling process, the response of ECAMA might not be able to instantly follow up. That is, an anti-windup compensation against saturation of supplied current grow rate is therefore required. The forthcoming research by the authors will be focused on this issue.

7 FIGURES

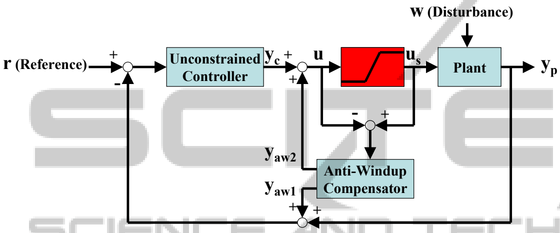

Figure 1: Schematic Diagram of Anti-Windup Compensation.

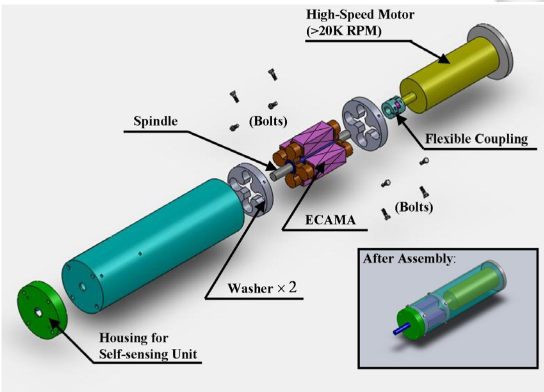

Figure 2: ECAMA and Spindle for Mill Machine.

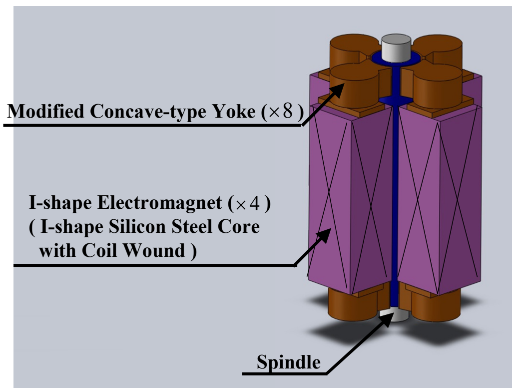

Figure 3: Configuration of ECAMA.

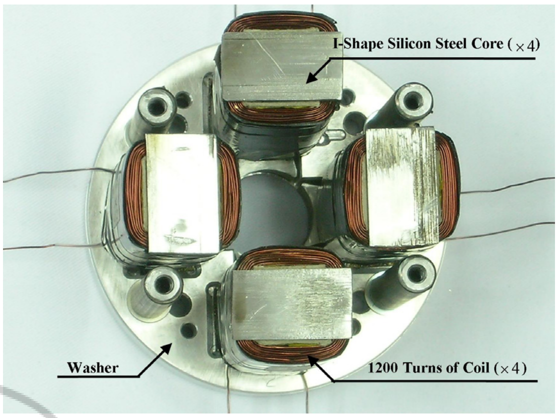

Figure 4: Prototype of I-shape Electromagnets (Bottom View).

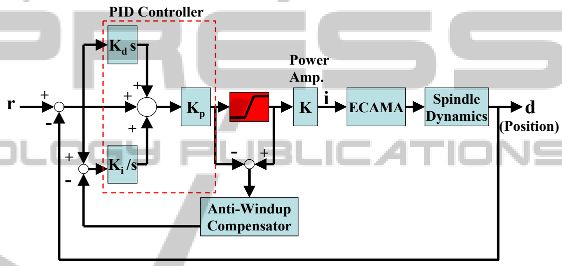

Figure 5: Block Diagram of Spindle Position Control System.

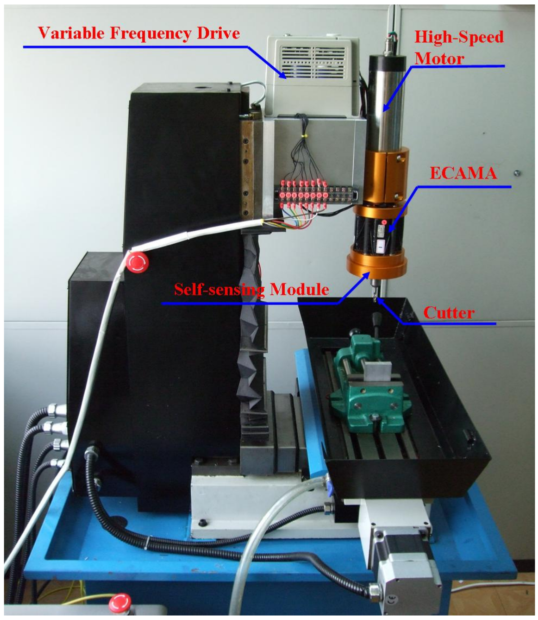

Figure 6: Test Rig for AW Compensation.

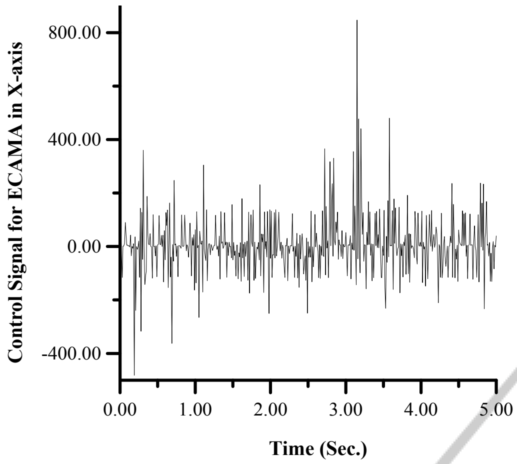

Figure 7: Controller Output w/o AW Compensation (Speed: 6000RPM).

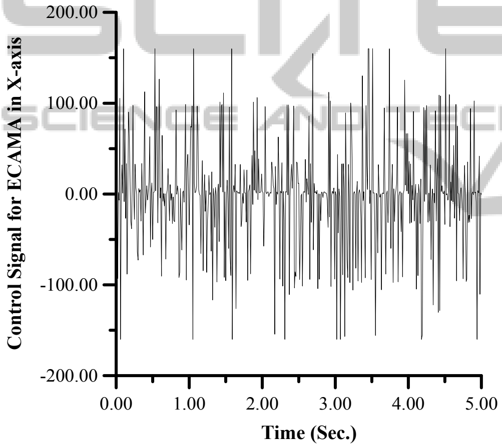

Figure 8: Controller Output with AW Compensation (Speed: 6000RPM).

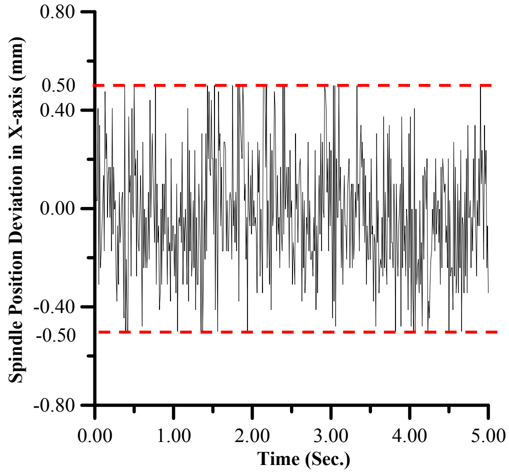

Figure 9: Spindle Position Deviation w/o AW Compensation (Speed: 6000RPM).

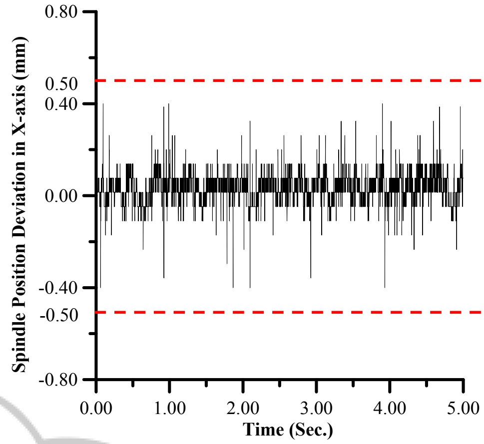

Figure 10: Spindle Position Deviation with AW Compensation (Speed: 6000RPM).

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