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Digital current regulator for proportional electro-hydraulic valves with unknown disturbance rejection

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ABSTRACT

Solenoid current regulation is well-known and standard in any proportional electro-hydraulic valve. The goal is to provide a wide-band transfer function from the reference to the measured current, thus making the solenoid a fast and ideal force actuator within the limits of the power supplier. The power supplier is usually a Pulse Width Modulation (PWM) amplifier fixing the voltage bound and the Nyquist frequency of the regulator. Typical analog regulators include three main terms: a feedforward channel, a proportional feedback channel and the electromotive force compensation. The latter compensation may be accomplished by integrative feedback. Here the problem is faced through a model-based design (Embedded Model Control), on the basis of a wide-band embedded model of the solenoid which includes the effect of eddy currents. To this end model parameters must be identified. The embedded model includes a stochastic disturbance dynamics capable of estimating and correcting the electromotive contribution together with parametric uncertainty, variability and state dependence. The embedded model which is fed by the measured current and the supplied voltage becomes a state predictor of the controllable and disturbance dynamics. The control law combines reference generator, state feedback and disturbance rejection to dispatch the PWM amplifier with the appropriate duty cycle. Modeling, identification and control design are outlined together with experimental result. Comparison with an existing analog regulator is also provided.

1. Introduction

1.1. Goal and rationale of the paper

Solenoid current regulation of proportional electro-hydraulic valves appears to be a standard and mature control problem [1]. To the authors' knowledge, few scientific papers [2] have been recently devoted to the subject, whereas tens of integrated circuits and boards are available on the market. Nowadays, major emphasis is directed toward current regulators of small synchronous motors [3–5], AC drives [6,7] and automotive applications [8–10]. This paper aims to design a solenoid digital current regulator, aided by a model-based design methodology like the Embedded Model Control (EMC) [11,12], and to assess the experimental results in comparison with an existing analog regulator. The 100 W solenoid under study drives an off-the-shelf proportional electro-hydraulic valve. The solenoid is driven by a 24 V Pulse Width Modulation (PWM) amplifier switching at 10 kHz. The input signals of the current regulator are the digital output of a milliampere-accurate current sensor and the current reference provided by the valve position control [13], acting as the outer loop of a hierarchical controller. Unlike moving coil motors, solenoids only provide a unidirectional force (in this case of the order of 100 N) which is contrasted by a spring assembly. Thus the current must be regulated around a variable current bias (about 1.6 A) so as to withstand the spring reaction force at the zero position of the useful valve stroke. Besides current bias, solenoid current regulation encounters targets and constraints that are typical of electric drives [1]: wide bandwidth (BW), large slew rate, bounded supply voltage, magnetic hysteresis, variable inductance, resistance and electromotive force, power amplifier delay, eddy currents if the magnetic circuit is not laminated which is the case of valve solenoids.

Current regulators of electric drives usually include a feedforward command, a proportional feedback, a direct compensation of the electromotive force and of the solenoid resistance variation [10]. As an alternative to direct compensation, proportional and integrative (PI) feedback is used [1,4,6], but the PI feedback must be equipped with an anti-windup strategy to withstand supply voltage saturation [14]. The design of digital regulators is often approached by converting continuous time to discrete time [6,8].

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Direct discrete-time design can account for transport delays as in [14]. Very often simple algorithms are preferred because of a limited computing time.

Here a discrete-time model-based design as suggested by the Embedded Model Control (EMC) is applied to a valve solenoid. Advantages of an EMC regulator are the following:

(1) An accurate model of the solenoid dynamics and of the PWM response is made available, included in the control algorithm (it will be referred to as the embedded model), and it may be tailored and tuned to a specific solenoid class. The model may be pushed by identification to include PWM and sensor delays, as well as eddy current dynamics [15] close to the PWM Nyquist frequency $f_{\max}=5$ kHz. An identification algorithm has been designed and tested on purpose. In fact, a mere chain of integrators as suggested by Active Disturbance Rejection Control (ADRC, [16,17]) does not fit, since eddy currents make the solenoid dynamics of fractional order, and delays are added by PWM and sensor electronics.

(2) The control algorithm features automatic rejection of parametric uncertainty and variability (for instance, the resistance drift due to temperature [18]) as well as of external disturbances like the electromotive force. Rejection is designed so as to avoid supplementary measurements (solenoid temperature, plunger velocity) and integrative actions. This is achieved by completing the embedded model with a stochastic dynamics capable of updating the disturbance state within a wide frequency band, which is only limited by sensor noise and neglected dynamics. Disturbance estimation and rejection of unknown disturbances (including parametric uncertainty) is an effective procedure that is usually dealt with the aid of a state observer [19,20]. Here as in other applications of the EMC [21,22], the concept and practice of the embedded model is exploited for building up a real-time model of the plant and disturbances, which is capable of being continuously updated, and can therefore provide the right information (the state variables) to the control law.

(3) EMC disturbance observers appear to be different from ADRC. The latter observers are built around a high-frequency model of the controllable dynamics taking the form of a chain of integrators, whose size matches the input-output relative degree (denominator less numerator degree, here of fractional order). A further integrator is included, the output playing the role of input disturbance. A static output-to-state feedback as in Kalman filters is drawn from the output error (the same as the EMC model error) to the input of each integrator and the feedback gains are tuned for guaranteeing stability and bandwidth just on a model basis. On the contrary, EMC assumes that the embedded model is perturbed at higher frequencies by a neglected dynamics, which increases the model relative degree to the detriment of the overall stability and performance. The observer eigenvalue tuning in Section 3.3 has been proved by EMC (Refs. [11,12]) to be the key tool for blocking neglected dynamics and high-frequency uncertainty from entering feedback and destabilizing the whole closed-loop system. For instance, uncertainty in the high-frequency gain (the sole model parameter in the ADRC case) may be so large as to require a wide BW, which may conflict with the upper limit imposed by the neglected dynamics and render control design unfeasible, as pointed out in Section 3.3. Further design issues that are solved by EMC are: (i) delays cannot be treated as integrators, which suggests direct discrete-time design, (ii) the observer feedback variables are treated as noise components (Section 2.3) to be designed together with the disturbance dynamics, (iii) disturbance dynamics must be given the right state equation (not necessarily of the first order) which is capable of describing the class of the plant uncertainty to be rejected, and (iv) the disturbance entry points in the controllable dynamics may be everywhere, which requires a specific disturbance rejection law as in Section 3.4.

(4) Driving the embedded model with the same command which is dispatched to the plant, eliminates any integral windup when the command saturates. The reason is that the disturbance state of the embedded model is continuously updated by the residual discrepancy between plant and model running under the same command. As a result the EMC control law in Section 3.4, unlike PID feedback laws, becomes static, the only state variable being a delay between pre-computed and current command. The reference generator in Section 3.2 provides a reference duty cycle and reference state variables that are coherent with the duty-cycle range. In this manner, contribution to command saturation of tracking errors and disturbance rejection is minimized.

(5) The overall input–output dynamics is shaped for meeting the requirements in Section 3.1. This is achieved by eigenvalue tuning as shown in Sections 3.3 and 3.4.

(6) Last but not least, the current regulator fits into the hierarchical control scheme of a valve position control [13], since it receives the reference current $\underline{I}$ from the position control and provides the latter control with current and current derivatives (Fig. 1).

The goal of a current regulator is to convert solenoids into ideal force actuators of position controllers. In other words, a current regulator becomes the inner loop of a position control loop as in Fig. 1. In view of a position bandwidth wider than 100 Hz, a milliampere-accurate repeatability of the current reference $\underline{I}$ is demanded from DC to about 1 kHz. The regulator is fed by a current reference $\underline{I}$, generated by the position controller, and must guarantee fast and accurate tracking of the reference current within the limits of the PWM amplifier, i.e. voltage bound, $|V| \le V_{\max}=24$ V, and delay. The solenoid plunger and the magnetic circuit are carefully designed and shaped to provide a plunger force that is near-proportional to the solenoid current in the useful stroke of the position control [23]. Outside this range, for instance close to the valve rest position, the force becomes proportional to the current square.

Three main performance indices characterize a solenoid current regulator.

(1) The first is the slew rate $(dI/dt)_{\max}$ in response to reference steps. The slew rate is limited by the PWM voltage $V_{\max}$ and by the self-inductance. It may be identified and assessed from the response to a square-wave reference.

(2) The second is the tracking delay in the linear response region. It may be identified and assessed either by the harmonic response or by the time response to canonical reference signals.

(3) The third is the accuracy of the tracking error to be measured under steady state and transient conditions.

The paper starts in Section 2 with a discrete-time dynamic model and the relevant identification procedure. Fine and simplified models are discussed to fix the embedded model of the control algorithm. The current regulator is outlined in Section 3. This is the combination, in accordance with the EMC, of a reference generator, state predictor and control law. The state predictor, made by embedded model and noise estimator, is essential to estimate the unknown disturbance to be rejected. The attribute 'unknown' emphasizes the fact that no supplementary measurements are necessary to the purpose. The experimental tests discussed in Section 4 prove the regulator performance and show the advantage of the proposed disturbance rejection. Formulation is reduced to a minimum.

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