Survey of Certain Properties of Repetitive Gain Scheduling Control Systems Using the Method of the Algebraic Derivative

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Key Words: Repetitive gain scheduling control systems; methods for synthesis and analysis of performance; method of the algebraic derivative.

Abstract. The present study systematizes certain methods for analysis at priori un-certainty and proposes new methods for analysis of the filtration features of the repetitive gain scheduling control systems under the conditions of periodic harmonic interference. For analysis of the filtering features of the repetitive gain scheduling control systems, the following methods have been proposed and applied to a particular example: temporal analysis with "test" periodic impacts in nominal parametric mode and frequency analysis, using the method of the algebraic derivative.

1. Introduction

There are control systems with parametric compensation (GSC Systems – Gain Scheduling Control Systems). The idea for this class of systems, realizing member of GSC-control strategy is proposed by J. Shamma, M. Athans [1,2]. It consists of introducing the additive compensation variables affecting basic management to compensation and parametric stabilization of transient gain of control systems. The analytical synthesis of these variables is based on previously known functional relationships of reparameterization (restructuring) in the model of control plant of measurable external disturbance signal. Based on a systematic study of these relationships with control valve [3,4,5] strategy for gain scheduling control and its industrial applications GSC-systems developed in [6,7,8,9]. Repetitive control is an effective strategy for control and/or stabilization of industrial plant. The foundations of the idea and the principles of repetitive control placed by Normey-Rico Julio Elias [10], Eduardo F. Camacho [11], Ramon Costa-Castelly [12,13], Liuping Wang [14,15]. Strategy repetitive control is designed to ensure high performance and maximum efficiency of the control systems, characterized in operating conditions with the presence of permanent periodic external signal interference; the parameters (time, frequency) are fixed and known in advance by value at the design stage of the system. The realization of repetitive control is performed using memory $\mathcal{ML}$ -filters included series in the basic structure of the control algorithm. Principles of synthesis of repetitive $\mathcal{ML}$ -control systems and their industrial applications are addressed systematically [16,17,18].

2. Objective and Tasks of Development

The objective of this paper is to explore the possibilities of structural configuration and synthesis of a new class of control systems – **systems with repetitive parametric compensation** ($\mathcal{ML} \circ \text{GSC}$ -systems) and to analyze their performance and filtering properties being offered effective methods for this analysis. Implementation tasks to: analytic design of GSC-systems and $\mathcal{ML} \circ \text{GSC}$ -control systems of a specific plant, a comparative performance analysis of the nominal parameter mode and robust performance frequency analysis of the synthesized systems.

3. Formulation and Solution of the Problem of Structural Configuration

Consider the structure (figure 1) of the traditional $[6 \div 9]$ GSC-system with a fixed control algorithm R_{GSC} for generalized plant G in industrial operating conditions, where:

the controller $R^* \xleftrightarrow[\{\sigma = \text{const}\}]{} G^*$ is optimally set in the context

of the criterion σ of nominal model G^* of the object $G = G_1 G_2$; embarrassed at the upper limit of the plant model $G^{\blacksquare}$; y – process control variable; y^0 – setpoint processing; ε – system error; μ – control output processing of G_1 ; q – volumetric flow rate for G_2 ; v – disturbance loading; s – hydrodynamic loads to G_1 ; ξ – parametric disturbance in the process G_2 ; f – perturbation to measurement; $\nabla \ell$, ∇a – compensating variables of GSC (1), where κ_{ℓ_i} (2) control system transfer gain; $-s$ normalized hydraulic loading factor; P^0 – pressure supply. The analytical synthesis $[6 \div 9]$ of GSC-algorithmic (1) is independent of G^* and $G^{\blacksquare}$, and is a function of (1) only by the type of control valve – linear^(lin) or logarithmic^(log) [3,4,5] after fixing the setting of $R^*(p) \xleftrightarrow[\{\sigma = \text{const}\}]{} G^*(p)$. The design method of GSC-algorithm (1) is "compensatory parametric equation of balance" (3) at optimality criterion "a constant value of the transfer gain of control system" $k_{\ell_i, t} = \text{const}$ (3).

In this paper it is proposed structural configuration of a new class $\mathcal{ML} \circ \text{GSC}$ -systems (figure 2), which unlike to

GSC (figure 1) have the structure of the control algorithm $R_{ML \circ GSC}$ and ML (**Memory Loop**) memory [16 ÷ 18]. By their nature, the latter is a bandpass filter, synthesized so that discarded (filtered cut maximum reduced damping) the impact of constant going external harmonic disturbance on the $d_p = \sin(\omega_p t)$ process control variable y . It is assumed that the frequency ω_p respectively the period T_p , are known in advance. Analytical synthesis ML -filter is implemented in a consistent method for frequency correction **°rejecting module bandpass filter criterion°** (4) under criterion **°in horizontal profile module sensitivity-community°** of repetitive system (5) [16 ÷ 18]. The synthesis of the ML -filter is independent of G^* , R^* , $G^\square$ and GSC is a function exclusively of the frequency ω_p of the disturbance d_p .

4. Methods for Solution of the Problem of Synthesis of $ML \circ GSC$ -Control Systems

The stated in the previous section is the reason why this paper proposes a method for the analytical synthesis of $ML \circ GSC$ control systems **°compensatory equation parametric balance and rejecting module bandpass filter°**, summarizing dependencies (3) and (4) in integral optimality criterion **°constant value of the transfer gain and the horizontal profile of the module sensitivity of the control system°**,

Figure 1

summarizing (3) and (5). The work is available analytically designing a control algorithm $R_{ML \circ GSC}$ (figure 2) in three stages. **The first task** of deciding the optimal choice and adjustment of the basic regulator in the system

$R^* \Leftrightarrow G^*$ $\{\sigma = const\}$. **The second stage** takes into account the type of control valve used in the system and analytical configured (1) both compensating variables $\nabla \ell$, ∇a . **The third stage**, on the basis of (4), (5) and (6), consists in the synthesis of the ML -filter and is connected with the choice of the structure of the filter and the number of units memory e^{-pT_p} in her.

5. Analytical Synthesis of $ML \circ GSC$ -Control Systems. Numerical Example

In this work was considered a numerical example in which it is necessary to synthesize the GSC -system (figure 1) and $ML \circ GSC$ -control system (figure 2) for the plant G (figure 3) with the set (7) ÷ (10) at a local optimality criterion **°critical aperiodic process°** ($\sigma = const$) and integral criterion **°constant value of the transfer gain and the horizontal profile of the module sensitivity control system°** (3), (5) in the presence of a permanently functioning periodic external signal interference d with frequency $\omega_p = 0,0346 \text{ rad / s}$ (11).

Figure 2

$$(1) \quad \left\{ \begin{array}{l} G_{GSC} = \begin{bmatrix} \nabla l \\ \nabla a \end{bmatrix} = [c^* \quad C^*] \begin{bmatrix} \nabla s \\ \nabla y \end{bmatrix}, \\ c^* = -\frac{\kappa_{s_i}}{\kappa_{l_0}} \left(c_{log}^* = \frac{0.5(e^{2n(l-1)} - 1)}{n s e^{2n(l-1)}}; c_{lin}^* = \frac{0.5(l^{-2} - 1) l^3}{s} \right) \\ C^* = C_i^*; \nabla y = \left(\frac{dy}{dl} \right)^{-1} \approx \left(\frac{\Delta y}{\Delta l} \right)^{-1} \end{array} \right\}$$

$$(2) \quad \kappa_{l_i} = \frac{\partial q}{\partial l} \Delta l + \frac{\partial q}{\partial s} \Delta s; \quad k_i = k_{l_D} \left(\frac{\partial y}{\partial l} \Delta l + \frac{\partial y}{\partial s} \Delta s \right); \quad \left(s = (I + (P^0 - P_l)(P_l - P_2)^{-1})^{-1}, \quad \nabla s = s_{i-1} - s_i \right)$$

$$(3) \quad k_{l_i, l} = const \Leftrightarrow (R^*(\sigma)); \quad \left(\frac{k_{l_0}(\Delta l + \nabla \ell_l) + k_{s_0}(\Delta s + \nabla s_l)}{d l} = \frac{k_{l_0} \Delta l + k_{s_0} \Delta s_l}{d l} \right)$$

$$\begin{aligned}
(4) \quad & d \left| \mathcal{M}_{\mathcal{L}, i}(j\omega) \right| / d\omega = 0, \forall \omega \in \Delta\omega_i; \\
& \left| \mathcal{M}_{\mathcal{L}, i}(j\omega) \right| = \text{const} \lll 1, \forall \omega \in \Delta\omega_i; \\
& \left| \mathcal{M}_{\mathcal{L}, i}(j\omega) \right| \equiv 1, \forall \omega \in [0, \omega_{b,i}], \forall \omega \in [\omega_{h,i}, \infty); \\
& \Delta\omega_i \in [\omega_{b,i}, \omega_{h,i}], (\omega_{b,i} < \omega_p < \omega_{h,i}) \\
(5) \quad & \left| \mathcal{M}_{\mathcal{L}, i}(j\omega) \right| \equiv \begin{cases} 0, & \forall \omega \in \Delta\omega_i, (\omega_{b,i} < \omega_p < \omega_{h,i}) \\ 1, & \forall \omega \in [0, \omega_{b,i}], \forall \omega \in [\omega_{h,i}, \infty), (\omega_{b,i} < \omega_p < \omega_{h,i}) \end{cases} \\
(6) \quad & \mathcal{M}_{\mathcal{L}, i}(p) = \left(2 - \prod_{q=2}^n (e^{-p T_p})_q \right)^{-1} = (2 - e^{-p q T_p})^{-1}
\end{aligned}$$

Figure 3a

Figure 3b

$$\begin{aligned}
(7) \quad & G^*(p, s) = G_1^*(p, s) G_2^*(p, \xi) = G_q^*(p, s) G_2^*(p, \xi) = \frac{y(p, s)}{\ell(p)} \\
& G^*(p, s) = \hat{G}^* \cdot e^{-\tau^* p} = \frac{y(p, s)}{\ell(p)} \\
& \hat{G}^* = \frac{(p+1)}{(1.6p+1)} \cdot \frac{(1-s(1-e^{-s}))^{-0.5}}{(0.04p+1)} \left(\frac{15}{(4p+1)(9p^2+3p+1)} \right) \\
& (s=0.00315, \xi=\text{const}, e^{-\tau^* p} \hat{=} (1+(p\tau/3))^{-3} \hat{=} (1+p)^{-3}, (\tau=\tau^*=3, s))
\end{aligned}$$

$$\begin{aligned}
(8) \quad & G^\blacksquare(p, s) = G_1^\blacksquare(p, s) G_2^\blacksquare(p, \xi) = G_q^\blacksquare(p, s) G_2^\blacksquare(p, \xi) = \frac{y(p, s)}{\ell(p)} \\
& G^\blacksquare(p, s) = \hat{G}^\blacksquare \cdot e^{-\tau^\blacksquare p} = \frac{y(p, s)}{\ell(p)} \\
& G^\blacksquare(p) = \frac{(p+1)}{(1.6p+1)} \cdot \frac{(1-s(1-e^{-s}))^{-0.5}}{(0.04p+1)} \left(\frac{15}{(4p+1)(9p^2+3p+1)} \right) \cdot (1+1.66p)^{-3} \\
& (s=0.815, \xi=\text{const})
\end{aligned}$$

$$(9) \quad G_q(p, s) = \frac{q(p)}{\ell(p)} = \frac{(a(w_0)p+1)}{(b(w_0(t))p+1)} \cdot \frac{(1-s(1-\sigma^{-2}(\ell)))^{-0.5}}{(T(s)p+1)}$$

$$(10) \quad G_{\Delta_E}(p) = \frac{\Delta_E(p)}{\ell(p)} = c \cdot s \cdot \frac{(a(w_o)p + 1)}{(b(w_o(t))p + 1)} \cdot \frac{(1 - s(1 - \sigma^{-2}(\ell)))^{-0.5}}{(T(s)p + 1)}$$

$$(11) \quad d = \sin(\omega_p t) = \sin(0,0346 t) = \text{const}, (\omega_p = \omega_{pf} = 0,0346 \text{ rad/s}; T_{pf} = 181,595 \text{ s})$$

$$(12) \quad R^*(p) = \frac{2(2p+1)}{2p} \frac{(p+1)}{(0.2p+1)}, \quad (R^* \stackrel{\{\sigma = \text{const}\}}{\Leftrightarrow} G^*)$$

$$(13) \quad \nabla \ell_t = -\frac{0,5(l^{-2} - 1)l^3}{s} \nabla s_t; \quad \nabla a_t = c_0^* \left(\frac{d y_t}{d \ell_t} \right)^{-1}$$

$$(14) \quad \mathcal{M}_L(p) = \left(2 - \sum_{k=1}^m W_k(p) e^{-p k T_p} \right)^{-1} \triangleq (2 - e^{-p T_p})^{-1}, \quad (k=1; T_p \equiv T_{pf} = 2\pi(\omega_{pf})^{-1} = 2\pi(0,0346)^{-1})$$

$$(15) \quad \alpha_{i, GSC}^{(\omega_i)}(\omega) \triangleq \frac{d e_{GSC}(\omega)}{d \omega} = \frac{d \left((I + R_{GSC}(j\omega) G^*(j\omega))^{-1} \right)}{d \omega} \equiv \frac{d \left(\Phi_{y^0_E}^{GSC}(\omega) \right)}{d \omega}$$

$$(16) \quad \alpha_{i, ML \circ GSC}^{(\omega_i)}(\omega) \triangleq \frac{d e_{rep}(\omega)}{d \omega} = \frac{d \left((I + R_{ML \circ GSC}(\omega) G^*(\omega))^{-1} \right)}{d \omega} \equiv \frac{d \left(\Phi_{y^0_E}^{ML \circ GSC}(\omega) \right)}{d \omega}$$

$$(17) \quad \alpha_{i, ML \circ GSC}^{(\omega_i)}(\omega) \Big|_{\omega=\omega_p} \ll \alpha_{i, GSC}^{(\omega_i)}(\omega) \Big|_{\omega=\omega_p}$$

$$(18) \quad \left. \frac{d e_{ML \circ GSC}(\omega)}{d \omega} \right|_{\omega=\omega_p} \ll \left. \frac{d e_{GSC}(\omega)}{d \omega} \right|_{\omega=\omega_p}$$

In the analytical description of the plant: Δ_E are hydrodynamical energy losses; w_o – initial velocity of fluid throttle; $\sigma^{-2}(\ell)$ – some theoretical transmission characteristic control valve; a, b, T – known design constants control valve.

The characteristics of the given numerical example in plant are shown in *figure 4*. Based on the systematized analytical methods for synthesis and set optimality criteria, solving the problem of analytical synthesis of the GSC -system (*figure 1*) and $ML \circ GSC$ – control system (*figure 2*) set with (7) ÷ (10) plant (*figure 3*), defines the main algorithmic components of R_{GSC} (*figure 1*) and $R_{ML \circ GSC}$ a (*figure 2*) as shown at (12) ÷ (14). The characteristics of R_{GSC} , $R_{ML \circ GSC}$ and the mechanism of compensating variables $\nabla \ell$, ∇a are illustrated in *figure 5*.

6. Solution of the Problem for Analysis

6.1. Analysis of Performance in Nominal Parameter Mode

Both systems (*figure 1*, *figure 2*) are modeled. The results of the simulation models – timing and frequency characteristics of the decision (12) ÷ (14) for closed loop Φ_i and open loop W_i parametric compensation system and repetitive parametric compensation $ML \circ GSC$ -control system specified by (7) ÷ (10) plant (*figure 3*) are shown in *figure 6*, *figure 7*. The characteristics of the systems are displayed in **nominal (7) parameter mode** ($G \triangleq G^*$, $\xi = \text{const}$, $d_i \equiv 0$, $s = 0,00315 = \text{const}$).

Used were the following: • indexes systems: parametric compensation GSC -system (figure 1), repetitive gain scheduling control system $ML \circ GSC$ (figure 2) • indications: h_{ϕ_i} – transfer functions, $\Phi(j\omega)$, $W(j\omega)$ – frequency characteristics of closed and open systems, $e(j\omega)$ – characteristics of the sensitivity of the closed systems.

Performance analysis in nominal (7) parameter mode

Figure 4a

Figure 4c

Figure 5a

systems (figure 1, figure 2) confirms that both systems: • meet the criteria for °critical aperiodic process° (σ) (figure 6) and is provided an opportunity to report graphically times regulation setting fast response; • stability (figure 7), it has provided an opportunity to report their gain margin and phase margin of stability; • claimed satisfy performance requirements in the process of synthesis.

Figure 4b

Figure 4d

Figure 5b

Figure 5c

Figure 5d

Figure 6

Figure 7

6.2. Temporal Analysis of Filtering Properties

The analysis was conducted of the decision (12) ÷ (14) at a constant acting periodic external signal disturbance d with frequency ω_p (11). Disturbance is applied parallel to the synthesized models of both control systems (figure 1, figure 2) set with (7) ÷ (10) plant G (figure 3) in conditions of external perturbation is an analysis of the decision (12) ÷ (14) at a constant acting periodic external signal per-turbation with frequency (11). The time analysis of the filtering properties, designed to explore combating repetitive systems of external impact, consider the parallel behavior of the two systems (figure 1, figure 2) impact of periodic d (11) submitted to the canal systems: the assignment, parallel assignment and load measurement, parallel assignment and measurement parallel on the job and load and measurement.

Under these conditions, the time analysis of the filtering properties to “test” periodic effects systems (figure 1, figure 2) was conducted in nominal (7) parameter mode. The essence of the method of analysis time to “test” effects consists in modeling the system and evaluating the simulation results on time criteria. Both systems (figure 1, figure 2) are modeled on the transfer functions $h_i(t)$ of the recurrent impact d (11) are simulated. Weather characteristics of systems (hereinafter indicated by h_{GSC} and $h_{ML \circ GSC}$) in parallel as results of the simulation are illustrated in figure 8 ÷ figure 10 as follows of:

- Figure 8 – Disturbance with d (11) in y^0 ;
- Figure 9 – Disturbance with d (11) parallel in y^0 and d (11) the channel load v ;
- Figure 10 – Disturbance to d (11) in f ;
- Figure 11 – Disturbance to d (11) parallel in setpoint processing y^0 and d (11) in f ;
- Figure 12 – Disturbance to d (11) parallel in setpoint processing y^0 , and d (11) in the groove of the load v and with d (11) in the measurement channel f ;
- Figure 8a, figure 9a, figure 10a, figure 11a, figure 12a – at external interference (11) and hydrodynamic load in control valve $s = 0,00315 = const$;
- Figure 8b, figure 9b, figure 10b, figure 11b, figure 12b – at external interference d (11) and hydrodynamic load control valve $s = 0,005315 = const$;
- Figure 8c, figure 9c, figure 10c, figure 11c, figure 12c – at external interference d (11) and hydrodynamic load control valve $s = 0,007315 = const$;
- Figure 8d, figure 9d, figure 10d, figure 11d, figure 12d – at external interference d (11) and hydrodynamic load control valve $s = 0,01315 = const$.

The results of the study by the method of analysis of temporal filtering properties of systems with “test” effects the following conclusions (in terms of quantitative assessments of the performance of processes – overshoot, overshoot number, time adjustment):

- repetitive gain scheduling control system – $ML \circ GSC$ (figure 2) is invariant to the harmonious effect d (11), for which it is designed, which is especially pronounced in cases where d (11) is channel assignment,

load parallel and task and a load;

- for all research cases discussed and illustrated in figure 8 ÷ figure 12 there is no reference value that repetitive gain scheduling control system – $ML \circ GSC$ (figure 2) not superior parametric compensation system GSC (figure 1);

- in terms of quantitative assessments of performance to repetitive gain scheduling control system – $ML \circ GSC$ (figure 2) outperforms GSC gain scheduling control system – (figure 1) efficiency to counteract the constant perturbation with frequency $\omega_p = 0,0346 \text{ rad / s}$ (11).

6.3. Frequency Analysis Filtering Properties with Algebraic Derivatives

For analytical reflection, testing and comparative evaluation of the properties of the filter systems, the use of a method of frequency $\alpha_i^{(\omega)}$ analysis using the algebraic derivative [16] in the direction of sensitivity of the system (figure 1, figure 2) in the nominal (7) parameter mode. It is an analytical method and consists in the effective use of the algebraic derivative [16] in a direction $\alpha_i^{(\omega)}$ defined by (15), (16) for each of the analyzing system (figure 1, figure 2). In comparison in figure 13 and figure 14 are shown the characteristics of sensitivity and algebraic derivatives (15) (16) system (figure 1, figure 2).

The analysis of the algebraic values of the derivatives (figure 14) in the direction of the sensitivity of the compared systems unambiguously prove that they are in a ratio of (17) corresponding to the reflected (18). The analytical method of frequency analysis of the filtering properties of systems using algebraic derived from the direction of the sensitivity of the system is a tool to quantify the filtering properties of the repetitive systems control. With his help determine:

- meet the criteria for treatment with the presence of “horizontal profile of the module sensitivity” beforehand to set frequency value $\omega_i = \omega_p$ (11);
- analytical criterion (5) satisfaction of ensuring the implementation of the filtering requirements of periodic external effects d with frequency $\omega_i = \omega_p$ (11) of repetitive system;
- criterion benchmarking of filtering properties of systems control by defining the value of the algebraic derivatives (15) (16), illustrated in figure 14;
- in comparative terms in their filtering properties repetitive gain scheduling control system – $ML \circ GSC$ proved superior in the context of (5) gain scheduling control system – GSC (figure 1).

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Figure 8a

Figure 8b

Figure 8c

Figure 8d

Figure 9a

Figure 9b

Figure 9c

Figure 9d

Figure 10a

Figure 10b

Figure 10c

Figure 10d

Figure 11a

Figure 11b

Figure 11c

Figure 11d

Figure 12a

Figure 12b

Figure 12c

Figure 12d

Figure 13

implementation of the filtering requirements of periodic external effects d with frequency $\omega_i = \omega_p$ (11) of repetitive system;

- criterion benchmarking of filtering properties of systems control by defining the value of the algebraic derivatives (15) (16), illustrated in figure 14;
- in comparative terms in their filtering properties repetitive gain scheduling control system – $ML \circ GSC$) proved superior in the context of (5) gain scheduling control system – GSC (figure 1).

7. Analysis of the Decision

The analysis of the survey results and the performance of the filtering properties of the synthesized control systems (figure 1, figure 2) of the plant (7) ÷ (10) was held by three methods. Each of them proved that repetitive gain scheduling control system – $ML \circ GSC$ satisfies the criteria brought in its synthesis by applying the method of:

- **performance analysis in nominal (7) parameter mode** systems (figure 1, figure 2) confirmed that both systems: the criteria for "critical aperiodic process" (σ), are stable, but the $ML \circ GSC$ system (figure 2) at one the same other terms and superior GSC – system (figure 1) a fast response and the stability marge;
- **time analysis of filtering properties of systems with "test" impacts** and assessment of transitional functions (figure 8 ÷ figure 12) confirmed that the $ML \circ GSC$ - system (figure 2) satisfies the criterion in the design of the filter for horizontal profile of the module sensitivity (4);
- **frequency analysis of the filtering properties** of systems using algebraic derivative in the direction of the **sensitivity of the system** (figure 14) in nominal (7) parameter mode was shown to $ML \circ GSC$ -system (figure 2) satisfies the criterion (4) filtering periodic external effects d with frequency $\omega_i = \omega_p$ (11).

8. Conclusion

New and original in this paper are:

Figure 14

- configuring and the design method of a new class of repetitive gain scheduling control systems;
- proposed methods for performance analysis and filtering properties of gain scheduling control system and repetitive gain scheduling control that are classified as methods:
 - performance analysis in nominal parameter mode;
 - temporal analysis of filtering properties to "test" periodic impacts in nominal parameter mode;
 - frequency analysis of the filtration properties using algebraic derivative in the direction of the sensitivity;
- results of the application of the proposed methods for performance assessment and filtering properties of control systems.

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