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An Outline And Further Development Of Smith Predictor Based Methods For Compensation Of Processes With Time Delay

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Abstract – **An extensive literature review is presented and a new modified Smith predictor structure is subsequently presented.**
Keywords – **Smith predictor, Dead-time compensator**

I. INTRODUCTION

In the 1950's, O.J. Smith [1] developed the Smith predictor structure to compensate systems with time delay, which are a feature of many industrial processes. The Smith predictor structure utilises a mathematical model of the process in a minor feedback loop. One of its advantages is that the Smith predictor approach for a SISO system may be directly extended to the MIMO system with the same delay.

Since the Smith Predictor structure was proposed, many modifications have been proposed to improve the servo response, the regulator response or both. Modifications were accomplished to adapt the structure to stable, integrative or unstable systems. This paper reviews the modifications to the Smith predictor proposed in the literature, proposes a generalised form of the predictor and presents a new modified Smith predictor structure.

II. EXISTING MODIFIED SMITH PREDICTOR STRUCTURES

a) Stable processes

The modified Smith predictor structures may be classified into three types: Disturbance rejection improvement structures, Two degrees of freedom structures and Other structures. Hang and Wong [2], in their fast disturbance detector structure, interchange the model dead time and the process model, so the detector does not experience the dead time in the closed loop. In Watanabe *et al.*'s [3] structure, a dynamical compensator is included in the main feedback loop. The same structure is used by Romagnoli *et al.* [4-5], but instead of a compensator, the authors use a filter designed to obtain pole-zero cancellation. Palmor and Blau [6] develop tuning rules for this structure. Palmor and Powers [7] elaborate a structure, which improves the regulatory response for measurable disturbances. Ferreira [8] develops two structures to maximise the disturbance rejection if the disturbance consists of few-time-independent frequency components. This "disturbance accommodation controller" employs a disturbance observer with a predictor into the main feedback path, while the "disturbance predictor filter" uses a filter instead of the disturbance observer. In their modification, Huang *et al.* [9] include a compensator between the main feedback loop and the minor feedback loop to approximate the inverse of the dead time at low frequencies in the feed-forward path.

The second type of modified Smith predictor structure for stable systems is the two degrees of freedom structure, which decouples the servo and regulatory problems (i.e. each response has its associated controller, which permits a separate design). To do so, Datsych [10] includes a controller to optimise the regulator response into a feedback path coming back at the input of the process model. This structure, labelled the "disturbance detector structure", was used by Hang and Wong [2] for unstable processes. Gorecki and Jekielek [11-12] modify the Smith predictor structure to obtain a new structure

labelled a “simplifying controller”. In this structure, the process model and the model time delay are fed-back directly to the input without being compared to the output signal. In their structure, labelled the “double controller structure”, Tian and Gao [13-14] feed back the load controller signal before the disturbance input signal. In [15], Tian and Gao implement this structure in a thermoplastic injection-modelling example. This structure is modified by Vrecko *et al.* [16] by adding an extra network including a tuneable delay τ_x . By adding an extra network to the Smith predictor structure modified by Astrom *et al.* [17], Vrancic *et al.* [18] obtain a new structure called the “flexible Smith predictor”. The load controller is tuned to the process model delayed by a time τ_x . In [19], the authors extend the tuning rules for the flexible Smith predictor. In their structure, Zhang *et al.* [20] feedback the load controller signal before the disturbance input signal, and the process model output signal is not fed-back to the input. Debelak and Rutherford [21] develop a structure called “partitioned error control”, which belongs to the family of model-based controllers. Guo and Jutan [22] propose a multi-controller structure, which consists of a set-point controller, two load controllers and a feed-forward controller. Normey-Rico and Camacho [23] add a set-point tracking controller before the main feedback loop. This structure may be used for the control of integrative processes. Sung and Lee [24] propose a complex modified version of the Smith predictor structure, which is suitable for integrative and unstable processes. Majhi and Atherton [25] add a complex network onto the Smith predictor structure, which contains three controllers. This structure may be used to control stable, integrative or unstable processes.

Some modified Smith predictor structures are difficult to classify because their aims may be wider than one objective or their structure does not correspond to a specific form (one-degree or two degrees of freedom). Hang and Wong [2] for example, include a filter in the feedback path to overcome the problem of performance degradation due to the noise. The authors call this structure the “open-loop filter structure”, as a simple first order filter is sufficient to improve the performance. Chiang and Durbin [26] consider the variable gain control of a Smith predictor structure to track changes in the process gain. The authors use a second order lag plus dead time process model. They develop a procedure for model gain control, which employs a reference model. Kantor and Andres [27] include two proportional controllers, one in the forward path and the other in the feedback path of the minor loop. This modified structure permits the elimination of the steady state servomechanism offset, and the regulation errors. A few authors (Durbin [28], Smith [29-30], Kaya [31]) combine the advantage of the Smith predictor structure with the advantage of a cascade structure. Mitchell [32] modifies the Smith predictor structure by adding a scaling filter between the two feedback loops and a predictive element in the main feedback path. The predictive element counteracts the effect of the delay. Deshpande [33-34] includes PID terms and a lead/lag network into the Smith predictor structure. He considers that the disturbance may be modelled by a first order lag plus dead time system. Benouarets and Atherton [35] suggest that a compensator modelling the time delay mismatch may be defined and included in a further feedback path from either the process or model output to the error signal position of the Smith predictor structure. In their modification, Al-Sunni and Al-Nemer [36] combine a Smith predictor structure with fuzzy logic, which is used to auto-tune the PI primary controller when the Smith predictor structure compensates for the dead time. Hang *et al.* [37] develop tuning rules for the Smith predictor structure and they use a second order system plus dead time form for the process and the model transfer functions. Tan *et al.* [38] present an equivalent representation of the Smith predictor structure. The authors explain that this representation shows that the Smith predictor structure contains an inherent phase-compensated element in the feedback loop and that the single loop controller can be viewed as a special mismatched Smith predictor system.

b) Integrative processes

The modified Smith predictor structures may be classified and two types can be identified: dependent structures and two-degrees of freedom structures. First the dependent structures will be discussed. Watanabe and Ito [39] include a constant in the major feedback path and re-design the model transfer function. Normey-Rico and Camacho [40] include a filter at the input of Watanabe and Ito’s [39] structure. Matausek and Micic [41-42] modify the Smith predictor structure by adding a feedback path from the difference of the process output and the model output signals. The primary controller used is a proportional controller. In [42], the authors change the proportional controller into a lead/lag controller. As for stable systems, it is possible to obtain two degrees of freedom structures for integrative systems. Astrom *et al.* [17] construct the major feedback loop between the controller and the disturbance input; a compensator is included in the feedback loop. Zhang and Sun [43] extend Astrom *et al.*’s [17] modified Smith predictor to control a general integrator/time delay process by developing a new transfer function for the load controller. Leonard [44] extends this structure to improve the system performance; the

To eliminate the mismatch term, the controller G_{c2} must be equal to zero. The following expressions may be calculated for G_{c1} and G_{c3} by designing for perfect servo and regulator responses.

$$G_{c1} = -\frac{1}{G_m} \quad (3), \quad G_{c3} = -\frac{1}{G_m e^{-s\tau_m}} \quad (4)$$

If the non-delayed model is represented by equation (5) below, then equations (3) and (4) become equations (6) and (7), respectively.

$$G_m = \frac{K_m}{T_m s + 1} \quad (5)$$

$$G_{c1} = -\frac{T_m s + 1}{K_m} \quad (6) \quad \text{and} \quad G_{c3} = -\frac{T_m s + 1}{K_m e^{-s\tau_m}} \quad (7)$$

The controllers are impossible to implement with real systems, so approximations are used. It was decided to add an integrator to both controllers to allow the steady state servo response to be unity and the steady state regulator response to be zero. The inverse of the delay (equation (7)) cannot be implemented, so the approximation developed by O'Dwyer [49] is used:

$$\frac{1}{e^{-s\tau_m}} = \frac{1 + B(s)}{1 + B(s)e^{-s\tau_m}} \quad (8) \quad \text{with} \quad B(s) = \frac{T_m s + 1}{T_m s + p} \quad (9)$$

Expressions (10) and (11) are the realisable controller forms.

$$G_{c1} = \frac{T_m s + 1}{K_m T_1 s} \quad (10) \quad \text{and} \quad G_{c3} = \frac{T_m s + 1}{K_m T_2 s} * \frac{1 + B(s)}{1 + B(s)e^{-s\tau_m}} \quad (11)$$

The absolute values of the controllers are used in equations (10) and (11) to maintain system stability.

V. SIMULATION

To use the Smith predictor structure, a primary controller must be designed to achieve perfect responses (i.e. $\frac{Y_p}{R} = 1$ and $\frac{Y_p}{L} = 0$). This gives a primary controller of the following form (equation (12)) and its implementable approximation is given by equation (13).

$$G_c = -\frac{T_m s + 1}{K_m (1 - e^{-s\tau_m})} \quad (12) \quad \text{and} \quad G_c = \frac{T_m s + 1}{K_m (s + 1)(1 - e^{-s\tau_m})} \quad (13)$$

The expression for the controller G_{c3} in the modified Smith predictor (equation (11)) becomes equation (14).

$$G_{c3} = \frac{\alpha T_m s + 1}{\alpha K_m T_2 s} * \frac{1 + B(s)}{1 + B(s)e^{-s\tau_m}} \quad (14)$$

Table 1 presents tuning rules developed for each controller and the range of possible values for α and p depending on the index $\frac{\tau_m}{T_m}$.

	G_{c1}	G_{c3}	α	p
$0 < \frac{\tau_m}{T_m} \leq 0.5$	$T_1 = \frac{0.01T_m}{K_m}$	$T_2 = \frac{T_m}{K_m}$	$1 \leq \alpha \leq 1.6$	$p = 10$
$0.5 < \frac{\tau_m}{T_m} \leq 1$	$T_1 = \frac{0.01T_m}{K_m}$	$T_2 = T_m$	$\alpha = 1.4$	$p = 4$
$1 < \frac{\tau_m}{T_m} \leq 2$	$T_1 = \frac{0.01T_m}{K_m}$	$T_2 = \frac{5T_m}{K_m}$	$0.8 \leq \alpha \leq 1.2$	$2 \leq p \leq 5$

Table 1: Tuning rules and the range of values for α and p

The full panorama of simulation results cases covered by seven benchmark processes and their models show that it is possible to achieve both better servo and regulator responses using the modified Smith predictor proposed instead of using the Smith predictor in the vast majority of cases. For example, if system performance is evaluated using the Integral Absolute Error (IAE) index, the servo responses of the modified Smith predictor are better than those of the Smith predictor in 20 of 21 simulations taken. The regulator responses of the modified Smith predictor are better than those of the Smith predictor in all 21 of the simulations taken. Thus, the modified Smith predictor gives more favourable results overall in 41 out of 42 (or 97.62%) of the simulations taken. One representative simulation result for

$0 < \frac{\tau_m}{T_m} \leq 0.5$ is shown in Figure 2. For this simulation, $G_m e^{-s\tau_m} = \frac{1.96}{1 + 4.65s} e^{-1.73s}$ (15),

$G_p e^{-s\tau_p} = \frac{1.2}{1 + 3.1s + 3.1s^2} e^{-0.7s}$ (16), $\alpha = 1$ and $p = 10$.

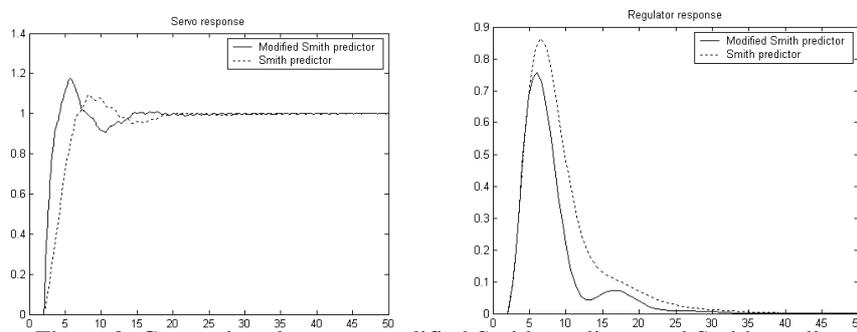


Figure 2: Comparison between modified Smith predictor and Smith predictor

VI. CONCLUSION

After an extensive literature review, a generalised Smith predictor structure is developed. A modified Smith predictor structure is subsequently developed with the aim of achieving excellent servo and regulator responses. From the simulations of our implementation of this structure, it may be concluded that better servo and regulator responses are achieved in the vast majority of cases when the modified Smith predictor is used instead of the corresponding Smith predictor. Further work will concentrate on the development of an autotuning strategy for the modified Smith predictor.

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