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The R-S-T digital controller design and applications

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Abstract

The two-degrees-of-freedom R-S-T digital controller is becoming a standard for computer control in industry. This paper presents a methodology for the design of the R-S-T controller, which involves identification of the plant model from data, combined with a robust control design. The performance of the controller can be further enhanced by plant model identification in a closed loop, and re-tuning of the controller. For large parameter variations, adaptation has to be considered in order to maintain the performance. Software packages are available for the design, implementation and commissioning of the R-S-T digital controllers. The methodology is illustrated by its application to the control of deposited zinc in hot-dip galvanizing at SOLLAC (Florange, France). © *1998 Elsevier Science Ltd. All rights reserved.*

Keywords: System identification; digital control; robust control; adaptation; software tools

1. Introduction

A "good" control system has in general an important economic impact in industry. Fig. 1 illustrates the histogram of a controlled variable for "poor" control and for "good" control, respectively.

If the variance of the controlled variable is high, a significant number of the measurements will lie far from the desired value. In a large number of applications, a minimal acceptable value is imposed (e.g., the humidity of the paper, the depth of the coating, etc.) and poor quality of the control will require the choice of a higher value for the reference. As a consequence, more energy or material will be needed, and the direct consequence is an increase in production costs.

If one has a "good" controller, which significantly reduces the variance of the controlled variable around the reference value, this will on the one hand improve the quality and, on the other hand, will allow a reduction of the reference value. This leads in general to energy and material savings which correspond to a reduction in production costs.

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Therefore, the impact of "good" control is:

(1) Improvement in the quality of the products.
(2) Energy and material savings.

However, it is important that the investment return gained by improvements in control can be clearly evaluated, in order to justify the investment.

The question is: How does one improve the investment return for high-performance control systems?

The answers to this question are:

(1) Reduction in the design cost.
(2) Reduction in the implementation cost (including commissioning).
(3) Achievement of the desired performance.

Therefore, it is necessary to develop an efficient design and implementation methodology. This development has to be considered in the context of computer control, which is now widespread in industry. All the advantages and features of using computers for control have to be taken into account. Among these aspects, those of system identification and the introduction of a standard form for a digital controller (the R-S-T controller) play a crucial role.

Fig. 2 summarizes the basic principles of control system design. In order to design and to tune a good

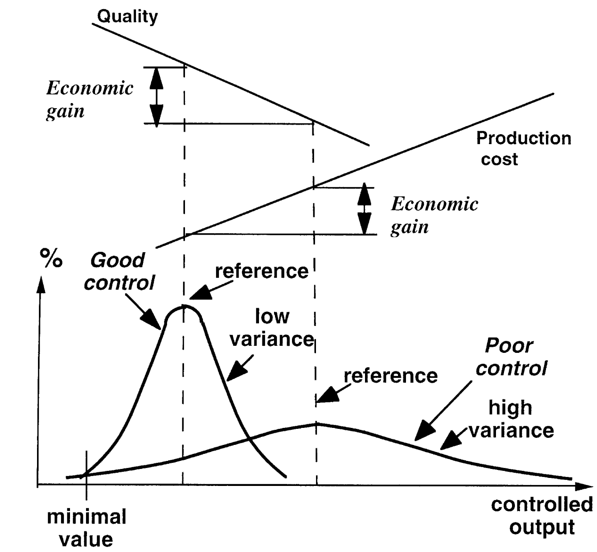

Fig. 1. Histograms for good and poor control.

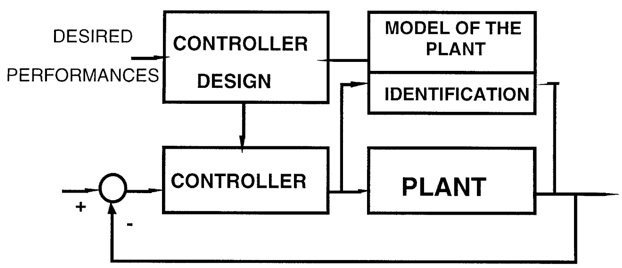

Fig. 2. Principle of controller design.

controller one needs:

(1) To specify the desired control-loop performances.
(2) To have a dynamic model of the plant to be controlled (this can be obtained from real data by identification).
(3) To possess a suitable controller design methodology, compatible with the desired performance and the corresponding plant model.
(4) To have a procedure for controller validation and on-site re-tuning.
(5) To have appropriate software packages with real-time capabilities for data acquisition, system identification, control design and on-site commissioning.

This paper will present such a methodology for the design and application of R-S-T digital controllers. The methodology will be illustrated by its application to the control of the deposited zinc in hot-dip galvanizing at SOLLAC (Florange, France).

2. Identification of discrete-time models for industrial processes

Fig. 3 illustrates an appropriate setting for a computer control system. The set D.A.C. + plant + A.D.C. is interpreted as a discretized system, whose control input is the sequence $\{u(t)\}$ generated by the computer, the output being the sequence $\{y(t)\}$ resulting from the A/D conversion of the system output $y(\tau)$. The discretized plant is characterized by a discrete-time model, which should be identified.

Note that the sampling frequency is selected in accordance with the bandwidth of the continuous-time plant, and more specifically in accordance with the desired bandwidth of the closed loop. The basic rule is:

$$f_s = (6 \text{ to } 25)\, f_B^{Cl}$$

where f_s is the sampling frequency and f_B^{Cl} is the desired bandwidth of the closed loop.

The discrete-time model of the plant to be controlled is described in the time-domain by:

$$y(t) = -\sum_{i=1}^{n_A} a_i\, y(t-i) + \sum_{i=1}^{n_B} b_i\, u(t-d-i)$$

where d is the integer number of sampling periods contained in the time-delay of the plant, t is the normalized discrete time (0, 1, 2, 3,…) and corresponds to the discrete time divided by the sampling periods T_s. The discrete-time model of the plant to be controlled can alternatively be represented by its pulse transfer operator $H(q^{-1})$:

$$y(t) = H(q^{-1})\, u(t).$$

$H(q^{-1})$ is defined by:

$$G(q^{-1}) = \frac{q^{-d} B(q^{-1})}{A(q^{-1})} = \frac{q^{-d-1} B^*(q^{-1})}{A(q^{-1})}$$

where q^{-1} is the backward shift operator ($q^{-1} y(t) = y(t-1)$) and

$$A(q^{-1}) = 1 + a_1 q^{-1} + \dots a_{n_A} q^{-n_A}$$

$$B(q^{-1}) = b_1 q^{-1} + \dots b_{n_B} q^{-n_B} = q^{-1} B^*(q^{-1}).$$

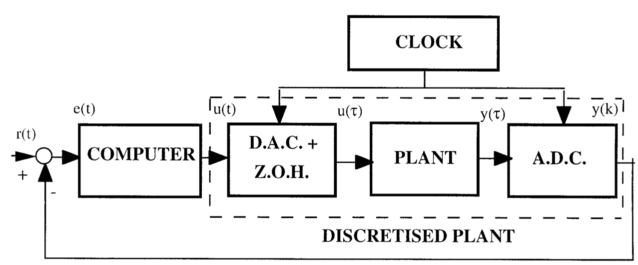

Fig. 3. Computer control system. D.A.C.: Digital-to-Analog Converter, Z.O.H.: Zero-Order Hold, A.D.C.: Analog-to-Digital Converter.

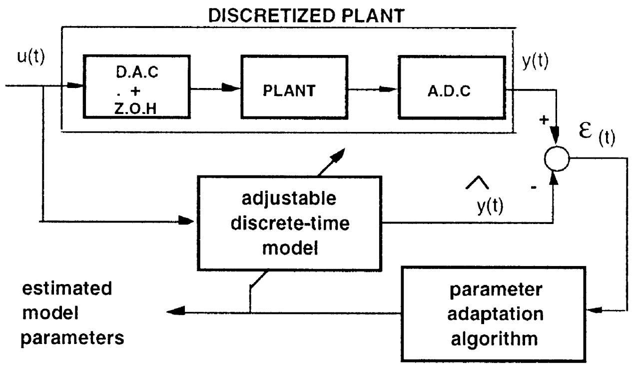

Fig. 4. Parameter estimation of discrete-time models.

For models with constant parameters, replacing q by z (the complex variable) in the expression of the pulse transfer operator gives the pulse transfer function.

The principle of the identification of discrete-time models is illustrated in Fig. 4.

A discrete-time model with adjustable parameters is implemented on the computer. The error between the system output at instant t, $y(t)$, and the output predicted by the model, $\hat{y}(t)$, (known as the prediction error) is used by a parameter-adaptation algorithm which, at each sampling instant, will modify the model parameters in order to minimize this error. The input is in general a very low-level pseudo-random binary sequence, generated by the computer (sequence of rectangular pulses with randomly variable duration). Once the model has been obtained, an objective validation can be made by carrying out statistical tests on the prediction error $\varepsilon(t)$ and the predicted output $\hat{y}(t)$. The validation test enables the best algorithm to be obtained for the estimation of the parameters.

This approach provides much more accurate models than the methods based on step response or frequency response. In addition, it requires an input signal of much lower magnitude than those used for step or frequency response.

The identification methodology includes four steps:

(1) Input-output data acquisition around an operating point, using as input in general a centered pseudo-random binary sequence (PRBS) of small magnitude,
(2) Estimation (choice) of the model complexity (structure),
(3) Estimation of the model parameters,
(4) Validation of the identified model (structure and values of the parameters).

One of the important facts to be emphasized is that the plant measurements are generally noisy. Unfortunately, no unique parameter-estimation method exists which may be used successfully for all the types of disturbances, such that the estimated parameters are always unbiased.

Therefore, a good identification of a plant model generally requires the use of an interactive system featuring various parameter-estimation methods and the corresponding validation techniques.

For a more detailed discussion see (Landau, 1990; Ljung, 1987).

3. The R-S-T digital controller

The canonical structure of the R-S-T digital controller is represented in Fig. 5.

This structure has two degrees of freedom, i.e., the digital filters R and S are designed in order to achieve the desired regulation performance, and the digital filter T is designed afterwards in order to achieve the desired tracking performance. This structure allows achievement of different levels of performance in tracking and regulation.

The case of a controller operating on the regulation error (which does not allow the independent specification of tracking and regulation performance) corresponds to $T = R$. Digital PID can also be represented in this form, leading to particular choices of R, S and T.

The equation of the R-S-T canonical controller is given by:

$$S(q^{-1})\,u(t) + R(q^{-1})\,y(t) = T(q^{-1})\,y^*(t+d+1)$$

where $u(t)$ and $y(t)$ are the input and output of the plant and $y^*(t+d+1)$ is the desired tracking trajectory, which is either generated by a tracking reference model (Bm/Am) or stored in the computer memory.

The polynomials $R(q^{-1})$, $S(q^{-1})$, $T(q^{-1})$ have the form:

$$R(q^{-1}) = r_0 + r_1\,q^{-1} \ldots + r_{n_R} q^{-n_R}$$

$$S(q^{-1}) = s_0 + s_1\,q^{-1} \ldots + s_{n_S} q^{-n_S} \quad (\text{often } s_0 = 1)$$

$$T(q^{-1}) = t_0 + t_1\,q^{-1} \ldots t_{n_T} q^{-n_T}.$$

The corresponding time-domain expression of the control law is given by ($s_0 = 1$):

$$u(t) = -\sum_{i=1}^{n_S} s_i\,u(t-i) - \sum_{i=0}^{n_R} r_i\,y(t-i) + \sum_{i=0}^{n_T} t_i\,y^*(t+d+1-i).$$

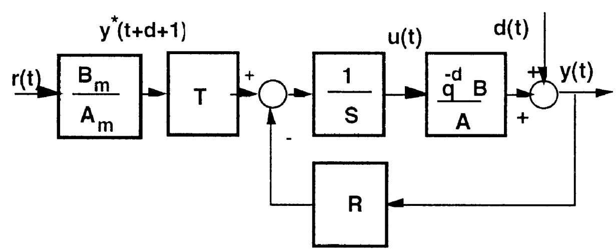

Fig. 5. The R-S-T canonical structure of a digital controller.

The closed-loop control transfer operator (between $r(t)$ and $y(t)$) is given by:

$$H_{\mathrm{CL}}(q^{-1}) = \frac{q^{-d}\,T(q^{-1})\,B(q^{-1})}{A(q^{-1})\,S(q^{-1}) + q^{-d}\,B(q^{-1})\,R(q^{-1})} = \frac{q^{-d}\,T(q^{-1})\,B(q^{-1})}{P(q^{-1})},$$

and the behaviour with respect to an output disturbance is given by the output sensivity function:

$$S_{yp}(q^{-1}) = \frac{A(q^{-1})\,S(q^{-1})}{A(q^{-1})\,S(q^{-1}) + q^{-d}\,B(q^{-1})\,R(q^{-1})} = \frac{A(q^{-1})\,S(q^{-1})}{P(q^{-1})}$$

where $P(q^{-1})$ defines the desired closed-loop poles (regulation behaviour).

The input sensitivity function which reflects the effects of an output disturbance upon the plant input is given by:

$$S_{up}(q^{-1}) = -\frac{A(q^{-1})\,R(q^{-1})}{P(q^{-1})}.$$

In general, the desired closed-loop poles are specified in the form:

$$P(q^{-1}) = P_D(q^{-1})\,P_F(q^{-1})$$

where $P_D(q^{-1})$ specifies the desired dominant poles of the closed loop, and $P_F(q^{-1})$ specifies the auxiliary poles of the closed loop.

Once the closed-loop poles have been defined, solving the equation:

$$P(q^{-1}) = A(q^{-1})\,S(q^{-1}) + q^{-\mathrm{d}}\,B(q^{-1})\,R(q^{-1})$$

allows the determination of $S(q^{-1})$ and $R(q^{-1})$, which will ensure the desired closed-loop poles.

Let the degrees of polynomials $A(q^{-1})$ and $B(q^{-1})$ be defined by:

$$n_A = \deg A(q^{-1});\ n_B = \deg B(q^{-1}).$$

Then the above equation has a unique solution (assuming that $A(q^{-1})$ and $B(q^{-1})$ do not have common factors) for:

$$n_P = \deg P(q^{-1}) \leqslant n_A + n_B + d - 1$$

$$n_S = \deg S(q^{-1}) = n_B + d - 1$$

$$n_R = \deg R(q^{-1}) = n_A - 1$$

in which:

$$S(q^{-1}) = 1 + s_1 q^{-1} + \ \dots\ s_{n_S} q^{-n_S} = 1 + q^{-1}\,S^*(q^{-1})$$

$$R(q^{-1}) = r_0 + r_1 q^{-1} + \ \dots\ r_{n_R} q^{n_R}.$$

However, in general the polynomials $R(q^{-1})$ and $S(q^{-1})$ of the controller may, for various reasons, contain some prespecified fixed parts. For this reason it is convenient to factorize the polynomials $R(q^{-1})$ and $S(q^{-1})$ as follows:

$$R(q^{-1}) = H_R(q^{-1})\,R'(q^{-1})$$

$$S(q^{-1}) = H_S(q^{-1})\,S'(q^{-1})$$

where $H_R(q^{-1})$ and $H_S(q^{-1})$ are prespecified polynomials. These polynomials are defined by the performance specifications (e.g., the integrator in the controller) and by considerations of robustness. For example, the introduction of an integrator in the controller requires one to take $H_S(q^{-1}) = 1 - q^{-1}$.

Many control strategies can be applied to the design of the R-S-T controller by an appropriate reformulation. See for example (Landau, 1990; Aström and Wittenmark, 1990; Landau et al., 1997), as well as the special issue of *European Journal of Control* Vol. 1, N°2, 1995, dedicated to a robust control benchmark.

However, the pole placement can be considered as the basic design technique, and most of the various designs can be related to it.

3.1. Pole placement

This control strategy can be used for plant models of any order, with or without time delay, and featuring stable or unstable zeros. The only assumption is that the polynomials $A(q^{-1})$ and $B(q^{-1})$ characterizing the plant model do not have common factors.

The controller polynomials $S(q^{-1}) = H_S(q^{-1})\,S'(q^{-1})$ and $R(q^{-1}) = H_R(q^{-1})\,R'(q^{-1})$ are obtained by solving the equation:

$$P(q^{-1}) = A(q^{-1})\,H_S(q^{-1})\,S'(q^{-1}) + q^{-d-1}\,B^*(q^{-1})\,H_R(q^{-1})\,R'(q^{-1})$$

where $P(q^{-1})$ defines the desired closed-loop poles.

The $T(q^{-1})$ polynomial is chosen as:

$$T(q^{-1}) = P(q^{-1})/B(1)$$

($B(1) = B(q^{-1})$ for $q = 1$), and the tracking behaviour is described by the equation:

$$y(t) = q^{-d-1}\,\frac{B^*(q^{-1})}{B(1)}\,y^*(t + d + 1).$$

In other words one follows the desired trajectory, filtered through the plant zeros. For more details see (Landau, 1990, 1993).

Note that unstable discrete-time zeros occur when a fractional delay larger than half of the sampling period is present, or when a high sampling frequency is used for continuous-time models having a difference of degree between denominator and numerator greater than or equal to 2 (Aström and Wittenmark, 1990; Landau, 1990). Both phenomena lead to the conclusion that the sampling frequency has to be chosen as low as possible, but in accordance with the desired closed-loop performance.

3.2. Relationship with other control strategies

For plant models with stable zeros, one can use the strategy called "tracking and regulation with independent objectives", which can be viewed as a particular case of the pole-placement strategy, where the desired closed-loop poles contains the zeros of the plant, i.e.,

$$P(q^{-1}) = P_D(q^{-1})\cdot B^*(q^{-1})\cdot P_F(q^{-1}).$$

"Internal model control" (Morari, 1989) corresponds to a pole-placement strategy where the desired closed-loop poles contain the poles of the plant model, i.e.,

$$P(q^{-1}) = A(q^{-1})\cdot P_F(q^{-1}).$$

Digital PID can be designed using pole placement. In this case, the orders of the plant model are limited to $n_A \leqslant 2$, $n_B \leqslant 2$, $d = 0$.

Predictive control strategies and an LQ control strategy using an appropriate formulation of the criterion to be minimized lead to an R-S-T controller, and can be viewed as an approximation of the pole placement in the sense of a certain quadratic criterion (Landau et al., 1997).

4. Robustness

Four indicators are generally used to express the robustness of a design in terms of the minimal distance with respect to the critical point $[-1, j0]$ in the Nyquist plane. These indicators are the gain margin (ΔG), the phase margin ($\Delta\phi$), the modulus margin (ΔM) and the delay margin ($\Delta\tau$). The modulus margin and the delay margin are the most interesting in applications. Fig. 6 illustrates the modulus, gain and phase margins.

The modulus margin is the minimal distance between the critical point $[-1, j0]$ and the Nyquist plot of the open-loop transfer function:

$$H_{\mathrm{OL}}(z^{-1}) = z^{-\mathrm{d}}\ B(z^{-1})\ R(z^{-1})/A(z^{-1})\ S(z^{-1}).$$

The modulus margin ΔM is defined as the radius of a circle, centered on $[-1, j0]$ and tangent to the Nyquist plot of $H_{\mathrm{OL}}(\mathrm{e}^{-jw})$ (see Fig. 6).

The result is that:

$$\Delta M = |1 + H_{\mathrm{OL}}(\mathrm{e}^{-jw})|_{\min}. = |S_{yp}^{-1}(\mathrm{e}^{-jw})|_{\min}. = (|S_{yp}\ (\mathrm{e}^{-jw})|_{\max})^{-1}.$$

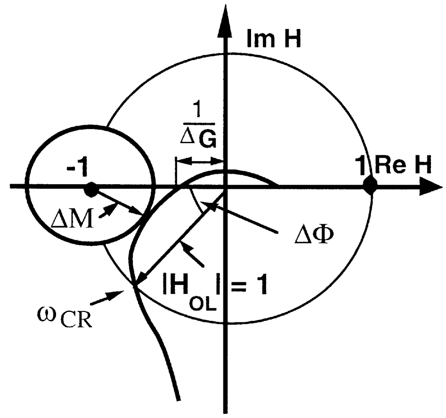

Fig. 6. Modulus, gain and phase margins.

In other words, the modulus margin corresponds to the inverse of the H_∞ norm of the output sensitivity function. Minimization of the H_∞ norm of $S_{yp}(\mathrm{e}^{-jw})$ will maximize the modulus margin.

To obtain the modulus margin, it is therefore sufficient simply to plot the frequency characteristics of the modulus (gain) of the output sensitivity function in dB. In this case:

$$\Delta M\ \mathrm{dB} = (|S_{yp}(\mathrm{e}^{-jw})|_{\max})^{-1}\ \mathrm{dB} = -\ |S_{yp}(\mathrm{e}^{-jw})|_{\max}\ \mathrm{dB}.$$

Note that a given value of the modulus margin will guarantee certain phase and gain margins, while the converse is not true (systems with good phase and gain margins can pass very close to the critical point).

The delay margin is the maximal additional delay that will be tolerated in the open-loop system without causing an instability of the closed-loop system. If the Nyquist plot of the open-loop system intersects the unit circle at several cross-over frequencies ω_{cr}^i, characterized by the corresponding phase margins $\Delta\phi_i$, the delay margin of the system is defined as:

$$\Delta\tau = \min_i \frac{\Delta\phi_i}{\omega_{\mathrm{cr}}^i}.$$

Typical values of these robustness indicators are:

- modulus margin: $\Delta M \geqslant 0.5$ (-6 dB)
- delay margin: $\Delta\tau \geqslant T_S$ (sampling period)
- gain margin: $\Delta G \geqslant 2$ (6 dB)
- phase margin: $30^\circ \leqslant \Delta\phi \leqslant 60^\circ$.

Note that $\Delta M \geqslant 0.5$ implies $\Delta G \geqslant 2$ and $\Delta\phi > 29^\circ$ (the converse is not necessarily true).

Sensitivity functions are related to the robust stability of the closed loop with respect to plant model uncertainties, see (Doyle et al., 1992). Bounds on the magnitude of the frequency-dependent model uncertainties convert to upper constraints upon the moduli of the various

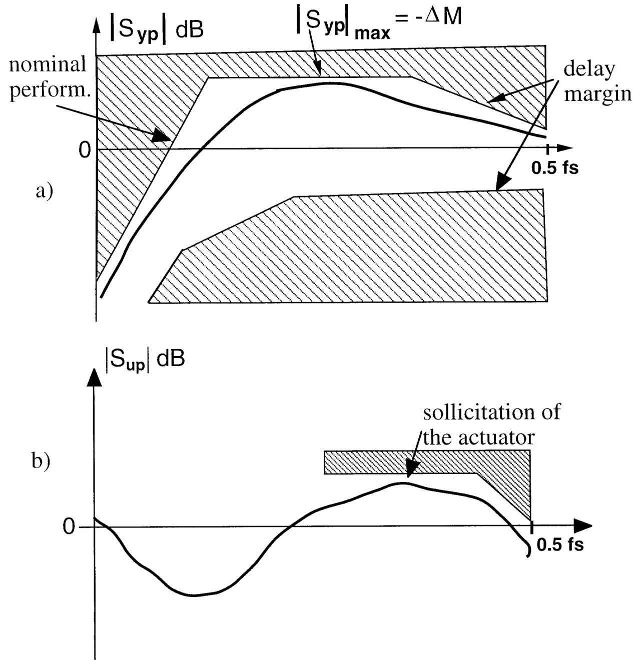

Fig. 7. Templates for the sensitivity functions: (a) output sensitivity function; (b) input sensitivity function.

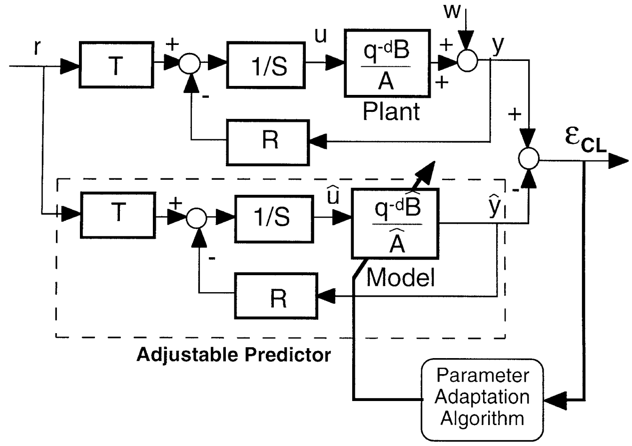

Fig. 8. Plant model identification in closed-loop operation.

sensitivity functions. These constraints, as well as those on the modulus margin and delay margin, can be translated into desired templates for the sensitivity functions. Conversely, constraints imposed on the sensitivity functions can be translated into tolerated model uncertainties.

Typical templates for S_{yp} and S_{up} are shown in Fig. 7. The upper and lower bounds on the output sensitivity function S_{yp} in the high-frequency region come from the translation of the delay margin constraints in the frequency domain (Landau, 1995).

The input sensitivity function reflects both tolerance with respect to additive uncertainties, and the activity of the input in the presence of disturbances (high values in certain frequency regions indicate low model uncertainty tolerance and important stress on the actuator).

A design methodology that combines pole placement with the shaping of the sensitivity function has been developed in order to ensure both performance and robustness. See (Landau, 1993; Landau et al., 1996).

5. Identification in a closed loop

In a number of practical situations, it may not be possible to operate the plant in an open loop in order to achieve system identification. Such situations are encountered, for example, when the plant contains an integrator, or when important drifts of the operating point may occur during input/output data acquisition. In a number of other situations, a controller already exists, but for various reasons cannot be disconnected. Therefore, techniques for plant identification in closed-loop operation should be used.

Significant progress in this area has been made in the last few years. New algorithms dedicated to identification in closed loops have been developed. For a detailed presentation see (Van den Hof and Schrama, 1995; Landau and Karimi, 1997; Landau et al., 1997).

A basic scheme for plant model identification in a closed loop is shown in Fig. 8 (Landau and Karimi, 1997). The upper part represents the true closed-loop system, and the lower part corresponds to an adjustable predictor for the closed loop, re-parameterized in terms of a known fixed controller and an adjustable plant model. The error between the system output and the closed-loop predictor output (called a closed-loop output error) is used by a parameter-adaptation algorithm that will drive the parameters of the estimated plant model in order to minimize the error between the two closed-loop systems. In other words, the model obtained in a closed loop will allow for better prediction of the behaviour of the closed-loop system.

6. Controller validation and on-line retuning

As indicated in Section 1, validation of the designed controller is a key issue in assessing the effective performance of the closed-loop system. Identification of the closed loop will allow the performance achieved to be compared with the designed performance by comparing the achieved and the designed closed-loop poles. It will also allow the robustness of the control schemes to be assessed by comparing the designed and achieved sensitivity functions in the frequency domain.

However, with the same data, acquired in a closed loop, one can also identify a new plant model. The new model, identified in the closed loop, is then used for re-tuning of the controller.

This procedure is used for two purposes:

– improvement of a previous design
– controller maintenance.

Examples can be found in (Zhang et al., 1995; Langer and Landau, 1996; Landau et al., 1997).

7. Adaptation

When "system identification" plus "robust control design" does not allow one to obtain a single linear controller, giving acceptable performance for the whole range of operating points because of the too-wide variations in the dynamic characteristics of the plant, one has to consider the "adaptation" of the controller.

The term "adaptation" (adaptive control) refers to a set of techniques for the automatic tuning of the controller in real time, in order to maintain the desired performance when the plant parameters vary.

One can distinguish between two basic adaptive control techniques:

(1) "closed-loop" adaptive control (Fig. 9)
(2) "open-loop" adaptive control (Fig. 10).

The "closed-loop" adaptive control system usually combines a real-time identification algorithm with the computation of the controller in real time, based on a current estimation of the plant model and the desired performance.

However, in a number of applications, the characteristics of the dynamic model of the plant depend upon a set of measured variables, which define an operating point. In this case, one can use an "open-loop" adaptive control (Fig. 10). The range of operating points is divided into a number of operating intervals. For each interval, a relevant operating point is selected and a corresponding controller is designed, based on an identified model. This controller assures the desired performance for all the operating points located in the interval. The corresponding controllers are stored in a table. When the plant is operating at a certain point, the corresponding values of the controller parameters will be used, according to the table.

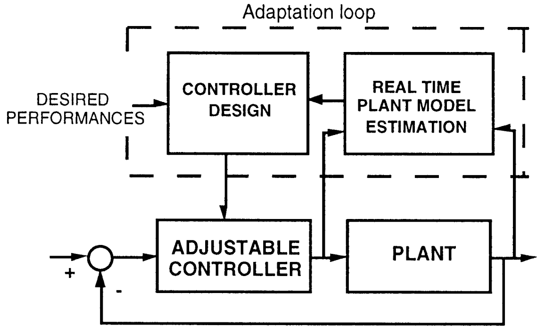

Fig. 9. "Closed loop" adaptive control.

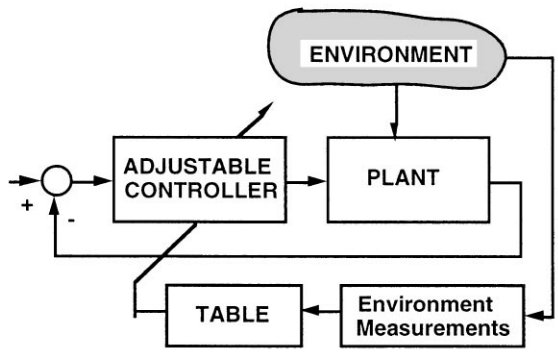

Fig. 10. "Open-loop" adaptation.

8. Hot-dip galvanizing at SOLLAC (Florange)

The objective of the galvanizing line is to obtain galvanized steel with formability, surface quality and weldability equivalent to uncoated cold rolled steel. The variety of products is very large in terms of deposited zinc thickness and steel strip thickness. The deposited zinc may vary between 50 to 350 g/m^2 (each side), and the strip speed may vary from 30 to 180 m/mn.

The most important part of the process is the hot-dip galvanizing. The principle of hot-dip galvanizing is illustrated in Fig. 11. Preheated steel strip is passed through a bath of liquid zinc, and then rises vertically out of the bath through the stripping "air knives", which remove the excess zinc. The remaining zinc on the strip surface solidifies before it reaches the rollers, which guide the finished product. The measurement of the deposited zinc can be made only on the cooled, finished strip. The effect of the air knives depends on the air pressure, the distance between the air knives and the strip, and the speed of the strip. Nonlinear static models have been developed for computing the appropriate pressure, distance and speed for a given desired value of the deposited zinc.

The objective of the control is to assure good uniformity of the deposited zinc, whilst guaranteeing a minimum value of the deposited zinc per unit area. Tight control (i.e., a small variance in the controlled variable) will allow a more uniform coating and a reduction of the average quantity of deposited zinc per unit area. As a consequence, in addition to an improvement in quality, tight control of the deposited zinc per unit area has an important commercial impact since the average consumption for a modern galvanizing line is of the order of 40 tons per day (price $\approx$ 1 500 USD/ton).

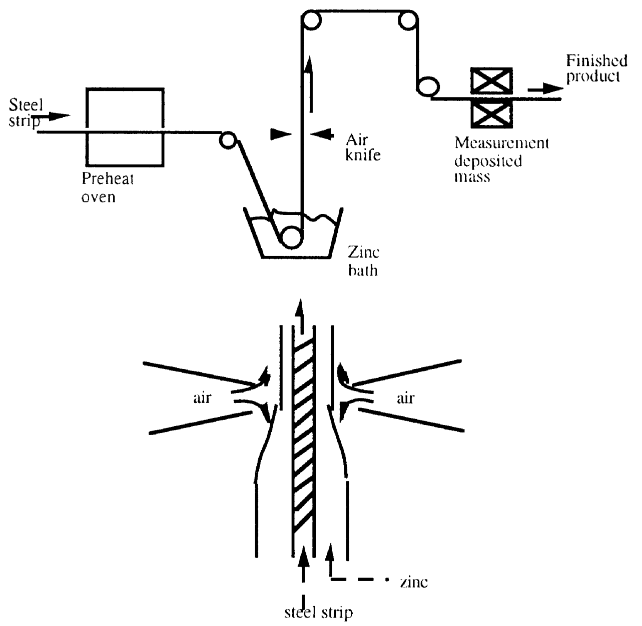

Fig. 11. Process description.

9. Model of the process

For an analysis of the process, the model originally proposed by Harvey and Carton (1974) and completed by Jacobs (1991) can be used:

$$m = KD\sqrt{\frac{V}{P}} + \zeta_m$$

where m is the deposited mass per unit area, K is a constant of proportionality, D is the distance between the air knives and the strip, P is the air pressure and V is the strip speed. ζ_m accounts for unpredictable effects and/or modelling errors. At SOLLAC Ste Agathe, the control variable is the air pressure.

A linearized model around an operating point (P_0, V_0, D_0) can be obtained using a standard Taylor series expansion for variations of pressure (ΔP), speed (ΔV) and distance (ΔD). It has the form:

$$m = KD_0\sqrt{\frac{V_0}{P_0}} + \alpha\,\Delta D + \beta\,\Delta V - \mu\,\Delta P + \xi_m;$$

$$\alpha, \beta, \mu > 0.$$

It can be seen that, by using the pressure as the control variable, one can compensate for the disturbances created by variations in distance and speed as well as by the term ξ_m.

The pressure in the air knives is regulated through a pressure loop, which can be approximated by a first-order system. The delay of the process will depend linearly on the speed. Therefore, a continous-time linear dynamic model, relating variations in the pressure to variations in the deposited mass, of the form:

$$H(s) = \frac{G\,e^{-s\tau}}{1+sT}; \quad \tau = \frac{L}{V}$$

can be considered, where L is the distance between the air knives and the transducers, and V is the strip speed. When discretizing this model, the major difficulty comes from the variable time-delay. In order to obtain a controller with a fixed number of parameters, the delay of the discrete-time model should remain constant. Therefore, the sampling period is tied to the strip speed using the formula:

$$T_s = \frac{(L/V) + \delta}{d}; \quad (d = \text{integer})$$

where d is a small additional time-delay due to the implementation, and d is the discrete-time delay (an integer).

The corresponding linearized discrete-time model will be of the form:

$$H(q^{-1}) = \frac{q^{-d}(b_1 q^{-1})}{1 + a_1 q^{-1}}.$$

The fractional delay (which corresponds to the presence of an additional term $b_2 q^{-2}$) is negligible because of the way in which the sampling period T_s is selected; this was confirmed by the model identification procedure. However, the parameters of the model, given above, will depend on the distance D and on the speed V.

10. Identification of the discrete-time plant model

The process comprises the air-pressure control loop and the coating process. The control input to the process is the reference of the air pressure control loop, and the output of the process is the measured deposited mass per unit area (see Fig. 12).

The PC used for data acquisition, identification and control is connected to the process through an industrial network. The identification has been done with the coating process operating in an open loop.

The sampling frequency has been chosen at each operating point, in order to have the discrete-time delay $d = 7$. The data acquisition is illustrated in Fig. 13. First, an analog anti-aliasing filter is used, before a high-frequency sampling is undertaken (a multiple of the desired sampling frequency). A digital anti-aliasing filter is inserted between the two samplers.

The input used was a P.R.B.S. (Pseudo Random Linary Sequence) of a magnitude of $\pm 4\%$ with respect to the static pressure (P_0). The P.R.B.S. was generated by a shift register with N = 5 cells and a clock frequency equal to half of the sampling frequency (length of the

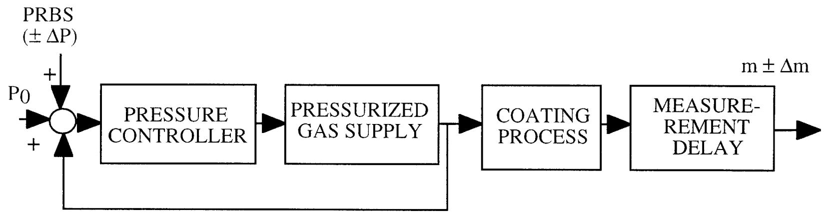

Fig. 12. Process block diagram.

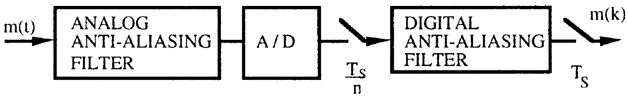

Fig. 13. Data acquisition.

sequence: 64). 100 to 160 (average: 128) measurements have been used for the various identifications made in the different regions of operation. The choice made for the P.R.B.S. allowed at least one full sequence to be sent for each experiment, and yielded the largest pulse width (10 T_s) comparable with the rise time of the process. As both sides of the steel strip have to be galvanised, and because the positions and physical realisations of the two actuators are not symmetrical, both "front" and "back" models have been identified.

As no unique identification method gives unbiased results for all types of disturbances, the following recursive identification methods have been used (Landau, 1990):

- Recursive least squares
- Extended least squares
- Recursive maximum likelihood
- Instrumental variable with auxiliary model
- Output error
- Generalized least squares

For validation of the identified models and comparison of the models obtained with the different methods, a cross-correlation between the predicted output (using an output error predictor) and the output error has been used (Landau, 1990). (For the first four methods, the whiteness test on the prediction error has also been used for validation and comparison). "Output error" consistently provided the best results for this application.

It was observed that a significant variability in the parameters occurs with a change of the operating points. This necessitated splitting the operation of the plant into several regions. However, a variability of the parameters is observed, even within a region of operation at a constant distance and with relatively small speed variations. One of the causes is the imperfect measurement of the strip/air-knives distance. This variability will require a robust control design.

11. Controller design and adaptation

The "tracking and regulation with independent objectives" (which in this case is equivalent to the poles placement, since the model does not have finite zeros) has been used.

Robust control design using an identified model and based on shaping of the sensitivity function allowed a modulus margin greater than -6 dB, to be obtained with a delay margin greater than $2T_s$. These robustness margins assure satisfactory performance in a region of operation, despite the variability of the model.

In order to ensure satisfactory performance for all regions of operation, an "open-loop adaptation" technique has been considered. The open-loop adaptation is made with respect to:

- steel strip speed,
- distance between the air knives and the steel strip.

The strip speed directly affects the sampling period according to the relationship:

$$T_s = \frac{L + \delta}{V}$$

where δ is the equivalent time-delay of the industrial network and of the programmable controller used for pressure regulation. The speed range and the distance range have been split into 3 regions, giving a total of 9 operating regions. For each of these operating regions an identification has been performed, and controllers based on the identified model have been computed and stored in a table.

Anti-wind-up procedures have been used for the implementation of the controller, and a smooth transfer from open-loop to closed-loop operation has also been assured. For a detailed presentation of this application see (Fenot et al., 1993).

12. Results

Fig. 14 shows typical results, obtained when one of the sides is under digital regulation and the other side is

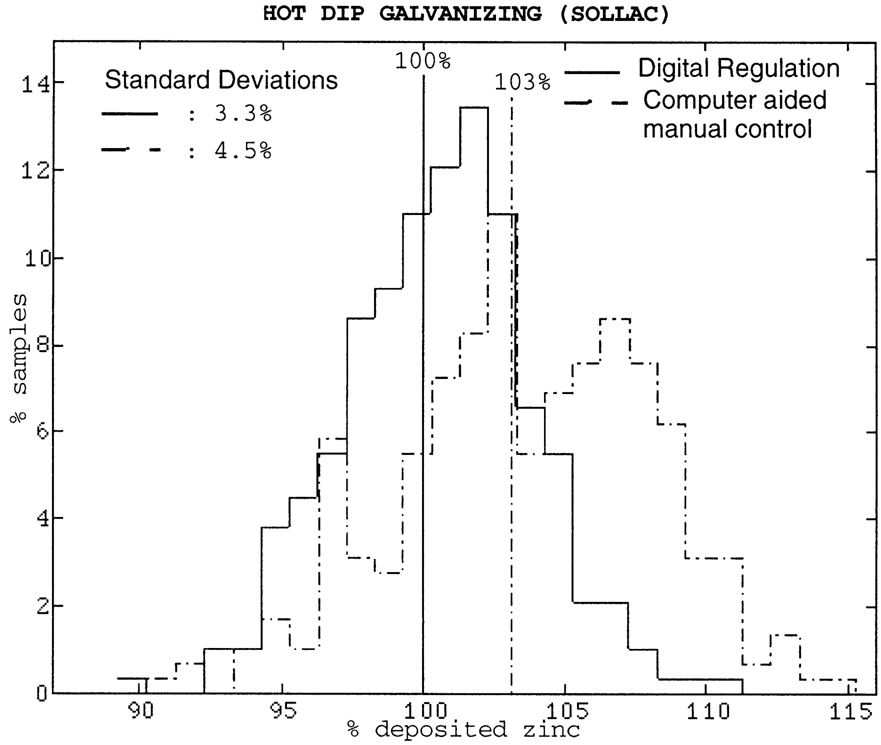

Fig. 14. Typical performance of the digital regulation of the deposit zinc.

under computer-aided manual control (the operator has on display a moving short-time history of the deposited zinc and applied pressure).

A reduction in the dispersion of the coating is noticed when closed-loop digital control is used. This provides a better-quality finished product (extremely important in the automotive industry, for example).

The average quantity of deposited zinc is reduced by 3% when closed-loop digital control is used, while still guaranteeing the specifications for minimum zinc deposition. Taking into account the line production and the price of the zinc, this corresponds to an annual saving over 350 000 USD. The closed-loop operation also reduces the task of the operator, thereby creating better working conditions.

13. Conclusions

A methodology for the design and tuning of R-S-T digital controllers has been presented. These controllers have already been used in a significant number of industrial applications (Rolland and Landau, 1991). The economic impact of the improved performance has largely justified their use. Software packages are available for the design, implementation and commissioning of the R-S-T digital controllers.

References

Aström, K.J., Wittenmark, B., 1990. Computer Controlled Systems–Theory and Design. Prentice Hall, N.J. (2nd Edition).

Doyle, J.C., Francis, B.A., Tannenbaum, A.R., 1992. Feedback Control Theory. MacMillan, New York.

Fenot, C., Rolland, F., Vigneron, G., Landau, I.D., 1993. Open loop adaptive digital control in hot-dip galvanizing. Control Engineering Practice 1(5), 779–790.

Harvey, C.F., Carlton, A.J., 1974. Mathematical Modelling of Air Jet Coating Mass, J. Lysagh Ltd. Res. Tech. Rep. Australia.

Jacobs, O.L.R., Chen, D.S., 1991. Regulation of Deposited Zinc in hot-dip Galvanizing. Proceedings of the first European Control Conference, Grenoble, 1, 773–778.

Landau, I.D., 1990. System Identification and Control Design. Prentice Hall, Englewood Cliffs, N.J.

Landau, I.D., 1993. Identification et Commande des Systèmes (seconde édition), Hermès, Paris.

Landau, I.D., Karimi, A., 1997. Recursive algorithms for identification in closed loop – A unified approach and evaluation. Automatica 33(8).

Landau, I.D., Langer, J., Rey, D., Barnier, J., 1996. Robust control of a 360° flexible arm using the combined pole/placement sensitivity function shaping method. IEEE T-CST, 4(4), 369–383.

Landau, I.D., Lozano, R., M'Saad, M., 1997. Adaptive Control. Springer Verlag, London.

Langer, J., Landau, I.D., 1996. Improvement of robust digital control by identification in closed loop, application to a 360° flexible arm. Control Engineering Practice 4(8), 1079–1088.

Ljung, L., 1987. System Identification. Theory for the user. Prentice Hall, Englewood Cliffs, N.J.

Morari, M., Zafiriou, 1989. Robust process control. Prentice Hall, N.J.
Rolland, F., Landau, I.D., 1991. Pour mieux réguler, le PC va vous aider. Mesures, n°640, pp. 71–73, Déc.
Van den Hof, P., Schrama, R., 1995. Identification and control – closed-loop issues. Automatica 31(12).
Zang, Z., Bitmead, R.R., Gevers, M., 1995. Iterative weighted least-squares identification and weighted lqg control design. Automatica, 31(11).