# ROBUST DECENTRALIZED CONTROL OF REACTIVE DISTILLATION PROCESS IN DIMETHYLACETAMIDE PRODUCTION

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Abstract: The paper deals with the sequential synthesis procedure of decentralized (multi-loop) PID-controllers based on the estimation of control loops interaction in the form of multiplicative plant uncertainty. It is shown that the each synthesis iteration is accompanied by the correction of the robust performance criteria for the coupled SISO-systems. The results of industrial application of proposed sequential design for reactive distillation unit is cited as well as comparison analysis with the other techniques is given.


Keywords: Decentralized control, Distillation columns, PID controllers, Robust performance, Uncertain dynamic systems.

## 1. INTRODUCTION

Nowadays the widespread technology for control performance improvement of multivariable chemical processes is an application of model predictive control (MPC) software packages as RMPCT, DMC, IDCOM and etc (Qin and Badgwell, 2003). However for their successful realization it is necessary to have special interfaces and sometimes DCS configuration work is not available. Because of the encountered technical problems of MPC application the fine tuning of multi-loop PID controller still remains as important task in industry.

It was proposed to consider the synthesis of robust multi-loops PID controllers as direct optimization problem solution using successive quadratic programming or linear matrix inequalities (Bao *et al*, 1999; Huang and Huang, 2004; Zheng *et al*, 2002). Such kind of methods are characterized by the high dimensionality of the vector of optimized parameters. Also the analysis will be more complicated when the uncertainty or transport delays of the non-diagonal elements of the process transfer matrix are considered. The alternative sequential design is considerably easy used in practice (Hovd and Skogestad, 1994) because of the low calculation efforts and based on the independent analysis of each closed loop systems. The bandwidths of SISO-systems are estimated. The final target is to find the PID parameters which can provide the fulfilment of the inequality imposed of the MIMO-system structured singular value. The previous investigations regarding the sequential approach did not handle the robust stability and performance conditions of separated SISO closed loop systems in the straightforward manner with their interactions. The additional lack is the absence of the strict mathematical guidance for the selection of the loops bandwidths.

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In the present work we are developing the sequential approach for robust multi-loop PID controller synthesis based on the example of reactive distillation column in dimethylacetamide production. It has been proposed to use the multiplicative uncertainty form in order to express interaction among the loops on the each iteration of design procedure. The high bound of interaction (by its multiplicative presentation) is estimated when the influence from the other SISO-systems has the maximum effect. The tuning of the single controller can be simplified when the high bound of the so-called interaction equivalent uncertainty is less then process model uncertainty.

## 2. REACTIVE DISTILLATION COLUMN MODEL AND ROBUST CONTROL PROBLEM FORMULATION

The integrated chemical processes are becoming more popular nowadays in industry. Their advantages consist in the low energy consumption and capital cost due to the concurrent implementation of several physical-chemical processes in the same apparatus. For example, the combination of chemical conversion of the substances with their distillation is realizing in the reactive distillation (RD) column (Taylor R. and R. Krishna, 2000; Noeres *et al*, 2004). The RD column is essentially nonlinear and non-stationary plant because of the drift of reaction rates under temperature and pressure variation, changes of the catalyst activity, inconstancy of the hydrodynamic conditions and etc. The features of RD columns operation make challenge for the nonlinear control design (Chen *et al*, 2003; Gruner *et al*, 2004). However, the accurate analytical synthesis of the nonlinear controller for industrial column is so complicated by the high dimensionality of the distillation model having a system from hundreds nonlinear differential and algebraic equations (Krivosheev and Torgashov, 2002). Therefore, the robust performance optimization of PID-controllers is motivated based on the empirical dynamic models which commonly used in practice (Engell and Fernholz, 2003). Moreover, according the work of Kienle and Marquardt, 2003 the stabilization of certain RD column steady-state in industry can be done in many cases using conventional PI-controllers.

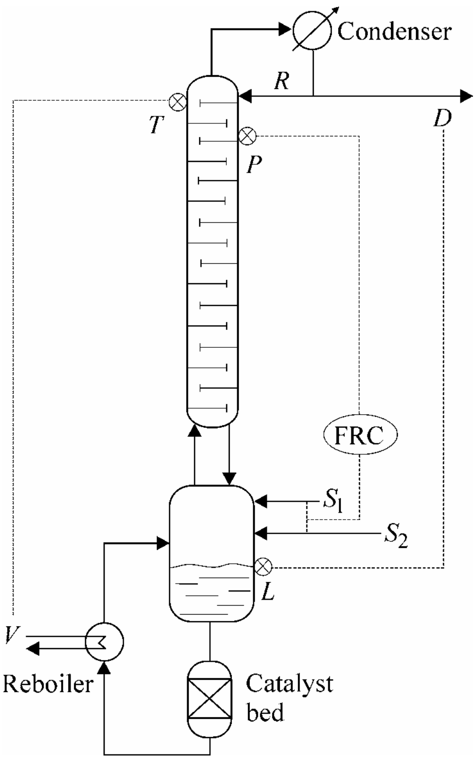


Fig. 1. Multi-loop control system configuration of reactive distillation column.

The investigated RD column of dimethylacetamide (DMAC) production is depicted on the Fig. 1. It has three available manipulated variables $\mathbf{u}=[u_1\ u_2\ u_3]^T$ and three controlled outputs $\mathbf{y}=[y_1\ y_2\ y_3]^T$. The pressure $P$ ($y_1$) is regulated by the molar flows ratio (FRC – $u_1$) of $S_1$ (acetic acid - AcOH) and $S_2$ (dimethylamine - DMA). The RD column product $D$ contains about 25% of impurities (DMA, AcOH). They are removed by subsequent distillation columns (not considered in the present paper). The temperature $T$ ($y_2$) is held by the manipulation of steam $V$ ($u_2$) used for the creation of vapor stream inside the column. The part of the vapor returns into the column as reflux after condensing. The level $L$ ($y_3$) in the bottom is controlled by the distillate $D$ ($u_3$). The reflux drum level is maintained by reflux $R$. The interaction of the vapor and liquid is accompanied by the chemical reaction DMA + AcOH ↔ DMAC + $H_2O$ with the distillation of reactants and reaction products. The some operation conditions details can be found in the work of Kerber *et al*, 1971. The reaction mechanism and kinetic were introduced by Fabrizio *et al*, 1973.

The chemical interaction among the reactants has so complex nature. At the first step the dimethylammonium acetate is formed by the following reversible reaction:

$$CH_3COOH+(CH_3)_2NH \leftrightarrow (CH_3)_2N^+H_2,CH_3COO^-.$$

At the second step the catalytic decomposition of the derived salt solution on the final product is processing:

$$(CH_3)_2N^+H_2,CH_3COO \xrightarrow[Catalyst]{} CH_3CON(CH_3)_2+H_2O.$$

In order to prevent the azeotrope formation between DMAC and AcOH the DMA flow is supplied in excess. Therefore, the pressure in the top of column is sensitive with respect to variation of ratio between $S_1$ and $S_2$. The following RD column transfer matrix was derived for nominal operating point:

$$\mathbf{G}(s)=\begin{pmatrix} \frac{0.82s+0.026}{9.61s^2+s}e^{-3s} & \frac{5.8s+0.14}{109s^2+20.8s+1}e^{-2s} \\ \frac{-0.17}{23.1s^2+12.4s+1}e^{-5s} & \frac{-3.66s-0.2}{193s^2+21.6s+1}e^{-5s} \\ \frac{0.003}{30.9s^3+11.1s^2+s}e^{-6s} & \frac{-6\cdot 10^{-5}}{3.77s^3+3.88s^2+s}e^{-5s} \end{matrix} \quad \ldots$$

$$\left.\begin{matrix} \frac{-3.6s^2-0.1s-0.006}{116s^3+26.9s^2+s}e^{-2s} \\ \cdots \quad \frac{0.207}{37.4s+1}e^{-2s} \\ \frac{-0.1s-0.007}{40.1s^2+s}e^{-5s} \end{matrix}\right). \quad (1)$$

The PID-controllers were implemented in Yokogawa DCS, therefore the all gains of the transfer function (1) were scaled for the range of **y** from 0 to 100% and the time constants are indicated in minutes. The investigation of industrial plant showed its very nonlinear and complex behavior (Fig.2).

The control system configuration on the fig. 1 was selected based on the RGA analysis $\Lambda(j\omega)=\mathbf{G}(j\omega)\cdot(\mathbf{G}(j\omega)^{-1})^T$ (Skogestad and Postlethwaite, 1996). The modules of the diagonal elements of $\Lambda(j\omega)$ have the values around unity excepting the range from 0.1 rad/min to 1.0 rad/min (fig.3). The interaction is appearing in that frequency range, i.e. the non-diagonal elements in (1) $\Lambda_{ij}^{|i\neq j}(j\omega)$ are approaching to unity. The condition number of $\mathbf{G}(j\omega)$ is increasing from 15 to 97 and hunting around 55 in the high frequency domain (fig.4). The fig.3-4 are confirming the validity of robust PID-controllers design for RD column.

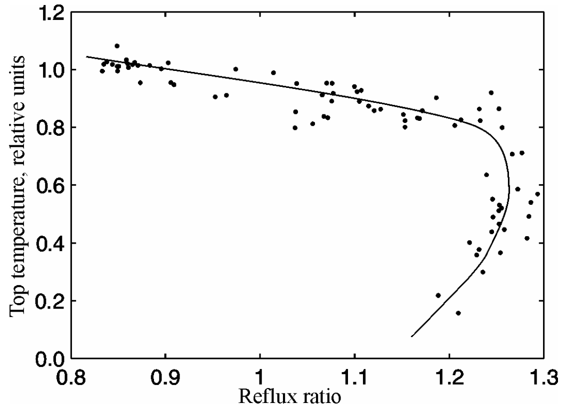


Fig. 2. Nonlinear steady-state characteristic of reactive distillation column: • plant data; – regression model.

The multiplicative form of plant model uncertainty representation is common and useful method in order to express robust performance and stability of closed loop system. The following weighted transfer functions for multiplicative uncertainty description are chosen for diagonal elements description in (1)

$$W_1^1(s)=\frac{s+0.01}{0.18s+0.02};\; W_1^2(s)=\frac{s+0.02}{0.29s+0.06};$$
$$W_1^3(s)=\frac{s+0.009}{0.2s+0.03}. \quad (2)$$

The expressions (2) were derived from the conditions of real parametric and structural uncertainty of $\mathbf{G}(j\omega)$. The upper indexes in (2) correspond to the numbers of diagonal elements in (1).

The statement of the robust $H_\infty$-optimal PID controller design problem for $i$-th closed loop has the following form

$$\max_{C_1^i, C_2^i \in K} \gamma_i \quad (3)$$

under constraints

$$\left\| \gamma_i W_p^i(s) S_{ii}(s) \right\|_\infty < 1, \quad (4)$$

$$\left\| W_u^i(s) T_{ii}(s) \right\|_\infty < 1, \quad (5)$$

where $C_1^i$, $C_2^i$ - transfer functions describing the $i$-th Yokogawa PID-controller (Astrom and Hagglund, 1995); $K$ – feasible domain of the parameters of $C_1^i$ and $C_2^i$; $S_{ii}$ – sensitivity function of $i$-th closed loop and element of the matrix $\mathbf{S}=(\mathbf{I}-\mathbf{GC}_1)^{-1}$; $W_p^i(s)$ - transfer function reflecting the desirable dynamic of the $i$-th closed loop; $T_{ii}$ – complementary sensitivity function, $\mathbf{T}=\mathbf{SGC}_2$; $\mathbf{C}_1$, $\mathbf{C}_2$ – diagonal matrices containing $C_1^i$ and $C_2^i$; $\gamma_i$ – real numbers characterizing the reaching of desirable dynamic; $i$=1,…,$n$; $n$ – the dimensionality of the vectors **u** and **y**; $W_u^i(s)$ - transfer function selected on each iteration from the condition

$$W_u^i(s)=\begin{cases} W_1^i(s), \text{ if } \left|\eta^i(j\omega)\right|>1, & \forall\omega \\ W_2^i(s), \text{ if } \left|\eta^i(j\omega)\right|<1, & \forall\omega \end{cases}; \quad (6)$$

$$\left|\eta^i(j\omega)\right|=\frac{\left|W_1^i(j\omega)\right|}{\left|W_2^i(j\omega)\right|}.$$

The difference of the current robust control problem (3)-(5) from previous known (Skogestad and Postlethwaite, 1996) is the direct consideration of interaction of SISO closed loop systems by the multiplicative uncertainty form (6). This allows make the optimal parameters calculations independently for $i$-th PID controller. The action from the another loops is taking into account using $W_2^i(s)$.

## 3. ESTIMATION OF LOOPS INTERACTION VIA MULTIPLICATIVE UNCERTAINTY DESCRIPTION

The matrices $\mathbf{R}^i$, $\mathbf{M}^i$ и $\mathbf{D}^i$ (fig.5) are introduced in order to estimate the total system influence upon the $i$-th open loop. The elements of $\mathbf{R}^i$, $\mathbf{M}^i$ и $\mathbf{D}^i$ depend from the number of selected loop. This is the zeros matrices of $n\times n$-dimensionality excepting the elements $D_{j1}^i=-1$, $R_{j1}^i=1$, $M_{i1}^i=1$ for $i$=1,…,$n$ and $j$=1,…,$n$. For example, if $i$=2 then

$$\mathbf{D}^2 = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix}; \; \mathbf{R}^2 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix};$$

$$\mathbf{M}^2 = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}. \qquad (7)$$

The values in (7) are based from the possible worst case directionality of the disturbances and set points acting on the $i$-th SISO system. The matrices like (7) represent a flexible tool for the investigation of the system dynamic under the real arrangement of disturbances sources. Thus, the robust controller is becoming less conservative in comparison with the tuning methods based on the minimization of the maximum singular values of weighted **S** and **T** (Skogestad and Postlethwaite, 1996) which taking into account the worst case directionality between disturbances and set points. However, the worst case directionality sometimes can not be met in real plant operation history.

After specifying of initial values in $\mathbf{C}_1$, $\mathbf{C}_2$, $\mathbf{R}^i$, $\mathbf{M}^i$ and $\mathbf{D}^i$ the following transfer matrix of the system on the fig. 4 will be obtained

$$\mathbf{\Phi}^i(s) = \frac{\mathbf{y}(s)}{\mathbf{h}(s)} = \mathbf{TR}^i + \mathbf{SGM}^i + \mathbf{SD}^i. \qquad (8)$$

The transfer function $\Phi_{ii}^i(s)$ in (8) is a reduced interaction of multivariable system caused on the $i$-th loop. In order to express it in the form of multiplicative uncertainty of $G_{ii}(s)$ the following calculation must be fulfilled

$$W_2^i(s) = \frac{\Phi_{ii}^i(s) - G_{ii}(s)}{G_{ii}(s)}. \qquad (9)$$

Figure 6 illustrates the example of equation (6) evaluation based on the (9) for (1)-(2) and (7). Obviously that the uncertainty bounds are extending for the SISO system plant model if the influence from the first and third loops are taken into account.

## 4. SEQUENTIAL SYNTHESIS OF ROBUST MULTI-LOOP PID-CONTROLLER

Before the start of design of multi-loop PID-controller it is necessary to solve $H_\infty$-optimization problem for the separated SISO-systems without taking into account their interaction. This allows to get acceptable initial elements of the matrices $\mathbf{C}_1$, $\mathbf{C}_2$ and to define the desirable dynamic of $i$-th loop by the following transfer function

$$W_p^i(s) = \frac{T_{cl}^i s + 1}{T_{cl}^i s + 10^{-5}}, \qquad (10)$$

where $T_{cl}^i$ - closed loop time constant. Let us to describe the proposed sequential design procedure in step-by-step manner.

Step 0. To formulate the initial values for $\mathbf{C}_1$, $\mathbf{C}_2$, $W_1^i(s)$ and specify the desirable dynamic for $i$-th SISO-system. $N$=1 ($N$ - iteration number).

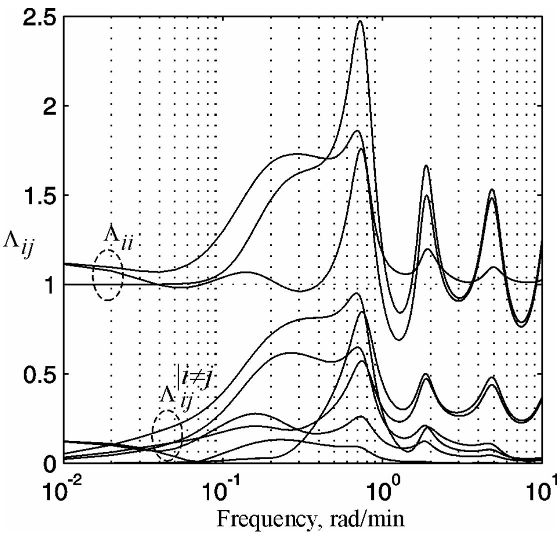


Fig. 3. Elements of relative gain matrix as function from frequency ($i$=1,2,3; $j$=1,2,3).

Step 1. To obtain transfer matrix for the system on fig.4 using (8).

Step 2. To derive values of $W_u^i(s)$ by means of (6).

Step 3. To perform the design of $i$-th robust controller based on the eq. (3)-(6).

Step 4. To complete the current iteration if steps 1-3 were passed for all $i$ from 1 to $n$. $N$ increases by 1.

Step 5. If $\left\| C_1^N(j\omega) - C_1^{N-1}(j\omega) \right\|_\infty < \varepsilon$ and $\left\| C_2^N(j\omega) - C_2^{N-1}(j\omega) \right\|_\infty < \varepsilon$ are fulfilled for $\forall \omega$ then make termination of synthesis.

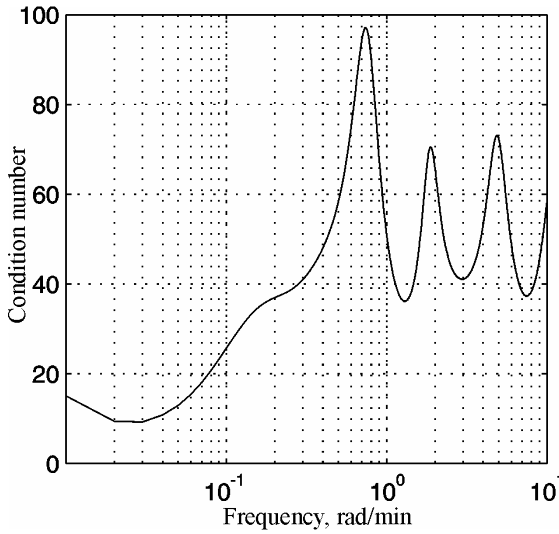


Fig. 4. The variation of condition number of transfer matrix (1).

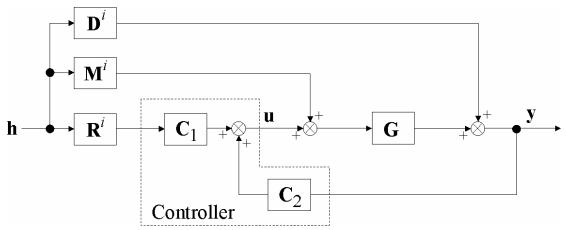


Fig. 5. The multi-loop control system for $W_2^i(s)$ estimation: **h** – vector of external signals.

The Tables 1-2 contain the parallel testing using proposed sequential design technique. The elements of the controller matrices pointed in table 1 were derived based on the minimization of structural singular value $\mu$ (Skogestad and Postlethwaite, 1996). The $\mu$ is an expression of the robust performance of control system. The second table reflects the usage of proposed approach. The $T_{cl}^i$ ($i$=1,…,$n$) was 120 min in both cases. As it was expected, the $\mu$ value in the second case is more higher because of its missing in optimization problems (3)-(6). It means that the total control system has a lack of robustness but in the same time has higher speed of response. Such result was obtained because of the exclusion of worst case inputs directionality acting on the **S** and **T** which is conventionally expressed by the maximum singular values of **S** and **T**. It was considered only directionality which takes place in the real plant operating conditions by means of additional matrices on the fig. 4. The singular values of the final **S** and **T** are depicted on the Fig.7.

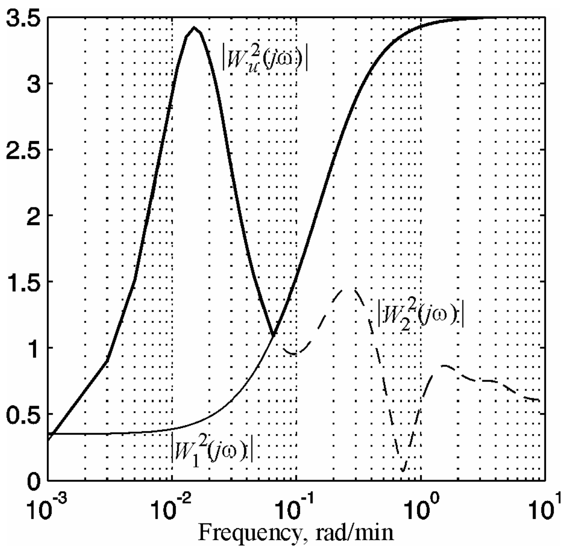


Fig. 6. The example of $W_u^2(j\omega)$ evaluation.

In order to check calculation results in Tables 1-2 the industrial experiments were implemented for RD column (fig.1). The top pressure ($P$) is main and disturbance-sensitive parameter. It is good indicator of mass transfer and rate of reaction. The operators frequently change the set point for $P$. The desirable values of $T$ and $L$ are almost always constant. Figures 8-9 show responses of the multi-loop control on the step change of $P$ set point approximately at identical initial conditions. In both cases controllers demonstrated successful suppression of interactions among the loops. The high speed of response with same robustness (with respect to model uncertainty and high frequency disturbances) is obtained with the help of the offered second controller.

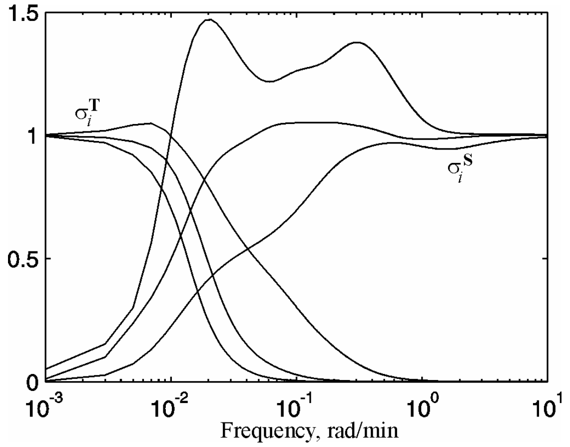


Fig. 7. Singular values of the sensitivity functions of the multi-loop control system with resulting robust PID-controller ($i$=1,2,3).

CONCLUSION

The calculated values of the matrices elements in Tables 1-2 correspond to structure of the PI-controller. It is caused by that the derivative time in a control algorithm leads to decrease of robustness because of increase singular values of weighted sensitivity functions (4)-(5) in high frequency domain. The given fact will agree with the results gotten in the previous research (Bao *et al*, 1999).

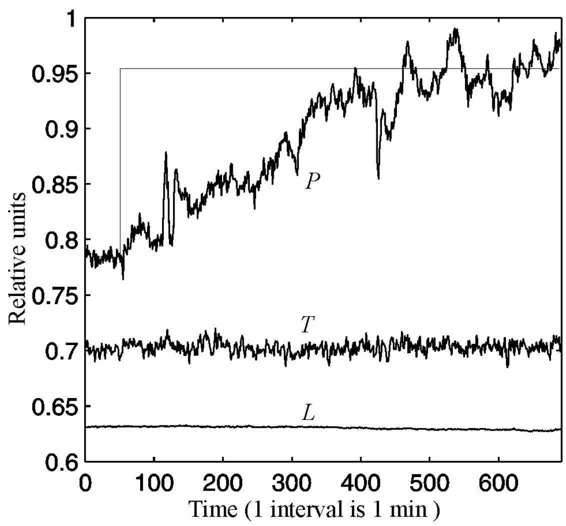


Fig. 8. Industrial test of robust controller: conventional design.

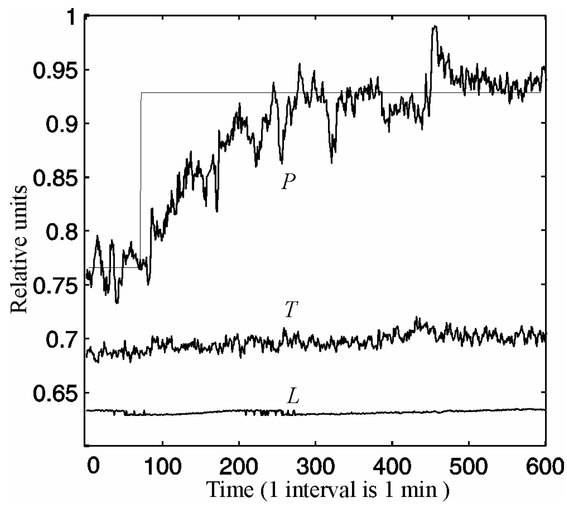


Fig. 9. Industrial test of robust controller designed by using proposed approach.

The proposed procedure of iterative synthesis allows to carry out calculation of each SISO-system independently using reduced measure of loops interaction as (9). The industrial experiments for RD column testify the approach validity, at which the worst input signals directionality for S and T is excluded from consideration in case of conformity of the given assumption in process operation conditions.

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Table 1 The results of conventional robust controller design

| № | Matrix | $\mu$ |
|---|---|---|
| $\mathbf{C}_1$ | $\begin{pmatrix} \frac{-0.22s-0.0014}{s} & 0 & 0 \\ 0 & \frac{1.11s+0.044}{s} & 0 \\ 0 & 0 & \frac{3.33s+0.02}{s} \end{pmatrix}$ | 1.86 |
| $\mathbf{C}_2$ | $\begin{pmatrix} \frac{1.16\cdot10^{-5}s+1.4\cdot10^{-3}}{s} & 0 & 0 \\ 0 & \frac{-3.7\cdot10^{-4}s-0.044}{s} & 0 \\ 0 & 0 & \frac{-1.7\cdot10^{-4}s-0.02}{s} \end{pmatrix}$ | |

Table 2 Results of proposed approach application for robust controller synthesis

| № | Matrix | $\mu$ |
|---|---|---|
| $\mathbf{C}_1$ | $\begin{pmatrix} \frac{-s-0.011}{s} & 0 & 0 \\ 0 & \frac{1.516s+0.101}{s} & 0 \\ 0 & 0 & \frac{2.22s+0.015}{s} \end{pmatrix}$ | 2.36 |
| $\mathbf{C}_2$ | $\begin{pmatrix} \frac{9.26\cdot10^{-5}s+0.011}{s} & 0 & 0 \\ 0 & \frac{-0.0008s-0.101}{s} & 0 \\ 0 & 0 & \frac{-0.00013s-0.015}{s} \end{pmatrix}$ | |