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HYBRID ADAPTIVE CONTROLLER FOR HSM60

Abstract:
Most of the servomotors used in practice are controlled by common PI controllers having clear and distinct effects on the controlled plant yet suffering from rather poor robustness in terms of changing parameters of a plant or load variations. The variations in both the plant parameters and the load necessitate adjusting controller gains to meet the performance indices. In this paper, a fuzzy controller with reference model is used for forcing a plant to behave as a first-order reference showing good results even for drastic changes of the plant parameters. The results are compared to a common PI controller with P and I gains tuned according to symmetric optimum criterion. The whole control scheme is implemented in Fuzzy Logic Toolbox under Matlab/Simulink.

Keywords:
adaptive controller, adaptive signal, fuzzy rule table, response, PI controller

INTRODUCTION

HSM60 servomotors are used in applications where superior dynamic properties are of utmost importance. They are suited for sophisticated and fast control tasks with possibility for simple logic control or speed control using variations in magnitude of voltage applied to the armature winding or PWM technique. HSM60 are usually controlled by means of a common PI controller, which can be tuned to achieve satisfactory performance but only for given plant parameters. Despite the fact that a small range of plant parameter variations is manageable even with PI controller, more significant changes of the plant parameters (inertia moment for instance) might cause large deviations from required responses for given inputs. It was shown in [1] that implementing minor acceleration control loop may improve the performance of such control system even under conditions of inertia moment variation. With digital control techniques fully available for servomotor control, it is natural to apply advanced control algorithms, which might improve the responses of a control system under conditions of parameter variation even more.

METHODOLOGY

In order to model the control system for HSM60 servomotor, the model in Fig.1 was used [5], where L_m – winding inductance, R_m – winding resistance, $C\Phi$ - electromagnetic coefficient, J – inertia moment, M_m – motor moment, M_z – load moment. According to the HSM60 manufacturer datasheet the values for these parameters are as follows [6]:
$L_m = 60.10^{-6}$ H, $R_m = 0{,}42\ \Omega$, $C\Phi = 0{,}0184$ V.rad^{-1}.s^{-1}, $J_n = 38.10^{-7}$ kg.m^2
This model neglects the effects of stray magnetic flux in excitation winding, mutual influence of particular windings, eddy currents and so on. Nevertheless, it can serve as a buildblock for a comparative study of qualitative aspects of the relevant control methodologies under conditions of inertia moment variation. As was mentioned before, this type of a servomotor is commonly controlled by a conventional PI controller. The aforementioned model was

tested also with this type of controller (the results are depicted in experimental part).

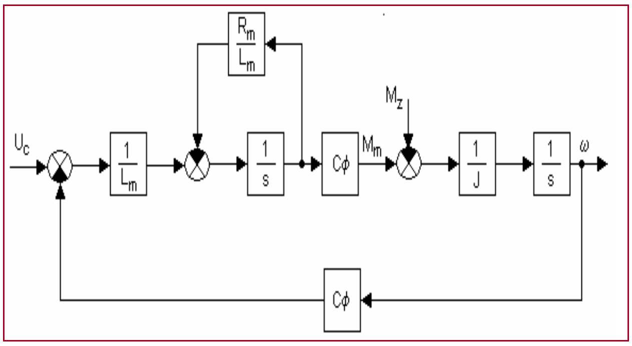

Figure 1. The model of HSM60

The motors of this type traditionally include also current controllers, which try to provide desired value of a motor moment by means of voltage acting upon the armature winding as a response to error between actual and desired value of a current. This controller is usually also of PI type [8]. In this case, the current controller was omitted. It is also supposed that the feedback signal is transferred without any delay (implying unity transfer function between actual speed and signal fed to the subtracting unit). The whole control system could be then represented in the form in Fig.2.

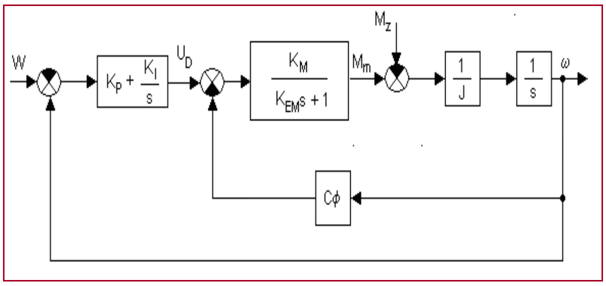

Figure 2. The whole control system of HSM60

The torque actuator is modelled by first-order delay transfer function with $K_M = \frac{C\phi}{R_m}$ *and* $K_{EM} = \frac{L_m}{R_m}$. *The friction of the mechanical subsystem was considered negligible. The overall transfer function is:*

$$G(s) = \frac{\frac{K_P}{K_I}s + 1}{\frac{JK_{EM}}{K_M K_I}s^3 + \frac{J}{K_M K_I}s^2 + \left(\frac{C\phi}{K_I} + \frac{K_P}{K_I}\right)s + 1} \qquad (1)$$

where K_P and K_I are proportional and integral gain. According to the denominator of this transfer function (i.e., the characteristic equation), this system is of the third order. Due to extremely low values of $K_{M,}$ K_{EM} and J ($0.0438, 1.42857.10^{-4}$ and 38.10^{-7} respectively) the absolute values of first two coefficients in characteristic equation are several orders lower than the value of the third coefficient, which implied the possibility of using the first-order reference model. The reference model was thus chosen in the following form:

$$G_R(s) = \frac{1}{0.025s + 1} \qquad (2)$$

FUZZY CONTROLLER DESIGN

The idea was to use an adaptive control methodology, which would provide the desired response (dictated by the reference model) even under conditions of plant parameter variations. Using the first-order reference model would provide non-oscillatory response for step changes in desired speed. In this case two controllers are actually implemented, one for eliminating the error between the actual and the desired speed while the other one for eliminating error between the response of the reference model and the response of the plant. Since the adaptation controller reacts directly to the difference between the desired and actual response (without first identifying appropriate parameters), this adaptation was indirect.

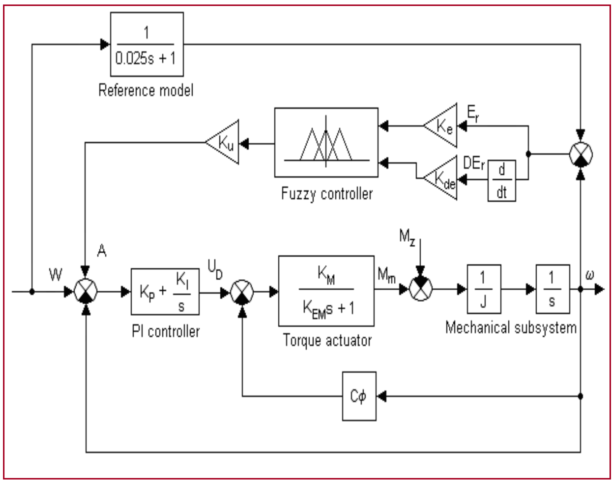

Figure3. Fuzzy signal adaptation with reference model for HSM60

In Fig.3 the schematic diagram for HSM60 control system with fuzzy adaptation is depicted. According to [4], two basic adaptation techniques are possible: parameter adaptation and signal adaptation. There are several factors to consider when choosing between these two as either of them possesses distinct advantages as well as disadvantages. The signal adaptation is said to be faster yet it might suffer from the higher oscillations. Nevertheless, this technique was selected for experimenting due to its adaptation speed with the assumption that the negative effect (oscillations) might be possibly suppressed by careful tuning of the fuzzy controller scaling gains.

The two input variables for fuzzy controller were the response trajectory error and its derivative and the one output variable was adaptation signal acting at the place of differentiator so that the error between the reference model response and actual plant response would be minimal.

$$A_e^j = \left\{ \left(x_1, \mu_{A_e^j}(x_1) \right) : x_1 \in X_e \right\}$$

$$A_{de}^k = \left\{ \left(x_2, \mu_{A_{de}^k}(x_2) \right) : x_2 \in X_{de} \right\} \qquad (3)$$

$$B_u^l = \left\{ \left(y, \mu_{B_u^l}(y) \right) : y \in Y_u \right\}$$

where A_e^j, A_{de}^k are j-th and k-th fuzzy sets on response trajectory error and its derivative universes X_e, X_{de} respectively, x_1, x_2 are inputs on these universes (error and derivative) where the crisp values are fuzzified using singletons. B_u^l is l-th fuzzy set on adaptation signal universe of discourse Y_u with y being crisp output value [7].

In this case, sum-min aggregation was used that could be written in this form

$$\mu_u(x_1, x_2, y) = \mu_{\cup_{i=1}^{r} FR^i}(x_1, x_2, y) = \sum \min{}_{i=1}^{r} \left[\mu_{R_{jk}}(x_1, x_2), \mu_{B_l}(y) \right] \qquad (4)$$

where FR^i is i-th activated fuzzy rule and R_{jk} is a fuzzy relation meaning the combination of p-th and q-th fuzzy sets on reference model response error and its derivative universes and B_l is l-th fuzzy set on adaptation signal universe of discourse. As a defuzzification method, COG was used (COA with sum aggregation) so that in case of several fuzzy rules having the same consequent part, those with lower membership value shall not be disregarded in the computed control signal. The output signal is then computed from the following formula [4]

$$y(x_1, x_2) = \frac{\sum_i y_i \sum_{j=1}^{r} \mu_{FR^j}(x_1, x_2, y_i)}{\sum_i \sum_{j=1}^{r} \mu_{FR^j}(x_1, x_2, y_i)} \qquad (5)$$

All three variables were normalized to the range <-1,1>. The fuzzy sets were of trapezoid shape as this is considered to make the resulting system more insensitive to a parameter variation [4]. Their distribution was determined based on the trial-and-error experimentation. The distribution of fuzzy sets over respective universes of discourse is depicted in Fig.4. The fuzzy controller was of Mamdani type with symmetric fuzzy rule table.

RESULTS

The P and I gains were set according to the symmetric optimum criterion. This criterion should provide sufficiently fast and well-damped responses by extending the bandwidth. Formulas for calculating optimal gains are given in the following form [8]:

$$K_P^{opt} = \frac{J}{2K_{EM}}; K_I^{opt} = \frac{J}{8K_{EM}^2} \qquad (6)$$

The resulting values were $K_P = 0.0133$ and $K_I = 23.27$. Experiments shown that the P gain had to be altered in order to get better damping in case the inertia moment varied and it was set to 0.2. In Fig.5, the responses of conventional PI controller for a step change in desired speed with varying value of J is shown.

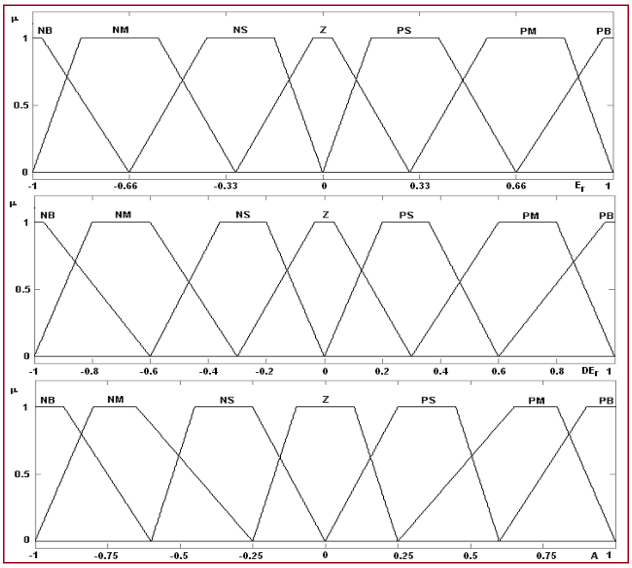

Figure4. Fuzzy membership functions distribution

For $J = 15J_n$ the overshoot was $\sigma = 21.3\%$ while the settling time for 1% error was $t_r = 0.56s$. In case of $J = 45J_n$, the overshoot was increased to $\sigma = 38.3\%$ and the settling time to $t_r = 1.41s$. In case of $J = 75J_n$, the overshoot was increased to $\sigma = 46.6\%$ and the settling time to $t_r = 2.33s$. It is evident that the variation of inertia moment had a profound effect on the responses of the control system, resulting in strong discrepancies between the desired and actual performance.

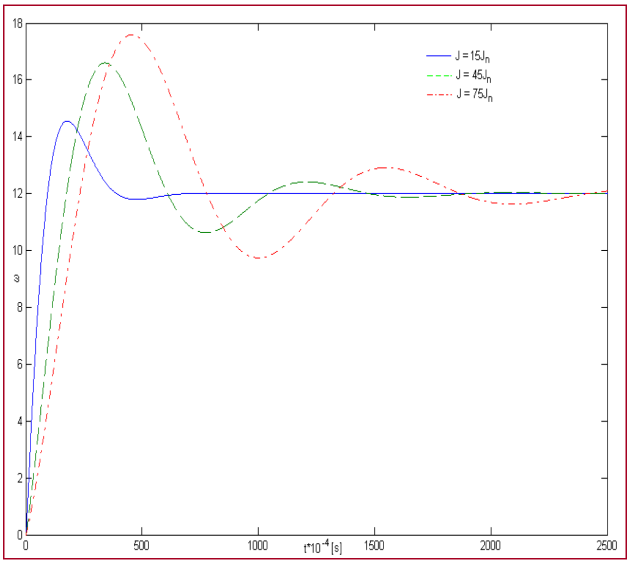

Figure5. Responses of HSM60 with PI controller for three different inertia moment values

In Fig.6, the responses of adaptive control system are depicted. The responses are slower compared to the case with PI controller due to time constant of the reference model (0.025). In all three cases the settling time is around t_r = 1.05s. The response for $J = 15J_n$ is comparable to the response of reference model in its time course with slight lead (0.013 s). In two remaining cases, the more distinct differences can be visible evidently due to a different responsiveness of the plant to the controller efforts (its derivative component) (the maximum value of reference model response error was 0.02 s for $J = 45J_n$ and 0.03 s for $J = 75J_n$). Changing the adaptation signal scaling gain could alter these responses but not without introducing some oscillations and thus creating the upper bound for its magnitude with given membership function distribution. It is clear from Fig.6 that no overshoot was present in any of the recorded responses.

In Fig.7 the load rejection capabilities of conventional PI controller for HSM60 are depicted. In t_s = 3s, a step change in load moment was applied ranging from 0 Nm to 0.1 Nm. The responses are shown from this particular moment on. In case of $J = 15J_n$ the maximum change of actual speed was 54% and the settling time for achieving 1% error was 0.053s. For $J = 45J_n$, the maximum change was reduced to 39.9% but the settling time increased to 0.151s. Finally for $J = 75J_n$ the maximum change was decreased again to 33.8% with settling time being 0.207s.

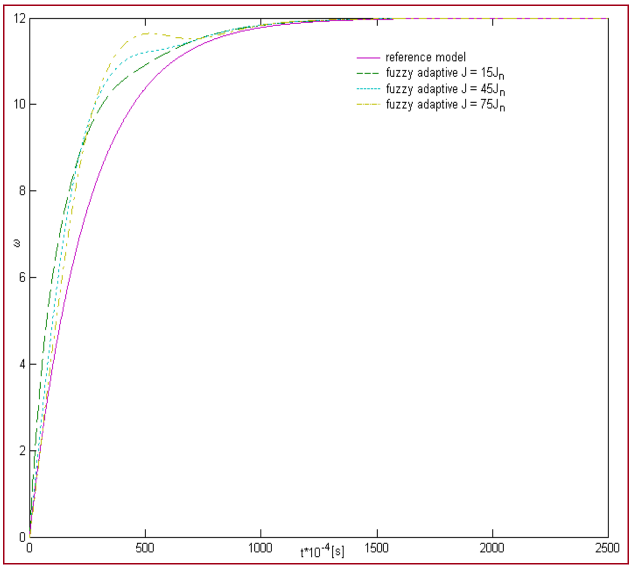

Figure6. Responses of HSM60 with fuzzy adaptive controller with reference model

In Fig.8 the responses for HSM60 with hybrid fuzzy adaptive controller are shown. In this case, the same step change in load moment from 0 Nm to 0.1 Nm was applied in t_s = 3s. It is clearly visible that the system with hybrid fuzzy adaptive controller is less disturbed by changes in load moment compared to PI controller. For $J = 15J_n$ the maximum change of actual speed was 14.6% and the settling time for achieving 1% error was 0.029s. After changing the inertia moment parameter to $J = 45J_n$, the maximum change in speed decreased to 11.75% while the settling time increased to 0.032s. The small overshoot in t_s = 3.036s did not exceed 1% error band around the desired speed. In case of $J = 75J_n$, the maximum change of actual speed was 10.4% and the settling time was 0.036s. Once again, the small overshoot in t_s = 3.039s did not exceed 1% error band around the desired speed.

DISCUSSION

The presented responses corroborate the idea that the robustness of conventional PI controller in terms of plant parameter variation (inertia moment) is rather poor. There are several criteria for tuning the gains but meeting the requirements for desired performance under drastic parameter changes with only PI controller would be hardly achieved. Increasing the inertia moment 15 times compared to the *nominal case produced relatively good response (Fig.5), but in two other cases the responses were much less favorable. It is obvious from (1) that the only option for decreasing the sensitivity to inertia parameter variation is to increase integral gain but this limited by the risk of instability. The responses in Fig.6 show that it is possible for the HSM60 control system with hybrid fuzzy adaptive controller to follow the response of first-order reference model with rather small error. This error naturally increases with the higher inertia moment, but it is still able to provide far better responses compared to PI controller. It must be said that there is a much higher number of parameters to tune for fuzzy controller than for PI controller, thus offering highly superior flexibility but at the cost of more difficult tuning. Since the design of fuzzy controller was completely heuristic, it must be considered suboptimal (especially the membership distribution). Using some method of optimization in the process of fuzzy controller design offers some space for improvement of the responses. From Fig.7, it is quite clear that the change in load moment (0.1 Nm) disturbs the control system with PI controller quite significantly. It restores the previously attained desired speed after at least two overshoots that exceed 1% error band. Moreover, the maximum deviations from the desired speed are quite large (more than 50% in case of $J = 15J_n$). The hybrid fuzzy adaptive controller is much less sensitive to the aforementioned step change in load moment and it restores the desired speed in much shorter time (the second overshoot remain in 1% error band even for $J = 75J_n$).*

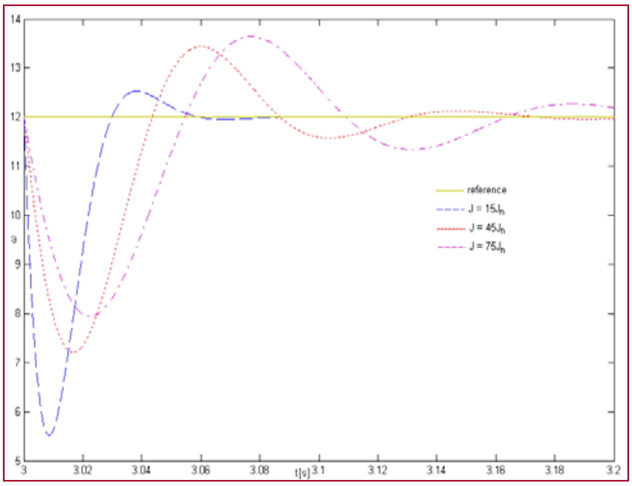

Figure7. Responses of the HSM60 control system with PI controller for a step change in load moment

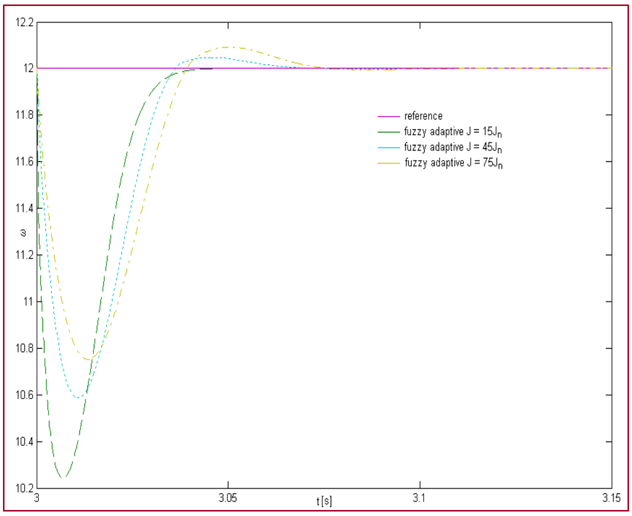

Figure8. Responses of the HSM60 control system with hybrid fuzzy adaptive controller for a step change in load moment

Again, the fuzzy set distribution optimization could further improve this load rejection capability.

CONCLUSION

The results in this paper strongly favor the use of fuzzy controller in addition to a conventional PI controller to create a hybrid fuzzy adaptive controller. Fixed gain settings for PI controller cannot meet the requirements put on control system performance under conditions of large parameter variations. Extending the conventional control system with adaptive fuzzy controller retains the desired capabilities of PI controller while adds a better insensitivity to load and plant parameter variations. It is worth mentioning that one has to consider the effects of unmodelled dynamics (e.g. feedback delay, current controller etc.) on the performance of such control system. This in turn might render a first-order reference model unsuitable for such task (in case the higher order coefficients were not negligible). Moreover, a lot of space for improvement remains due to the suboptimal fuzzy controller design. Further work should lie in finding a suitable way of optimizing the design of fuzzy controller (e.g. genetic algorithms), which could accentuate the positive effects of applying fuzzy adaptive controller and also in testing this method for a real HSM60 with all its subtleties.

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