Identification and Self-tuning Control of Time-delay Systems

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Abstract: - Time-delays (dead times) occur in many processes in industry. A Toolbox in the MATLAB/SIMULINK environment was designed for identification and self-tuning control of such processes. The control algorithms are based on modifications of the Smith Predictor (SP). The designed algorithms that are included in the toolbox are suitable not only for simulation purposes but also for implementation in real time conditions. Verification of the designed Toolbox is demonstrated on a self-tuning control of a laboratory heat exchanger in simulation conditions.

Key-Words: - Time-delay; Smith predictor; Process identification; ARX model; Self-tuning control; PID control; Pole assignment; Time-delay Toolbox; Heat exchanger

1 Introduction

The majority of processes in the industrial practice have stochastic characteristics and eventually they exhibit nonlinear behaviour. Traditional controllers with fixed parameters are often unsuitable for such processes because parameters of the process change. One possible alternative for improving the quality of control of such processes is application of adaptive control systems. Different approaches were proposed and utilized. One of the successful approaches is self-tuning control (STC) [1] – [5].

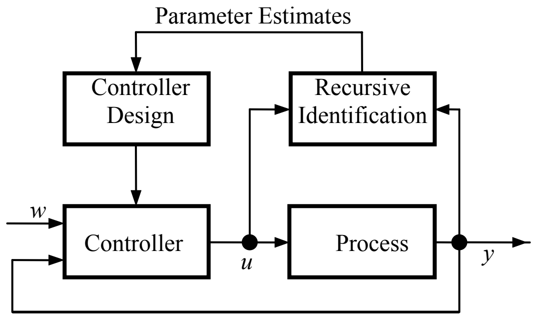

Fig. 1. Self-tuning control system

The block diagram of an STC is shown in Fig. 1, where *y*, *u* and *w* are the process output, the control signal and the reference signal. The main idea of the STC is based on combination of a recursive identification procedure and a particular controller synthesis. The self-tuning strategy was applied for design of control of time-delay systems.

Time-delays appear in many processes in industry and other fields, including economical and biological areas. They are caused by some of the following phenomena [6]:

- the time needed to transport mass, energy or information,
- the accumulation of time lags in a great numbers of low order systems connected in series,
- the required processing time for sensors, such as analyzers; controllers that need some time to implement a complicated control algorithms or processes.

Consider a continuous time dynamical linear SISO (single input $u(t)$ – single output $y(t)$) system with time-delay T_d. The transfer function of a pure transportation lag is $e^{-T_d s}$ where s is complex variable. Overall transfer function with time-delay is in the form

$$G_d(s) = G(s)e^{-T_d s} \qquad (1)$$

where $G(s)$ is the transfer function without time-delay. Processes with significant time-delay are difficult to control using standard feedback controllers. When a high performance of the control process is desired or the relative time-delay is very large, a predictive control strategy must be used. The predictive control strategy includes a model of the process in the structure of the controller. The first time-delay compensation algorithm was proposed by Smith 1957 [7]. This control algorithm known as the Smith Predictor (SP) contained a dynamic model of the time-delay process and it can be considered as the first model predictive algorithm.

Although time-delay compensators appeared in the mid 1950s, their implementation with analog

$$
\begin{aligned}
d_1 &= -(2\gamma + \alpha + \beta) \\
d_2 &= 2\gamma(\alpha + \beta) + \alpha\beta + \gamma^2 \\
d_3 &= -(2\alpha\beta\gamma + \gamma^2(\alpha + \beta)) \\
d_4 &= \alpha\beta\gamma^2
\end{aligned} \tag{33}
$$

Pole assignment with user-defined different real poles (PADP) method:
Polynomial (24) has two different real poles *α*, *β* and user-defined real poles *γ*, *δ*. Then polynomial (24) has the form

$$D(z) = (z-\alpha)(z-\beta)(z-\gamma)(z-\delta)$$

and it is possible to express its individual parameters as:

$$
\begin{aligned}
d_1 &= -(\alpha + \beta + \gamma + \delta) \\
d_2 &= \alpha\beta + \gamma\delta + (\alpha + \beta)(\gamma + \delta) \\
d_3 &= -\left[(\alpha + \beta)\gamma\delta + (\gamma + \delta)\alpha\beta\right] \\
d_4 &= \alpha\beta\gamma\delta
\end{aligned} \tag{34}
$$

5 Toolbox Functions

The Toolbox [11] contains three main scripts (**start_PAMP.m, start_PADP.m** and **start_PID.m**) and other programs functions, models and scripts) that are called by these main scripts. These scripts perform similar sequence of operations:

- definition of the controlled system (transfer function, time delay), sample time and controller parameters,
- off-line identification of the controlled system,
- pole assignment control or PID control of the system.

Toolbox files are summarized in Table 1. The detailed instructions for use of the Toolbox are introduced in the User's Guide [12].

A typical control scheme used is depicted in Fig. 5. This scheme is used for systems with time-delay of two sample steps. Individual blocks of the SIMULINK scheme correspond to blocks of the general control scheme presented in Fig. 1. The green blocks represent the controlled system. Constants bc0, ac2, ac1, and ac0 are parameters of a continuous-time system. Blocks Compensator 1 and Compensator 2 are parts of the Smith Predictor and they correspond to $G_m(z^{-1})$ and $G_d(z^{-1})$ blocks of Fig. 2 respectively. The control algorithm is encapsulated in Main Pole Assignment Controller which corresponds to $G_c(z^{-1})$ Fig. 2 block. The Identification block performs the on-line identification of a controlled system and outputs the estimates of the 2nd order ARX model (a1, b1, a2, b2) parameters.

Table 1. Toolbox Files

File	Description
start_PAMP.m	top-level script for pole assignment control (multiple pole γ)
start_PADP.m	top-level script for pole assignment control (poles γ,δ)
start_PID.m	top-level script for PID control
LSM_2or2td.m	off-line identification
Sm_adapt_pp2i.m	computation of control value in pole assignment control scheme SmP_ad_PA.mdl.
sid.m	on-line identification s-function used by both control schemes (SmP_ad_PA.mdl and SmP_ad_PID.mdl)
Ident_c_LSM.mdl	Simulink scheme used to collect data for off-line identification
SmP_ad_PA.mdl	Simulink control scheme of pole assignment control
SmP_ad_PID.mdl	Simulink control scheme of PID control

6 Experimental results

The experimental identification methods and use of the Time-delay Toolbox is demonstrated on a control of laboratory heat exchanger in simulation conditions. The laboratory heat exchanger [26], [27], {28] is based on the principle of transferring heat from a source through a piping system using a heat transferring media to a heat-consuming appliance. A scheme of the laboratory heat exchanger is depicted in Fig. 6.

The heat transferring fluid (e. g. water) is transported using a continuously controllable DC pump (6) into a flow heater (1) with max. power of 750 W. The temperature of a fluid at the heater output T_1 is measured by a platinum thermometer. Warmed liquid then goes through a 15 meters long insulated coiled pipeline (2) which causes the significant delay in the system. The air-water heat exchanger (3) with two cooling fans (4, 5) represents a heat-consuming appliance. The speed of the first fan can be continuously adjusted, whereas the second one is of on/off type. Input and