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## **A classification of techniques for the compensation of time delayed processes. Part 2. Structurally optimised controllers.**

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*Abstract*:- Following on from Part 1, Part 2 of the paper considers the use of structurally optimised controllers to compensate time delayed processes.

*Keywords*:- Time delay, compensation, PID, dead-time compensators.

### **1 Introduction**

Structurally optimised controllers are those in which the controller structure and parameters are adapted optimally to the structure and parameters of the process model [1, 2]. A classification of such controllers for time delay processes is provided.

### **2 The Smith predictor**

The Smith predictor [280] involves effectively removing the delay from the control loop; a 'primary' controller may then be designed for the delay free portion of the process. The applicability of the Smith predictor, especially compared to the PI/PID controller, has been discussed [20, 281-288]; Seborg *et al.* [20], for instance, quote studies stating that the Smith predictor performance for servo applications is up to 30% better than the use of a PID controller, tuned by minimising an integral squared error (ISE) criterion.

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 [289-299]. The Smith predictor may also be related to other delay compensator strategies [14, 182, 300-304].

The Smith predictor has been investigated in many simulation and implementation studies [133, 305-309]; Singh and McEwan [305], for instance, consider the implementation of the predictor, realised in continuous time, in a laboratory case study. A modification of the Smith predictor, labelled the predictive PI controller by Hagglund [310], has also been discussed [16, 59, 310-317]. Other contributions are also of interest [318-322].

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 [288, 323-334]. 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. Therefore, a

fundamental requirement is that the Smith predictor should be stable in the presence of mismatch; the performance of the resulting compensated system is also of interest. 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 [13, 136, 182, 288, 297, 335-345]; the internal model control (IMC) strategy is sometimes used in the analysis. Laughlin *et al.* [337], 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. The IMC procedure is used to formulate the primary controller. Other applications of the IMC strategy have also been recorded [20, 346-349]. Interestingly, some authors consider creating a deliberate mismatch between the process and model parameters to improve stability or performance [350-354].

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 [11, 68, 136, 288, 295, 313, 324, 355-375]; Watanabe and Ito [295], for example, modify the Smith predictor by including a lead-lag compensator in the feedback path of the major loop to improve the regulator properties of the compensated system.

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 [376, 377]. It is common to estimate the model parameters before designing the primary compensator; the delay may be estimated explicitly or the model may be overparameterised, without an explicit estimation of the delay [378-385]. Modifications of the Smith predictor have also been considered [302, 386-402]. A closely related structure is the analytical predictor [18, 20, 59, 80, 282, 360, 403, 404] and generalised analytical predictor [20, 360, 405, 406], which

include 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 [20, 348, 407-411].

Generalised continuous time and discrete time Smith predictors have been proposed to control delayed MIMO processes [290, 294, 412-424]. The robustness of these predictors is also discussed [425-428]; Feng [428], for example, derives a sufficient condition for compensator stability. Compensation of delayed MIMO processes, using the IMC approach, is also described [125, 336, 429-431].

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 [432]. A modified Smith predictor for the control of an unstable delayed process with one unstable pole has been detailed [433]. Other such compensation strategies for unstable SISO delayed processes are also proposed [355, 434, 435].

### 3 Direct synthesis methods

Typically, in the continuous time application of direct synthesis methods, the desired closed loop transfer function must include a delay greater than the process delay. The resulting controller has a delay compensator structure [20]. Other direct synthesis methods are also proposed, for delayed SISO [238, 436-440] and delayed MIMO [441-443] applications.

Sampled data controllers may also be designed; Dahlin [444], for instance, derives a controller by assuming that the desired closed loop transfer function is the discrete equivalent of a continuous first order lag plus delay (FOLPD) model. The desired time constant may be adjusted to give more sluggish control if the process parameters are not known accurately. This approach and its variations have been discussed elsewhere [12, 20, 59, 205, 296, 297, 304, 407, 445-453]. A pole placement design approach may also be used, when the process is in delayed SISO or MIMO form [1, 2, 17, 42, 284, 454-465]; the compensator may be designed by including the delay in an overparameterised process model [12, 381, 466-472], though the order of the resulting polynomial increases as the delay increases, making the method unattractive for the design of compensators for processes with large delays [12]. Alternatively, the compensator for stable delay

processes [473-475] and unstable delay processes [473] may be designed by approximating the delay by a rational polynomial. State-space design approaches have also been considered [1, 476-478]. Other pole placement controllers to compensate delayed MIMO processes have been developed [479, 480]. Adaptive pole placement controllers have been discussed for the compensation of delayed SISO processes in continuous time [481] and particularly in discrete time [482-487]. The design of such a controller for a delayed MIMO process is also described [488].

An alternative direct synthesis method is the finite spectrum assignment approach, which involves designing a feedback law based on pole assignment in either the time or frequency domains. The method may be used to compensate stable delayed processes [432, 489-501] and unstable delayed processes [432, 491, 493, 501, 502].

The advantages of the direct synthesis controller are that it may be detuned to avoid excessive control action, it provides delay compensation and it facilitates the control of processes with variable delay [12].

## 4 Optimal controller design methods

The controller is synthesised to minimise a criterion such as the variance of the controlled variable (minimum variance strategy) or the expected value of the square of the controlled variable plus a multiple times the square of the control signal (the linear quadratic strategy). The compensation of delayed SISO processes [136, 293, 326, 503-512] and delayed MIMO processes [326] in continuous time has been discussed. It is more common to consider delay compensator designs in discrete time; input-output model design approaches to compensate delayed SISO processes [2, 12, 14, 42, 292, 299, 378, 456, 484, 513-529] and delayed MIMO processes [416, 530-541] have been discussed. Alternatively, a state-space design approach may be used to specify the delay compensator in the SISO environment [542-545] or MIMO environment [414, 546-548]. Other optimisation strategies, such as the time optimal controller design approach, are also of interest [326, 549-558].

The minimum variance controller may be interpreted as a Smith predictor with a PI or PID primary controller, when the process is in FOLPD form or second order system plus delay (SOSPD) form, respectively [559]; it may also be interpreted

as a Dahlin direct synthesis controller for a general process model with delay [297, 452, 559]. Generally speaking, however, a minimum variance controller is not suitable for the control of delayed processes, because the delay is likely to be a non-integer multiple of the sample period, which may result in the process model being in non-minimum phase form. The resulting closed loop system may be destabilised, as the implementation of the compensator involves the inversion of the model numerator polynomial. Therefore, if stable compensation is to be achieved, the delay used in the minimum variance controller design must be larger than the actual process delay, which results in a non-optimal controller. In a similar manner, varying delays also cause problems for the design of a minimum variance controller [12, 456].

## 5 Predictive controllers

Predictive controllers calculate a future controller output sequence so that the predicted process output is close to the desired output. The controller is designed by minimising a cost function, with appropriate constraints. One such controller is the unified predictive controller [303]; the controller action involves calculating the future set point sequence at any sampling instant, predicting the controlled variable, minimising the cost function to provide the suggested control sequence, implementing the first element of the control sequence and then repeating the calculations. Good tutorial introductions exist to predictive control strategies, together with their industrial applications [560-562].

The generalised predictive control (GPC) algorithm is a special case of the unified predictive control algorithm and has attracted a lot of interest for the design of delay compensators [13, 42, 449, 451, 452, 484, 562-571]; Camacho and Bourdons [566], for instance, provide simple formulae to calculate the tuning parameters of the GPC controller, when the process is modelled in FOLPD form. Other predictive controller strategies have also been discussed [572-592].

## 6 Other compensation strategies

Feedforward-feedback control may be used to compensate a delayed SISO process; typically the feedforward element is specified after the feedback controller is designed [2, 19, 182, 311, 359, 384, 406, 509, 593-597]. A disadvantage

of feedforward control is that accurate knowledge of the process is required, though this may be overcome by using an adaptive feedforward-feedback controller implementation, in which the model parameters are continuously updated [2]. Feedforward-feedback controllers may also be used to compensated delayed MIMO processes [535, 536, 591].

Other strategies compensate delayed processes in a robust manner; Chou *et al.* [598], for example, design a feedback controller to robustly stabilise an uncertain, saturating delay process. Other robust methods have also been described [599-611]. Other authors consider fuzzy logic techniques [612, 613], neural network methods [614-617], variable structure controllers [618, 619], sliding mode controllers [620-623] or expert system approaches [624].

## 7 Conclusions

PI/PID controllers are appropriate for the compensation of non-dominant delay processes, with structurally optimised controllers being appropriate for the compensation of dominant delay processes. Overall, the Smith predictor is the optimal (or a component of the optimal) controller for dominant delay processes. An alternative perspective is that the Smith predictor may be used to reduce the dominance of the delay term, and thus facilitate the conversion of the compensation problem to the control of a non-dominant delay process. However, model based delay controllers are, in general, less robust than PID controllers, and are particularly sensitive to variations in process gain and delay, which are the process parameters most likely to change [59]. The use of predictive controller strategies appear to be the compensation methods that are attracting increasing attention from the applications community; for instance, a review paper [560] reports hundreds of such applications in real installation examples. This is significant, in view of the well known and often well founded reluctance of applications engineers to implement controllers other than the PID controller.

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