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A reference guide to Smith predictor based methods for the compensation of dead-time processes

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Abstract -- **An extensive literature exists on the compensation of time delayed processes. These compensation methods may be broadly divided into parameter optimised controllers, in which the controller parameters are adapted to the controller structure (the most common such controller is the proportional integral derivative, or PID, controller), and structurally optimised controllers, in which the controller structure and parameters are adapted optimally to the structure and parameters of the process model. Important structurally optimised compensator strategies are the Smith predictor and its variations. The purpose of this paper is to extract the essence of the developments in design, tuning and implementation of these controllers. In addition, an original variation on the Smith predictor structure is detailed.**

Keywords - **Time delay, compensation, Smith predictor.**

I INTRODUCTION

A time delay may be defined as the time interval between the start of an event at one point in a system and its resulting action at another point in the system. Delays are also known as transport lags or dead times; they arise in physical, chemical, biological and economic systems, and in measurement and computation. In manufacturing applications, delays typically arise whenever there is physical transport of material, for example, in a pipe or on a conveyer belt; the delay can be determined as the ratio of distance to be traveled to the speed of the material. Delays arise in a wide variety of other manufacturing applications, often in combination with other process dynamics; examples of such applications range from plastic part fabrication to heating, ventilation and air conditioning (HVAC) to industrial sewing machines.

The PID controller has traditionally been used to control processes with and without time delay, with some success; a large number of *tuning rules* (formulae) exist to set up the controller parameters [1]. In process control applications, more than 90%-95% of the controllers are of PID type [2-7]. However, PID controllers are less effective if the time delay term in the process dynamics is dominant. For such applications, the *Smith predictor* can give better performance. Though well known to the academic control engineering community, a recent survey of industrial practice in Scotland [6] has revealed only a single use of the Smith predictor. Hence, the motivation of this paper is to bring the extensive academic work on the Smith predictor to the attention of the wider systems community.

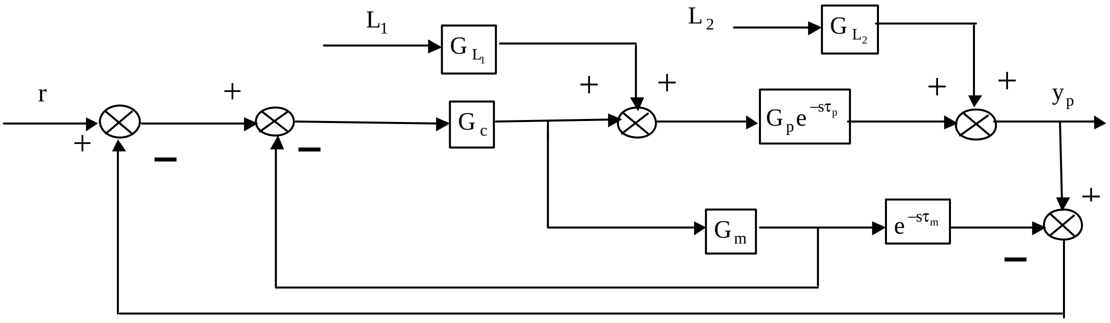
II THE SMITH PREDICTOR

The design of controllers for processes with long time delays has been of interest to academics and practitioners for several decades. In a seminal contribution, Smith [8] proposed a technique that reduces the dominance of the delay term in the closed loop characteristic equation; a 'primary' controller may then be designed for the non-dominant delay process. This method, called the Smith predictor, has been the subject of numerous experimental and theoretical studies. A block diagram of the Smith predictor is provided in Figure 1.

The applicability of the Smith predictor, especially compared to the PID controller, has been examined [9-23]; Seborg *et al.* [9], for instance, quote studies stating that the Smith predictor performance for servo applications is up to 30% better than the use of an appropriately tuned PID controller.

The Smith predictor is the optimal controller for a delayed process for servo applications, or for a step disturbance, if the optimal controller is designed using a constrained minimum output variance control law. If the disturbance is not of step form, then the optimal controller may be specified for regulator applications by the inclusion of an appropriate dynamic element in the feedback path of the Smith predictor structure [24-36]. The Smith predictor may also be related to other delay compensator strategies [37-45].

Figure 1: Block diagram of the Smith predictor structure



The Smith predictor has been investigated in many simulation and implementation studies [46-56]; Singh and McEwan [47], for instance, consider the implementation of the predictor, realised in continuous time, in a laboratory case study. Modifications of the Smith predictor, such as the predictive PI controller proposed by Hagglund [57], have also been discussed [2, 58-72]. Other contributions are also of interest [73-78].

In real applications, it is inevitable that the model will not be a perfect representation of the process, perhaps because the process and model are of different structure or because the process parameters change in an unknown way with operating conditions. The presence of such mismatch means that perfect delay compensation using the Smith predictor is not possible. In these circumstances, the model parameters in the Smith predictor could be adaptively updated as the process parameters vary [17, 53, 79-90]. The difficulty with many adaptive approaches is that the closed loop system may be unstable as a result of the mismatch, before the model parameters are updated to the process parameters. The conditions for stability in the presence of mismatch may be calculated using numerical techniques in both the time and frequency domains, though knowledge of the process parameters is required. An alternative is to specify robust stability and performance requirements for the Smith predictor implementation in the presence of mismatch [17, 34, 38, 91-107]; the internal model control (IMC) strategy is sometimes used in the analysis. Laughlin *et al.* [93], for instance, define a single multiplicative perturbation to represent the uncertainty in several process parameters; the authors subsequently derive analytical conditions for robust stability and robust performance of the Smith predictor, with the IMC procedure being used to formulate the primary controller. Other applications of the IMC strategy have also been recorded [9, 108-110]. Interestingly, some authors consider creating a deliberate mismatch between the process and model parameters to improve stability or performance [111-118].

The Smith predictor is designed with servo applications in mind. Modifications of the Smith predictor have been discussed to improve the regulator properties of the compensated system and/or the performance of the compensated system in the presence of measurement noise and process parameter variations [17, 25, 31, 32, 64, 80, 95, 114, 119-151]. Some authors, for example, suggest that improved responses may be obtained if appropriate dynamic terms are included in either the outer feedback loop or the inner feedback loop (e.g. [25, 31, 80, 114, 123, 126, 131, 139]).

Smith predictors are often implemented in discrete time, as it is more straightforward to implement a delay in this domain than in the continuous time domain (at least if the delay is an integer multiple of the sample period). Analytical procedures to investigate the robustness of the predictor, operating under process-model mismatch conditions in discrete time, have been developed [152, 153]. It is common to estimate the model parameters before designing the primary controller; the delay may be estimated explicitly or the model may be overparameterised, without an explicit estimation of the delay [154-161]. Modifications of the Smith predictor have also been considered [42, 162-179]. A closely related structure is the analytical predictor [9, 59, 125, 180-183] and generalised analytical predictor [9, 125, 184-186], which includes a disturbance filter in the feedback path; these algorithms combine good regulation behaviour with delay compensation. The IMC methodology may also be implemented in the discrete time domain [9, 108, 187-191]. More recently, generalised predictive controllers have been defined using the Smith predictor structure [192-194].

Generalised continuous time and discrete time Smith predictors have been proposed to control delayed MIMO processes [26, 30, 123, 195-210]. The robustness of these predictors is also discussed [211-214]; Feng [214], for example, derives a sufficient condition for compensator stability. Compensation of delayed MIMO processes, using the IMC approach, is also described [92, 215-220].

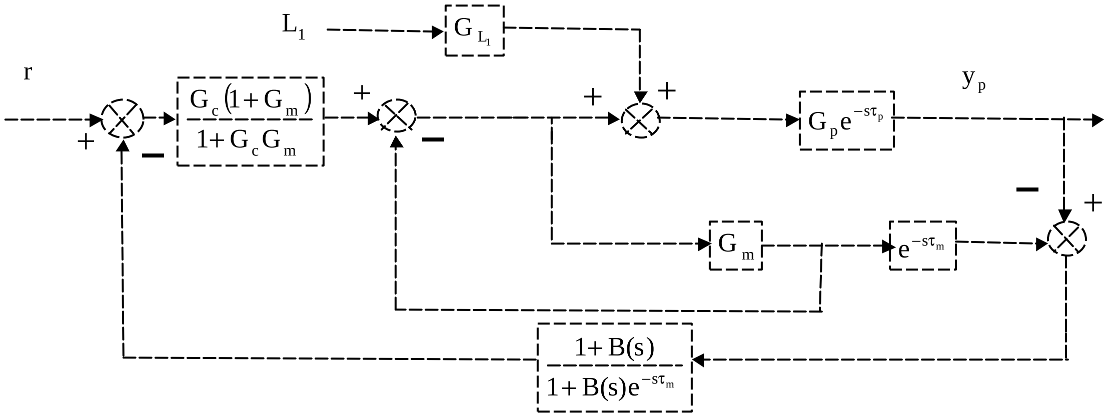
It is not possible to compensate unstable delayed processes with a Smith predictor, as the poles of the compensated closed loop system always contain those of the unstable process [221]. A modified Smith predictor for the control of an unstable delayed process with one unstable pole has been detailed [222]. Other such compensation strategies for unstable SISO delayed processes are also proposed [120, 150, 223-225].

III MODIFIED SMITH PREDICTOR DESIGN

A new modified Smith predictor which facilitates a servo response similar to that of the Smith predictor, with a modestly improved regulator response, is detailed. The block diagram of the modified Smith predictor is shown in Figure 2, assuming a disturbance input on L_1 only. The dynamic term in the outer feedback loop is an approximation for the unrealizable time advance term, $e^{s\tau_m}$, which would significantly improve the regulator response. The term $B(s) = (as+1)/(as+p)$, p > 1; a is chosen as the time constant of a FOLPD plant model, with p chosen iteratively.

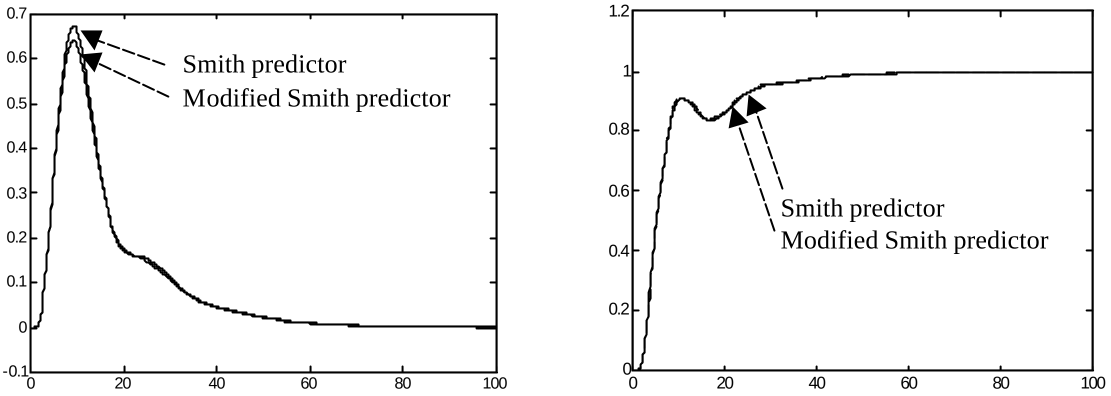
A number of simulation results, carried out in SIMULINK, showing the operation of the method are provided below. Nominal $G_p e^{-s\tau_p} = 2e^{-s}/1 + 8.5s + 22.5s^2 + 18s^3$. $G_m e^{-s\tau_m}$ is specified using the identification method described by O'Dwyer and Ringwood [226] i.e. $G_m e^{-s\tau_m} = 1.82e^{-3.47s}/(1+7.68s)$. The process parameter values are allowed to vary between upper and lower limits; a ±30% variation in process time delay is allowed, with a similar variation in the other non-gain process parameters; a ±40% variation in the gain is permitted. Following the procedure outlined, $B(s) = (7.68s+1)/(7.68s+20)$. G_c is specified assuming a servo time constant of 2.0s, when the process and model parameters coincide i.e. $G_c = 2.11(1+1/7.68s)$.

Figure 2: Block diagram of the modified Smith predictor structure

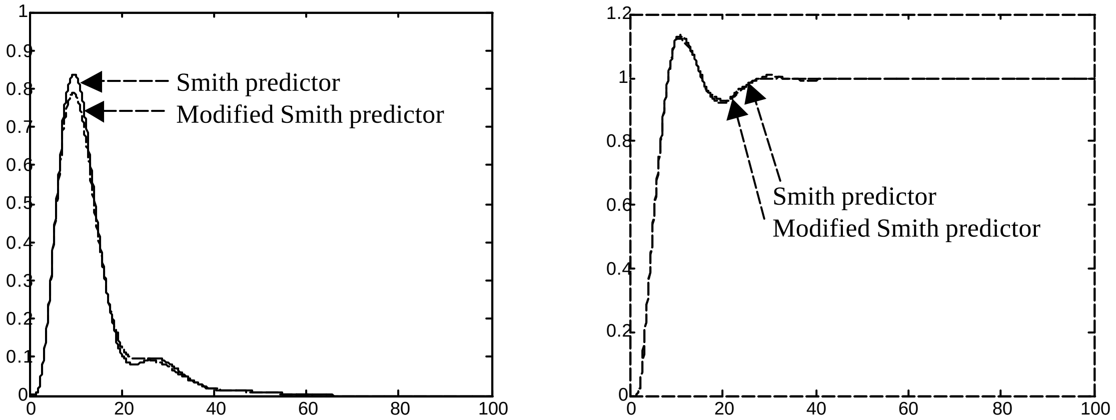


Regulator response Servo response

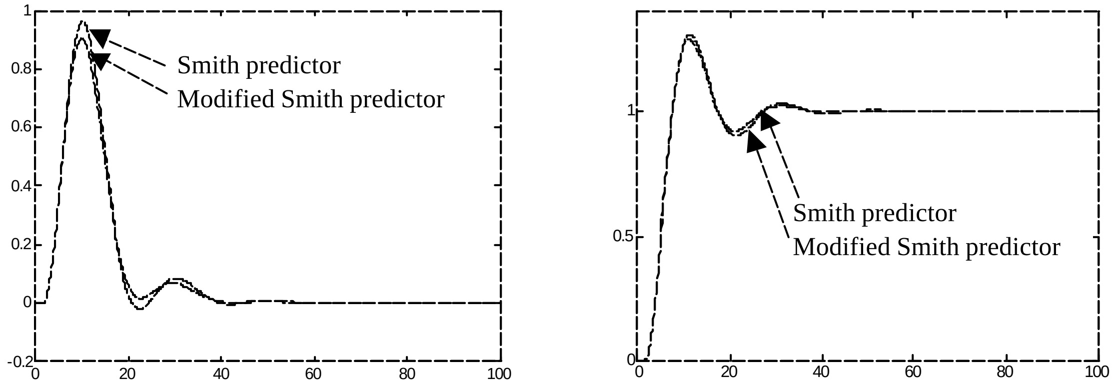
(a) $G_p e^{-s\tau_p} = 1.2e^{-0.7s}/1 + 5.9s + 15.7s^2 + 12.6s^3$, $G_m e^{-s\tau_m} = 1.82e^{-3.47s}/(1+7.68s)$



(b) $G_p e^{-s\tau_p} = 2e^{-s} \big/ 1 + 8.5s + 22.5s^2 + 18s^3$, $G_m e^{-s\tau_m} = 1.82e^{-3.47s} \big/ (1 + 7.68s)$



(c) $G_p e^{-s\tau_p} = 2.8e^{-1.3s} \big/ 1 + 11s + 29.3s^2 + 23.4s^3$, $G_m e^{-s\tau_m} = 1.82e^{-3.47s} \big/ (1 + 7.68s)$



The results show that the modified Smith predictor facilitates a modest improvement in regulator responses, with similar servo responses, compared to the Smith predictor, if the desired servo response is relatively slow.

IV CONCLUSIONS

Dead time compensators are appropriate for the control of dominant delay processes. The survey reveals the high level of interest in the use of the Smith predictor and its variations, at least in the academic research community. In general, there is a lack of comparative analysis regarding the performance and robustness of closed loop systems compensated by these dead time controllers. Comparative analysis of these compensators with PID compensators is also sparse, though it has been stated that dead time compensators of the type discussed facilitate, in general, less robust results than PID controllers, and are particularly sensitive to variations in process gain and delay, which are the process parameters most likely to change [59]. In addition, there are few tuning rules defined to allow straightforward determination of the compensator parameters (in contrast to the large number of tuning rules available for the determination of PID controller parameters). Future work should concentrate on the development of dead time compensator tuning rules and a critical analysis of existing dead-time compensator strategies.

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