Robustification of Generalized Internal Model Control based on the H_∞ method for the stabilization and tracking of a Hydraulic Actuator system

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ABSTRACT

In this paper, we propose a new method for robustification of generalized internal model control (GIMC) for the stabilization and tracking of a Hydraulic Actuator system, which using H_∞ mix sensitivity, to design the control system of the Hydraulic Actuator. It is well known that there is an intrinsic conflict between performance and robustness in the standard feedback framework. Generalized internal model controller is a new architecture which can separate the performance and robustness design in controller design. This architecture has two parts in this paper: a high performance controller, which is designed by PI controller, and then a robustification controller, which is designed by using H_∞ mix sensitivity controller design method. We also present the steps of controller design by using this method to make it easier to use. Based on the proposed method, numerical simulation are both carried out for a gyro stabilized Hydraulic Actuator tacking system. The numerical simulated result show that the Hydraulic Actuator using robustification of generalized internal model control based on the H_∞ mix sensitivity controller design is accurate and effective. Comparing with the same PI controller in standard feedback framework, the proposed method can guarantee the high tracking performance as same as the PI controller and improve the external disturbance restraining ability a lot. In conclusion, Robustification of generalized internal model control (GIMC) based on the H_∞ method is a new approach for the stabilization and tracking of a Hydraulic Actuator system.

KEYWORDS

Robust Controller, IMC Controller, Mixed Sensitivity Problem, Hydraulic Actuator.

1 INTRODUCTION

Among the problems that the control of physical systems poses, that of the synthesis of the laws of control performing with regard to the precision but also sufficiently robust to ensure the stability. The diversity of control structures is related to the objectives set, on the one hand, and the constraints on the quality of the process model. The Internal Model Control (IMC) design method uses observation in a specialized way to introduce a simple and effective design technique for robust feedback controllers. The IMC design method for zero-axis zero stable plants allows a controller in principle to obtain a closed-loop shape of magnitude equal to the desired transfer function (Morari & Zafiriou, 1989) [1]. The term IMC is used because, as defined the controller can be considered as a combination of two elements, one being a model of the plant. Generally in the standard feedback framework, there is an intrinsic conflict between performance and robustness [2]. For this, a compromise must be made between the nominal performance and robust stability against external disturbances and modeling uncertainties. For this reason, K. Zhou proposed a new controller structure called generalized internal model control (GIMC) [3]. After that, many scholars make a scrutiny into GIMC. This control structure is widely used in many domains as a method, which could improve external disturbance restraining ability, such as mechatronic system, magnetic suspension systems and motion control etc [4]. A direct design from input/output data of the youla parameter for compensating plant perturbation on GIMC structure was proposed in [5]. Meanwhile, worst-case robust control design techniques such as $H\infty$ control, have gained popularity in the last thirty years because of the robustness against model uncertainties and external disturbances [6]. Unfortunately, most robust control design techniques are based on the worst possible scenario which may never occur in a particular control system and it usually cannot achieve at the expense of performance [7]. In this paper, we study a method [8], combining the H_∞ method with GIMC for the design of a controller for hydraulic actuator against external disturbances [9]. Then, the structure of the GIMC is described to analyze its robust stability conditions. The details of the H_∞ method on the structure of the GIMC are presented. Then, a numerical simulation step is presented. Finally, we conclude this paper by emphasizing the highlights of the design method.

2. GIMC STURCTURE

2.1 GIMC control structure

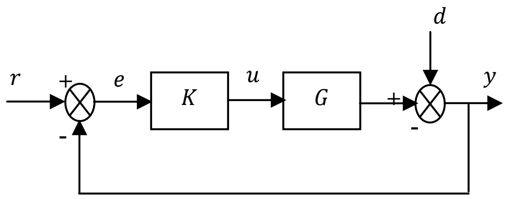

Figure 1: Standard feedback configuration

A standard feedback configuration [10] is shown in Figure 1 where G is a linear time invariant plant and K is a linear time invariant controller. It's well known that the object model G is not perfectly obtained generally. What we actually obtains is a nominal model G_N . We assume that K_0 could stabilize the nominal plant G_N and assume G_N and K_0 have the following coprime factorizations [11]:

$$\begin{cases} K_0 = UV^{-1} = \tilde{V}^{-1}\tilde{U} \\ G_0 = NM^{-1} = \tilde{M}^{-1}\tilde{N} \end{cases} \tag{1}$$

From the Youla controller parameterization [12], every stabilizing controller for G_0 can be written in the following form:

$$K = (\tilde{V} - Q\tilde{N})^{-1}(\tilde{U} + Q\tilde{M}) \tag{2}$$

For some $Q \in H_\infty$ such that $det(\tilde{V} - Q\tilde{N}) \neq 0$, or equivalently:

$$K = (U + MQ)(V - NQ)^{-1} \tag{3}$$

For some $Q \in H_\infty$ such that $det(V - NQ) \neq 0$.

K. Zhou proposed the controller which is presented in formula (2), as shown in figure 2 [13],

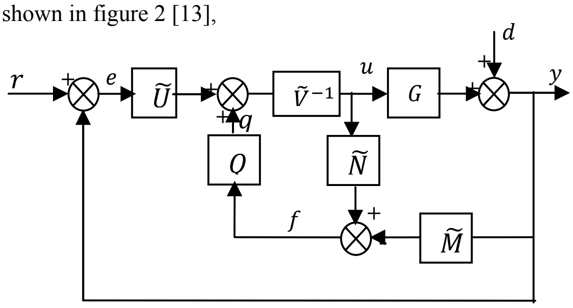

Figure 2: Generalized internal model control structure

The controller configuration illustrated in Figure 2 called generalized internal model control structure (GIMC). The distinguished feature of this controller implementation is that if there are not modeling uncertainties, i.e., if $G = G_N$, the inner loop feedback signal f is always zero, i.e., $f = 0$. A high performance and disturbance restraining system can be designed in two steps:

(a) Design K_0 to satisfy the system performance specifications with a nominal pant model.

(b) Design Q to improve the ability of anti-disturbance.

The standard Youla controller parameterization, $\tilde{U}$, V , $\tilde{U}$ and V are chosen in particular:

$$\begin{cases} \tilde{U}N + \tilde{V}M = I \\ \tilde{N}U + \tilde{M}V = I \end{cases} \tag{4}$$

However, we don't have to satisfy the restraining presented in formula (4) when K_0 stabilizes internally the feedback system shown in Figure 1. In this paper, we have definitions as follow:

$$\begin{cases} \tilde{U} = K_0, \quad \tilde{V}^{-1} = I \\ \tilde{N} = G_N, \quad \tilde{M} = I \end{cases} \tag{5}$$

Then we propose a new GIMC control structure shown in Figure 3 which makes formula (5) into Figure 2 [8].

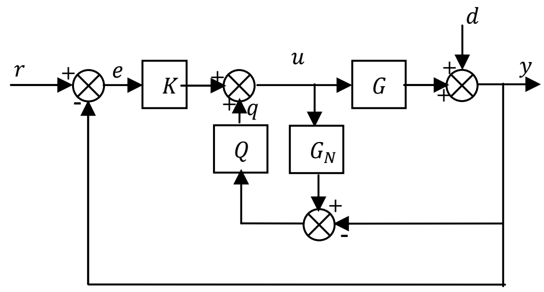

Figure 3: Reconfigurable GIMC control structure

In the system illustrated in Figure 3, we can obtain the transfer function from r to y is [14]:

$$T_{yr} = \frac{K_0 G}{1 + K_0 G + (G - G_N)Q} \tag{6}$$

For the external disturbance d, the inner loop feedback and outer loop feedback are active at the same time. The transfer function from d to y is [14] :

$$T_{yd} = \frac{1 + (G - G_N)Q}{1 + K_0 G + (G - G_N)Q} \cdot \frac{1 - G_N Q}{1 + (G - G_N)Q} \tag{7}$$

The formula (6) and (7) reveal that if there is no modeling uncertainty [7], [14] and [15] the transfer function T_{yr} is the same with it in the standard feedback configuration in Figure 1 and T_{yd} is different because of the inner loop feedback. The external disturbance rejection ratio of the system shown in Figure 3 is the sum of inner loop and outer loop

2.2 Robust stability of GIMC control

The relative error of plant model is defined as follows:

$$\frac{|G(jw) - G_N(jw)|}{|G_N(jw)|} = |H(jw)| \leq \gamma \tag{8}$$

In the formula (8), γ presents the upper limit of the relative plant model error, i.e. $\gamma = sup\ (|H(jw)|)$, G_N is nominal model. Plant multiplicative uncertainty is described in formula (8), and Figure (3) can be revealed as follows [7]:

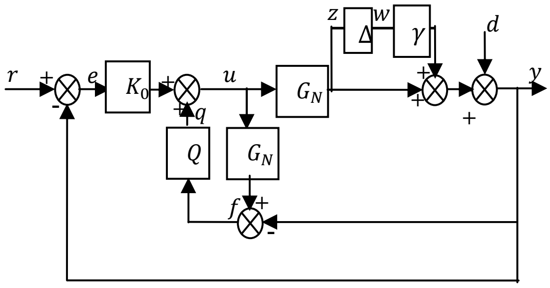

Figure 4: GIMC control structure with multiplicative uncertainty

By using the Small Gain Theorem, the sufficient condition for robust stabilization in the system as shown in Figure 4 can be obtained:

$$|T_{zw}| = \left|\frac{\gamma(K_0G_N - QG_N)}{1+K_0G_0+Q(G_0-G_0)}\right| = \gamma\left|\frac{G_N(K_0-Q)}{1+K_0G_N}\right| < 1 \qquad \forall w \tag{9}$$

$$\left|\frac{G_N(K_0-Q)}{1+K_0G_N}\right| < \frac{1}{\gamma} \qquad \forall w \tag{10}$$

3. H_∞ CONTROLLER

Due to the analysis in previous section, we know that we can design the outer loop feedback controller K_0 and inner loop feedback controller Q independently. When if there is no modeling uncertainty, the inner loop feedback cannot affect on the transfer feature from r to y which is on the behalf of the system performance. The outer loop feedback controller K_0 can be any form of controllers that can stabilize the nominal plant G_N . In this paper, we choose a simple PI controller [7]. For the design of inner loop feedback regulator Q , we use H_∞ mix sensitivity controller design method. Since inner loop feedback does almost not affect on system performance and it just affect on the external disturbance restraining ability. From the formula (7), we realize that the external disturbance rejection ratio of the system shown in Figure 3 is sum of outer loop feedback and inner loop feedback. Then we can design the inner loop feedback regulator Q independently and make outer loop open at the same time.

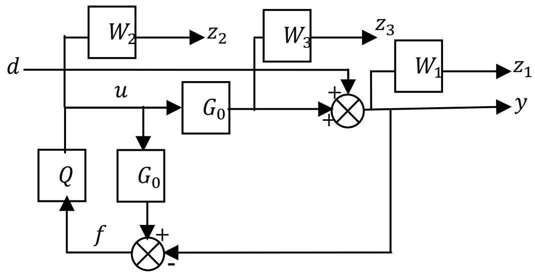

Figure 5: H∞ mix sensitivity problem

In Figure 5, $W_1(s)$ presents norm bound of system disturbance rejection ratio, corresponding to the norm bound of the system sensitivity function. $W_3(s)$ Presents the norm bound of plant multiplicative uncertainty, corresponding to the norm bound of complementary sensitivity T . $W_2(s)$ Presents the norm bound of plant additive uncertainty, corresponding to the function R in H_∞ mix sensitivity problem [7], [15], [16].

Now we can make the control structure illustrated in Figure 5 described in the standard framework of the weighted mix sensitivity problem:

$$\begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ f \end{bmatrix} = \begin{bmatrix} W_1 & W_1G_0 \\ 0 & W_2 \\ 0 & W_3G_0 \\ -I & 0 \end{bmatrix} \begin{bmatrix} d \\ u \end{bmatrix} \tag{11}$$

$$u = Q.f \tag{12}$$

From the formula (11), we can obtain the generalized plant:

$$P_0 = \begin{bmatrix} W_1 & W_1G_0 \\ 0 & W_2 \\ 0 & W_3G_0 \\ -I & 0 \end{bmatrix} \tag{13}$$

The Figure 5 can be redrawn as follows:

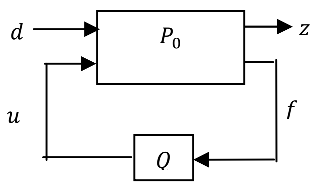

Figure 6: Standard H∞ control framework

Then the closed loop transfer function matrix based on formula (11) and (12) is:

$$P = \begin{vmatrix} W_1S \\ W_2R \\ W_3T \end{vmatrix} \tag{14}$$

H_∞ mix sensitivity problem is [17], [18]: find the rational function of the controller Q that stabilizes the closed loop system and satisfies:

$$\min \quad \|P\|_\infty \ or\ \|P\|_\infty \le \gamma\ (\gamma > \gamma_0) \tag{15}$$

In formula (15), the former called H_∞ optimization problem and the latter called H_∞ suboptimization problem.

In general, the H_∞ nix sensitivity problem can be reconfigurable as follows:

$$\begin{vmatrix} W_1 S \\ W_2 R \\ W_3 T \end{vmatrix} \le 1 \tag{16}$$

In our paper, the weighted matrixes are chosen in frequency. From this paper:

W_1 present the spectrum characteristic of external disturbance and it has low pass property.

W_3 has high-pass property and it can guarantee the high frequency disturbance rejection ability of the closed loop system;

W_2 presents the norm bound of plant additive uncertainty, and it's a constant in general for reducing the controller orders.

In next section, we take the numerical simulation for the hydraulic actuator stabilization and tracking by using method proposed previously and analyze the results in detail.

4. SIMULATION

4.1 Model for hydraulic actuator

In this section, the GIMC are applied to an hydraulic actuator (benchmark problem, see [14]) where its dynamic behaviour is modelled by the following nominal plant-model:

$$G_N(s) = \frac{9000}{s^3+30s^2+700s+1000} \tag{17}$$

Knowing that, all uncertainties that affect the above process have been modeled as an unstructured-multiplicative model called also $\Delta(s)$ which is satisfied the following condition:

$$\|\Delta(s)\|_\infty = \left\| \frac{G(s)-G_N(s)}{G_N(s)} \right\|_\infty < 1 \tag{18}$$

Where $G(s)$ denotes the perturbed system.

4.2 Result of the numerical simulation

The outer loop controller K_0 in Figure 3 is PI controller:

$$K_0 = \frac{0.6458\,(s+1.516)}{s} \tag{19}$$

The W_1 ,W_2 ,W_3 is respectively:

$$W_1 = \frac{0.1111\, s\text{^}2 + 6.667\, s + 100}{s\text{^}2 + 2\, s + 1} \tag{20}$$

The disturbance rejection ratio with inner loop feedback regulator Q is almost 50dB.

$$W_3 = \frac{9.494\, s + 94.94}{s + 300} \tag{21}$$

$$W_2 = [\,], \tag{22}$$

From the calculation, $\gamma = 0.9593$. Then the inner loop feedback regulator Q is:

$$Q = \frac{1.133e11\, s^7 + 8.552e12\, s^6 + 3.658e14\, s^5 + 9.019e15\, s^4 + 1.395e17\, s^3 + 1.123e18\, s\text{^}2 + 2.569e18\, s + 1.754e18}{s^8 + 6.68e04\, s^7 + 1.468e09\, s^6 + 1.769e13\, s^5 + 1.585e15\, s^4 + 5.981e16\, s^3 + 1.23e18\, s\text{^}2 + 1.212e19\, s + 1.58e19} \tag{23}$$

The controller K in standard feedback configuration is designed as K_0 . Then we can compare the transfer feature from r to y and d to y between standard feedback configuration and H_∞ mix sensitivity controller on GIMC control structure.

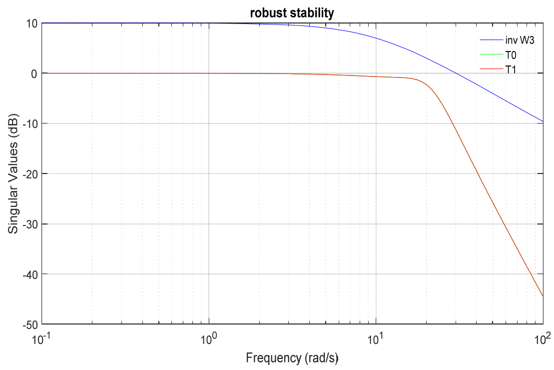

Figure 7: Robust stability information

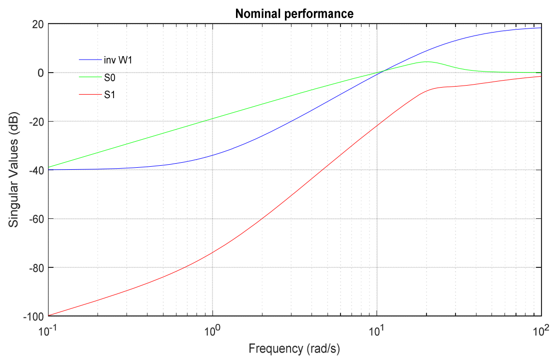

Figure 8: Nominal performance information

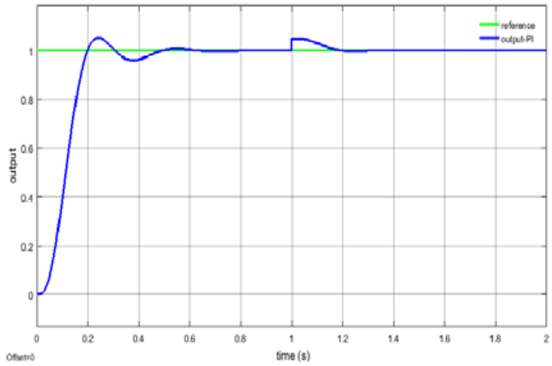

Figure 9: Temporal response of the loop system by a simple PI

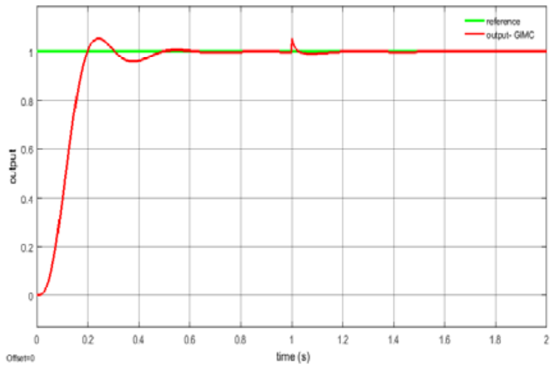

Figure 10: Temporal response of the loop system by a GIMC method

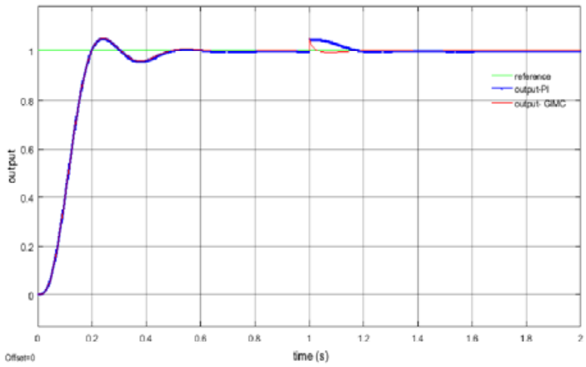

Figure 11: Comparison of the temporal response of the loop system by a simple PI, with a time response to the GIMC loop system

From the Figure 7, 8, 9, 10 and 11, we can know that performance of the H_∞ mix sensitivity controller on GIMC control structure is the same with the standard feedback configuration. Meanwhile, the disturbance rejection ratio of H_∞ mix sensitivity problem on GIMC control structure improves a lot than the PI control structure.

5. CONCLUSION

In this paper, we propose an approach which using H_∞ mix sensitivity controller base on GIMC control structure to improve the external disturbance rejection ratio a lot in hydraulic actuator stabilization and tracking system. The results of the numerical simulation reveal that this method is a practical and effective way to restraining the external disturbance.

6. REFERENCES

[1] Morari, M., & Zafiriou, E. (1989). *Robust process control*. Morari.

[2] Zhou, K., Doyle, J. C., & Glover, K. (1996). *Robust and optimal control* (Vol. 40, p. 146). New Jersey: Prentice hall.

[3] Zhongqiao, Z., Xiaojing, W., Yanhong, Z., Liang, X., & Yanglin, C. (2014). The Research on IMC-PID Control in Maglev Supporting System. *The Open Automation and Control Systems Journal*, *6*(1), 797-802.

[4] Namerikawa, T., & Miyakawa, J. (2007, July). GIMC structure considering communication delay and its application to mechatronic system. In 2007 American Control Conference (pp. 1532-1537). IEEE.

[5] Mizutani, A., Yubai, K., & Hirai, J. (2009, November). A direct design from input/output data of the youla parameter for compensating plant perturbation on GIMC structure. In *2009 35th Annual Conference of IEEE Industrial Electronics* (pp. 3047-3052). IEEE.

[6] Mei, T. X., & Goodall, R. M. (2001). Robust control for independently rotating wheelsets on a railway vehicle using practical sensors. *IEEE Transactions on control systems technology*, *9*(4), 599-607.

[7] Liu, Z. D., Bao, Q. L., Xia, Y., & Liu, X. (2013, August). H mix sensitivity controller design based on GIMC for electro-optical stabilization and tracking system. In *International Symposium on Photoelectronic Detection and Imaging 2013: Laser Communication Technologies and Systems* (Vol. 8906, p. 89061Y). International Society for Optics and Photonics.

[8] Campos-Delgado, D. U., & Zhou, K. (2003). Reconfigurable fault-tolerant control using GIMC structure. *IEEE Transactions on Automatic Control*, *48*(5), 832-839.

[9] Niksefat, N., & Sepehri, N. (2001). Designing robust force control of hydraulic actuators despite system and environmental uncertainties. *IEEE Control Systems Magazine*, *21*(2), 66-77.

[10] Doyle, J. (1982, November). Analysis of feedback systems with structured uncertainties. In *IEE Proceedings D-Control Theory and Applications* (Vol. 129, No. 6, pp. 242-250). IET.

[11] Paice, A. D. B., & Moore, J. B. (1990, December). Robust stabilization of nonlinear plants via left coprime factorizations. In *29th IEEE Conference on Decision and Control* (pp. 3379-3384). IEEE.

[12] Niemann, H., & Stoustrup, J. (2002, December). Reliable control using the primary and dual Youla parameterizations. In *Proceedings of the 41st IEEE Conference on Decision and Control, 2002.* (Vol. 4, pp. 4353-4358). IEEE.

[13] Zhou, K., & Ren, Z. (2001). A new controller architecture for high performance, robust, and fault-tolerant control. IEEE Transactions on Automatic control, 46(10), 1613-1618.

[14] SUNG, H. K., & HARA, S. (1988). Properties of sensitivity and complementary sensitivity functions in single-input single-output digital control systems. *International Journal of Control*, *48*(6), 2429-2439.

[15] Aidoud, M., Sedraoui, M., Lachouri, A., & Boualleg, A. (2016). Robustified GPC controller based on H∞ robust control for an hydraulic actuator. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *38*(7), 2181-2188.

[16] Aidoud, M., Sedraoui, M., Lachouri, A., & Boualleg, A. (2018). A robustification of the two degree-of-freedom controller based upon multivariable generalized predictive control law and robust H∞ control for a doubly-fed induction generator. *Transactions of the Institute of Measurement and Control*, *40*(3), 1005-1017.

[17] Tsai M. C., Geddes E. J. M. Postlethwaite I., "Pole-zero cancellations and closed-loop properties of an *H* ∞ mixed sensitivity design problem," *Automatica*, 28(3): 519-530(1992).

[18] Kwakernaak Hilbert, "Robust control and *H* ∞ optimization: tutorial paper," *Automatica*, 28(3): 255-273(1993).