REAL-TIME OPTIMIZATION OF DISTILLATION COLUMN VIA SLIDING MODES

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Abstract: The real-time optimization (RTO) system of distillation column has been proposed using sliding modes. On the basis of formulated optimization problem, the parameters for the distillate composition controller are so selected that the condition for the occurrence of sliding modes holds in order to provide a search procedure. An investigation of the transient performance of RTO-system under feed composition disturbances indicated a stable tracking for the shifted optimal distillation operating points.

Keywords: Distillation columns, Sliding-mode control, Optimization, Uncertain dynamic systems, Disturbance rejection.

1. INTRODUCTION

The maintaining an optimal steady-state of the distillation column in chemical industry presents the important task for control system. Due to the large-scale distillation dynamic model, the optimal controller can not be found using, for example, principle of maximum technique or another analytical method. The high dimensionality of distillation model is inciting the researchers to develop the more efficient RTO-systems in which the real model complexity can be considered as uncertainty.

Nowadays the widespread approaches for process optimization in real-time are divided on the two main groups: model-based (Duyfjes and Grinten, 1973; Forbes and Marlin, 1996; Cheng and Zafiriou, 2000) and direct search strategies (Rastrigin, 1974). The separate place among the methods of the optimal process operation search has a self-optimizing control guaranteeing a determination only a sub-optimal solution with the minimum criterion losses (Skogestad, 2000).

The main drawback of the model-based RTO-systems is the model uncertainty. In this case the identification procedure is required for the updating model parameters. Moreover, it is difficult to predict the final time of identification under continuously acting disturbances. In this issue the optimization process can lose a convergence property and may be unstable. Some results concerning the model-based RTO-systems design are generalized in the work (Zanin, *et al.*, 2000). It was shown that the integration a model-based strategy with Model

Predictive Control (MPC) sometimes does not provide a successful search, for example, using Sequential Quadratic Programming (SQP).

The direct search strategy does not depend from the accuracy of the model. The sequence of steps are organized in the direction of the criterion gradient descent. At the final steps, the stable auto-oscillations are observed near the criterion extremum neighbourhood. As noted in the work (Rastrigin, 1974), such RTO-systems fall into two main types. The first one is the backspacing -based systems. During the backspacing-based search, the switching of the optimizable variable (x) is fulfilled if the criterion derivative $dQ(x)/dx$ (where $Q(x)$ - criterion) reaches the small given value. The second type of the direct search systems is the RTO strategy based on the synchronous detection. Using the synchronous detection technique, the harmonic excitation signal (for instance, a sinusoid wave) arrives at the plant input and the criterion value is obtained. The phase between input and output is detected and the magnitude of $dQ(x)/dx$ is estimated by the corresponding manner in order to get an appropriate moving into extremum.

The common lack of the direct search approaches is the necessity to measure a gradient of function. In the real industrial conditions it is often possible to get an inaccurate gradient of function. This is the cause of the continuos or unstable search procedure. The work [7] shows that the sliding modes can be applied for the static optimization problem solution and it is unnecessary to measure criterion derivatives.

The present paper proposes the RTO-system based direct search via sliding modes. The profit is considered as criterion for developed RTO-system. The feed composition disturbances generate a drift of the optimal distillation steady-states. It will be demonstrated that the RTO-system is insensitive for the disturbances influence in the sliding mode and capable to track the optimal process performance.

2. RTO PROBLE FORMULATION

In this section we consider a steady-state optimization problem of the distillation column adopted from the work (Skogestad, 2000) because of its simplicity and convenience for a demonstration of developed RTO-system. The two product binary distillation column is examined (fig.1). The relative volatility of the separated compounds has the constant value α=1.12. The concentration of the light component comprises 99.5% in the distillate. The bottoms purity specification is not given. The distillate (D) and vapor boil-up (V) are taken as manipulated variables and the overhead product purity is adjusted by the distillate flow (fig.1). The column has one degree of freedom (i.e. V). Table 1 contains the nominal steady-state parameters of the distillation column. The profit function is formulated in the following way

$$P=p_D D+p_B B-p_F F-p_V V,$$

where the prices are given in [\$/kmol]: p_D=20; p_B=10-20x_B; p_F=10; p_V=0.1. Consider the case when there are no restrictions on the D and V. The RTO problem can be stated as the tracking task for the minimum of the function J=-$P(V)$ under feed composition disturbances z_F (fig. 2). Notice that such disturbance type has the significant and nonlinear affecting on the shifting of the criterion extremum as compared with a feed flow rate or liquid phase in the feed disturbances.

Table 1 Nominal operating point of the distillation column

Parameter	Value
Feed flow rate	F = 1 kmol/min
Vapor boil-up	V = 15.6381 kmol/min
Distillate flow rate	D = 0.6381 kmol/min
Feed composition (light component)	z_F = 65 %
Distillate composition	x_D = 99.5 %
Bottoms composition	x_B = 4.1575 %
Liquid phase in the feed	q_F = 1
Total number of trays	N = 112
Feed tray number	f = 39

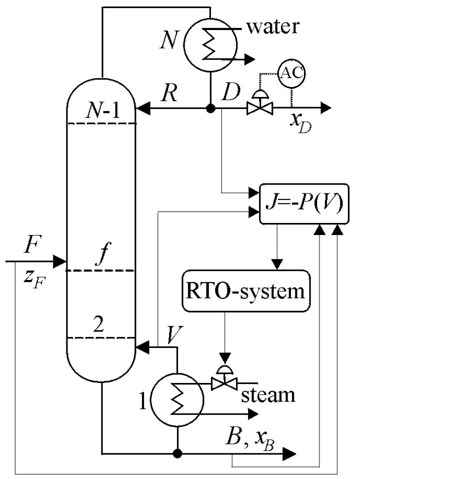

Fig. 1. The sketch of distillation column and RTO-system.

3. SLIDING MODES BASED RTO-SYSTEM FOR DISTILLATION COLUMN

As discussed in the work (Korovin and Utkin, 1974), the sliding modes can be successfully applied in the solving of static optimization problems. The framework of this approach is as follows. The plant output is compared with a certain specially selected reference input which is a monotonically decreasing function of time. Input actions of the plant are obtained from the difference between the output and the reference input and should reduce this difference to zero. As a result the plant output follows the monotonically decreasing setpoint and reaches a minimum. The main feature of this kind of tracking system is that the value and the sign of the varying local gain are unknown. The RTO-system must provide a trend in the plant output variation such that its output should always decreases by following up the reference input.

The proposed scheme of the sliding modes based RTO-system is depicted on the fig. 3 and described by the following equations (taking into account our statement of optimization problem)

$$J=-P(V),\ V=u,\ u=u_0\mathrm{sign}(\sigma_1\sigma_2),$$
$$\sigma_1=\varepsilon,\ \sigma_2=\varepsilon+\delta,\ \varepsilon=g-J, \qquad (1)$$

where $\frac{dg}{dt}=-\rho+h(\sigma_1\sigma_2)$;

$$h=\begin{cases}-M, if\ \sigma_1-\Delta>0\ and\ \sigma_2>0\\ 0,\ if\ (\sigma_1+\Delta)(\sigma_2-\Delta)<0\\ +M, if\ \sigma_1<0\ and\ \sigma_2+\Delta<0\end{cases}.$$

The switching elements are shown in the fig.4.

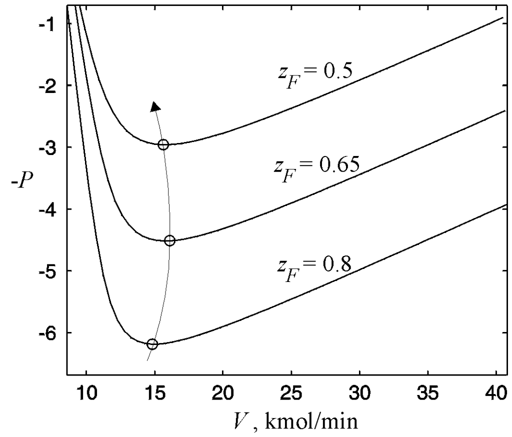

Fig. 2. Shifted optimum of the criterion under various z_F and constant value of x_D=99.5 %.

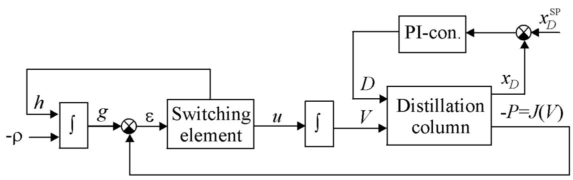

Fig. 3. RTO-system based on the sliding modes for distillation column with the distillate composition control loop (PI-controller).

The parameters of the RTO-system (fig.3) are chosen in accordance with the instructions cited in the article (Korovin and Utkin, 1972). The drift of the steady-state operating point is provided under disturbances rejection by the PI-controller in order to meet the following inequality

$$\left|\frac{\partial J(V)}{\partial V}\right|u_0\le\left|\frac{\partial J(V)}{\partial t}\right| \qquad (2)$$

Here, the parameters of the PI-controller are defined so that response time of the x_D-D control loop is significantly faster as compared with the P-V optimization loop. The transfer function of PI-controller has the form (subject to eq. (2))

$$W_{\mathrm{PI}}(s)=5\frac{0.1s+1}{0.1s}. \qquad (3)$$

For ensuring the sliding modes in the RTO-system, the following values of the variables in (1) were derived:

ρ=0.0006, u_0=0.0025, M=5, δ=1, Δ=0.1.

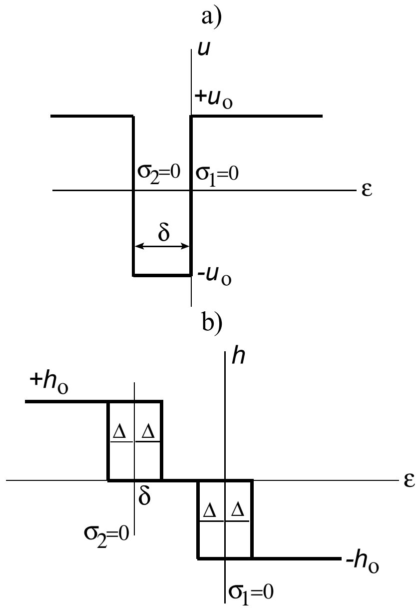

Fig. 4. Switching elements of RTO-system.

The dynamic distillation model of the considered column consists from 110 differential equations. The liquid and vapor molar flows inside the column are assumed to be constant. The liquid flows hydrodynamics is neglected. This model is so simple but contains the main features of the process and gives the possibility to analyze the proposed RTO-system. The disturbances variations schedule is presented in the Table 2 for three time intervals.

Figure 5 depicts the simulation results of the transient performance for RTO-system according to the feed composition disturbances in Table 2. It should be pointed that the system operating in the sliding mode is low-sensitivity for the acting feed composition disturbances and provides the automatic tracking of the optimal process steady-state.

Table 2 Operating points of distillation column under various feed compositions (RTO results)

No	Time (min)	z_F (kmol/kmol)	$-P^{opt}$ [$/min]	V^{opt} (kmol/min)
1	0-4000	0.65	-4.52	16.05
2	4000-8000	0.8	-6.19	15.80
3	8000-12000	0.5	-2.96	14.70

4. CONCLUSION

The application of sliding modes in RTO-system design for a distillation column has been proposed in the present paper. There are two main advantages of the developed RTO-system:

1) the missing of the criterion derivatives measurements for the establishing of the search procedure;
2) the independence from the uncertainty of a first-principle model as in the model-based RTO-systems.

The optimum operating points tracking task becomes more complex under disturbances influence because it is difficult to measure the vector-gradient function at the non-stationary conditions. Therefore, the RTO-system parameters (1)-(2) selection represents a try-and-error technique.

It was shown that the proposed RTO-system ensured a stable convergence toward the optimal distillation column steady-states even though the large initial deviations of the optimized variable from the V^{opt} and various feed composition disturbances were involved.

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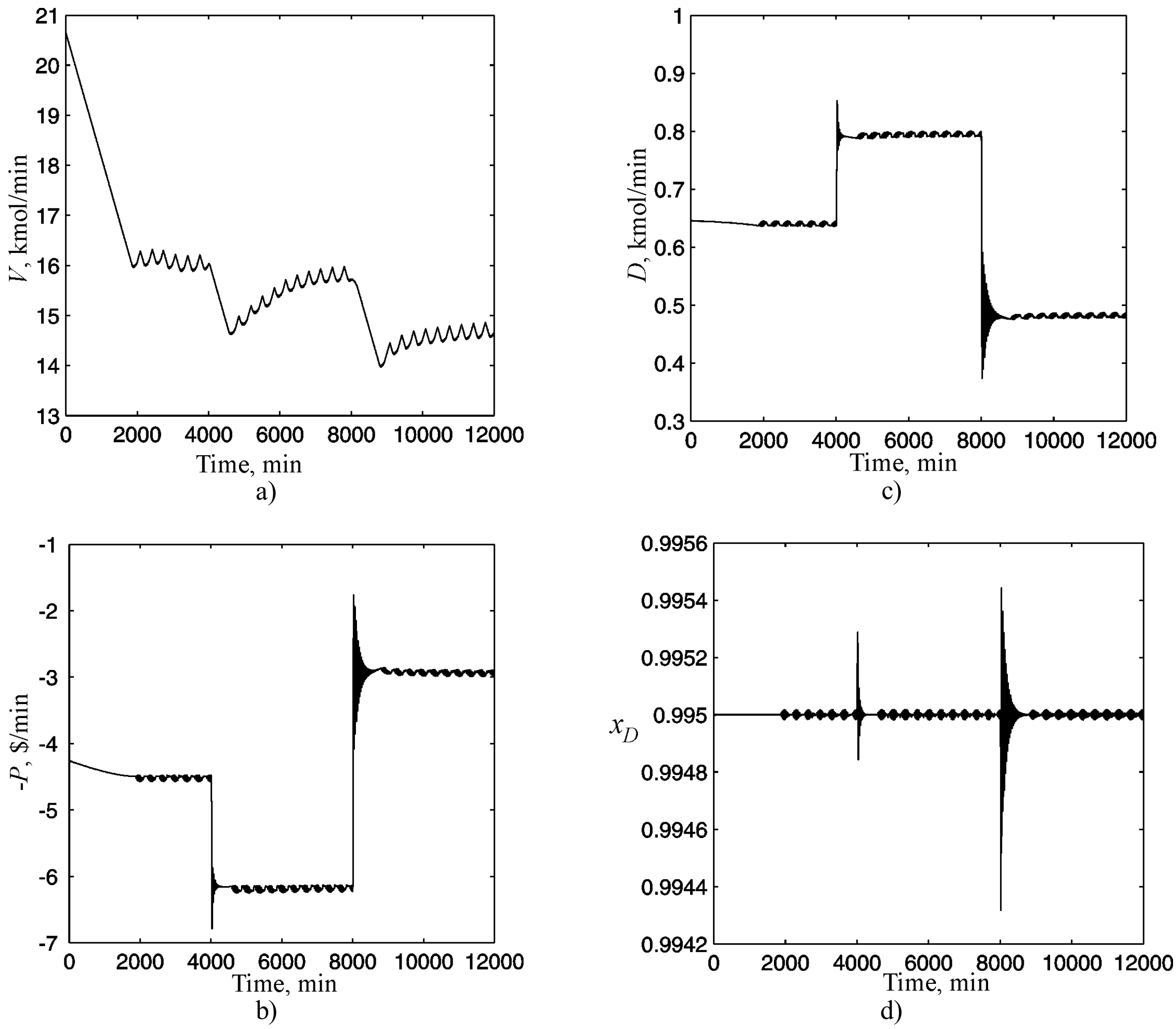

Fig.5(a-d). Optimal operating points tracking for distillation column by the sliding modes based RTO-system.