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Bypass Control System Design for HENs Based on Frequency Domain Analysis

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In this paper, a new approach to address bypass control system design for heat exchanger networks (HENs) is proposed based on frequency domain analysis. The classical bypass control system design methodology relies on the calculation of the relative gain array (RGA) which is commonly used as a measure of the interaction. The main drawbacks of this approach are the difficulties of analyzing the unstable process, and the complexity of measuring stability. Instead, the key idea of this work is to take stability margins into consideration when potential bypasses and controlled variables are paired. Firstly, on the basis of dynamic model, small singular values of the return difference matrix are presented for the simultaneous analysis of stability margin and flexibility. Secondly, the non-square relative gain array (ns-RGA) in the frequency domain is applied to study the interactions of potential bypasses and controlled variables, and some pairing rules are proposed. Thirdly parameters of PID controller are designed while phase margin and gain margin are in proper region, then the final pairing scheme is determined. Case studies illustrated the necessity to consider stability margins during the process of the bypass control system.

1. Introduction

The application of bypasses has been demonstrated for effective control of a target temperature. However, on one hand, as strong interaction exists in streams, HENs designed according to the chemical process often do not have enough bypasses. On the other hand, bypasses will also affect stability and optimality of HENs. Therefore, the BCS design is a challenging problem.

Stability margins often refer to gain margin and phase margin and are studied in many works. Structural singular value μ is proposed to calculate stability margins (Doyle, 1982). Safonov (1982) developed a readily computable lower bound for diagonally perturbed systems. Wang et al. (2014) pointed out that the distance between operating point and Hopf singular point is used as a measure of stability. Lehtomaki et al. (1981) proposed the concept of minimum singular value of return difference matrix which pays attention on gain margin and phase margin simultaneously. This paper intends to study the application of minimum singular value of return difference matrix in HENs.

Flexibility is a fundamental requirement of HENs and previous works on flexible analysis and designs are under the assumption that all control variables can be adjusted and HENs is stable. However, flexible HENs may come to be unstable with the existence of disturbance. Jiang et al. (2014) took stability into consideration when analyzing flexibility and they have a conclusion that flexible region contains unstable parts. However, they did not study the relationship between stability margins and flexibility.

Bypasses are widely used for optimizing the operation of HENs to maintain the control requirements. A key issue of BCS is particularly relevant to select the appropriate potential bypasses and controlled variables. Relative gain array (RGA) was introduced by Bristol (1966) and is commonly used as a measure of interaction. Flexibility and controllability are taken into consideration at the process of BCS simultaneously. A computational framework is proposed for the synthesis of HENs where flexibility and controllability are studied simultaneously (Escobar et al., 2013). A sequential procedure for flexible HEN synthesis and control structure design has been proposed by Braccia et al. (2018). RGA in the frequency domain is proposed (Xu et al., 2016) and can used to analyze the unstable process. Therefore, this work plans to introduce RGA in the frequency domain to HENs.

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PID controller is widely placed to ensure control performance. Nonetheless, the design of PID controller has not been an integral part of BCS design. There are several design schemes for optimally tuning PID parameters. PID parameters adjustment method is proposed in HENs under fouling conditions (Trafczynski et al., 2016). Carvalho et al. (2018) introduced tune strategies for overcoming fouling effects in PID controlled heat exchangers. Basically, they are based on the time-domain.
This paper investigates the incorporation of stability margins and BCS design. A method is presented to design optimal bypasses while achieving proper stability margins based on frequency domain analysis. Firstly, stability margins of HENs are analysed. Secondly, RGA in the frequency domain is applied to obtain the interaction of potential bypasses and controlled variables, and some pairing rules are given. Thirdly PID parameters are projected to design so that a single control system achieves proper stability margins.

2. Stability margin analysis of HENs

Stability is a prerequisite for a control system and stability criterion of open-loop system can be obtained according to Argument Principle,

$$P = R + Z = 0 \tag{1}$$

Where P is the number of open-loop system poles in the right half-plane, Z is the number of open-loop system zeros in the right half-plane, and R is the number of turns of Nyquist curve surrounding the origin. When P is equal to 0, the open-loop system is stable.
This paper will study stability margins of HENs based on the inverse return difference matrix (Li et al., 2014).

$$\begin{aligned} GM &= 20\lg(1+m) \\ PM &= 2\arcsin\frac{m}{2} \end{aligned} \tag{2}$$

Where m is minimum singular value of the inverse return difference matrix of HENs, PM is phase margin and GM is gain margin.
Stability and flexibility have been analyzed by Jiang et al. (2014) simultaneously. However, they did not take a deep insight into different stable points with different flexibility as shown in Figure 1.

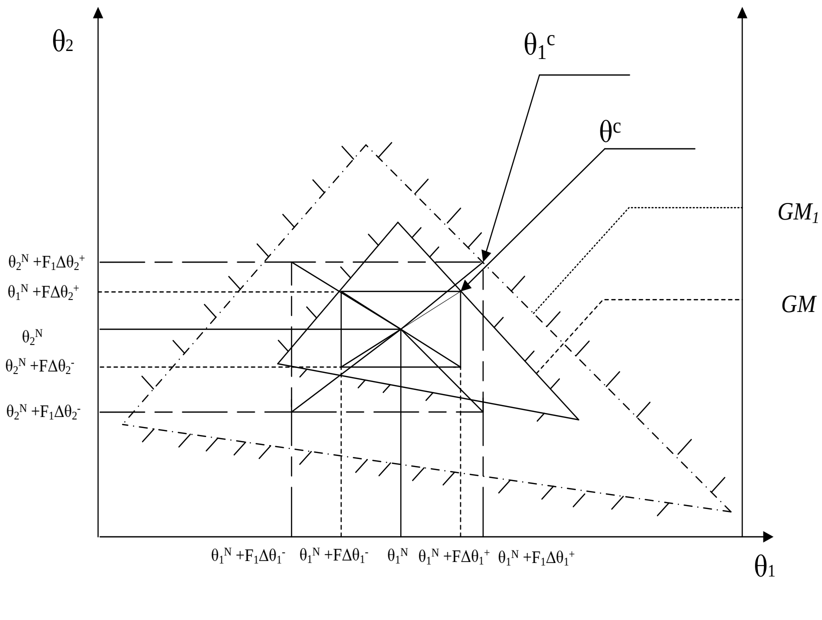


Figure 1: Flexible region with different stability margins

In Figure 1, flexibility index, gain margin and phase margin of HENs are F, GM and PM respectively when the design variable is d. Flexibility index, gain margin and phase margin of HENs are F_1, GM_1 and PM_1 respectively when design variable is d_1 .
A simple HENs provided by Sun et al. (2011) will be used to illustrate the relationship between stability margins and flexibility index. The nominal data is listed in Table 1 and the structure is showed in Figure 2.

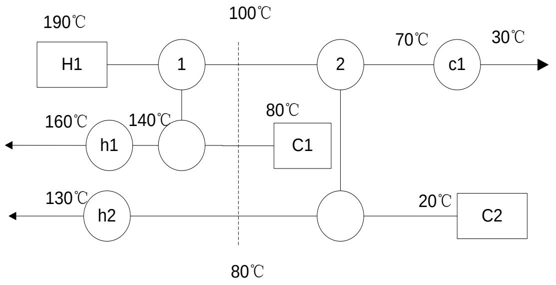
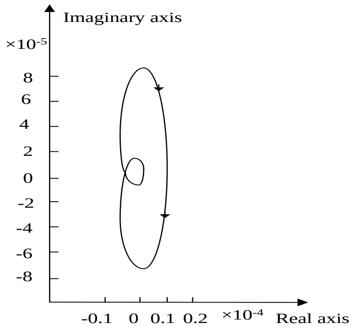


Figure 2: The structure of HENs

Table 1: The parameters of the hot and cold fluid

Stream number	Input temperature/℃	Output temperature/℃	Heat capacity/(MW/℃)
Hot(H1)	190	30	0.10
Cold1(C1)	80	160	0.15
Cold2(C2)	20	130	0.05

When the area of heat exchanger 1 and heat exchanger 2 is 1258.71 m^2 and 428.57m^2, the Nyquist curve is shown in Figure 3a.



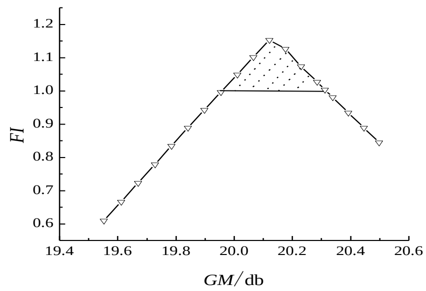


Figure 3a: Nyquist curve of HENs

Figure 3b: Relationship between flexibility index and gain margin

As shown in Figure 3a, the number of turns of Nyquist curve enveloping (0,0j) is 0, and the number of open-loop system zeros in the right half-plane is 0, so the HENs is stable.
In order to have better dynamic characteristics, gain margin of control systems is generally taken as A_m=[3, 6], and phase margin is taken as φ_m= [30°, 60°]. It can be known from Figure 3b that when the *FI* is more than 1, gain margin is more than 6db. So the HENs is over stable and PID controller should be placed to improve stability margins at the process of BCS design.

3. HEN control system design

3.1 HEN frequency domain RGA

Non-square RGA (ns-RGA) is used to measure the interactions of different variables for the number of controlled and manipulated variables is usually unequal in HENs. Compared with conventional ns-RGA in the time domain, in this paper *s* is replaced by *jω*, then *G(s)* in the time domain becomes *G(jω)* in the frequency domain. Assumed that there are *q* controlled variables and *n* potential bypasses in HENs. Ns-RGA in the frequency domain can be calculated by Eq(3) for *q* times.

$$\Lambda(\omega) = G(j\omega) \otimes [G^{\phi}(j\omega)]^{T} \quad (3)$$

The symbol ⊗ means an element-by-element multiplication (Schur product). $G^{\phi}(j\omega)$ is the pseudo-inverse matrix of *G(jω)*.

Each element in Eq(3) is plural number and cannot quantitatively analyse the impact of each potential bypass on the controlled variable. Then interaction measurement index (IMI) and the unit circle diagram in complex plane are proposed (Xu et al., 2016).

Steps of calculating IMI in HENs is as following,

Step 1: Choosing proper controlled variables and potential bypasses of HENs, then calculate the *Λ(ω).*

Step 2: Assumed that the element $\Lambda_{\mathrm{ip}}(\omega)$ in $\Lambda(\omega)$ is described as a(ω)+ b(ω)j, and then the distance between $\Lambda_{ip}(\omega)$ and (1,0j) is formulated as $\lambda_{ip}(\omega)$. Then IMI is calculated in Eq(4),

$$D_{\mathrm{ip}} = \frac{1}{\omega_n - \omega_0} \int_{\omega_0}^{\omega_n} \lambda_{\mathrm{ip}}(\omega) d\omega \tag{4}$$

The method based on the unit circle diagram in complex plane is as following,

Step 1: Choosing the controlled variables and potential bypasses of HENs, then calculates the *Λ(ω).*

Step 2: Since *Λ(ω)* is a function of ω, the integral mean of *Λ(ω)* to *ω* is calculated in Eq(5). And Λ_0 is defined as average ns-RGA in the frequency domain.

$$\Lambda_0 = \frac{1}{\omega_n - \omega_0} \int_{\omega_0}^{\omega_n} \Lambda(\omega) d\omega \tag{5}$$

In this paper the ω_0 is 0, and the ω_n is the bandwidth.

Based on ns-RGA in the frequency domain, some principles are obtained when potential bypasses and controlled variables in a control loop are paired.

(1) Removing the potential bypasses with interaction measurement indexes of 1 or close to 1.

(2) Drawing the remaining bypasses on unit circle of complex plane and removing the bypasses in the III and IV regions.

(3) Selecting the point close to the (1, 0j) point on unit circle of complex plane as the potential optimal bypass.

3.2 Controller parameters design

The interaction of potential bypasses and controlled variables is analyzed in section 3.1. However, controller parameters are neglected making it hard to meet stability margins.

Assume that HENs is a second-order system, and its frequency characteristics are describe as Eq(6),

$$G(j\omega) = \frac{d + c\omega j}{\mathrm{b} - \omega^2 + ja\omega} \tag{6}$$

The frequency characteristics of PI controller is shown in Eq(7),

$$G_c(j\omega) = K_P - \frac{K_I}{\omega} j \tag{7}$$

The frequency characteristics of control system is shown in Eq(8),

$$G(j\omega)G_c(j\omega) = \frac{d + c\omega j}{(\mathrm{b} - \omega^2 + ja\omega)}(K_p - \frac{K_I}{\omega} j) \tag{8}$$

Controller parameters K_P and K_I are non-negative. Assumed that gain margin and phase margin are A_m and φ_m respectively. The crossover frequency and cut-off frequency are ω_x and ω_c.

$$\begin{cases} K_P = -\dfrac{(bd - d\omega_{\mathrm{x}}{}^2 + ac\omega_{\mathrm{x}}{}^2)}{A_m(c^2\omega_{\mathrm{x}}{}^2 + d^2)} \\ K_I = \dfrac{\omega_{\mathrm{x}}(c\omega_{\mathrm{x}}{}^3 + ad\omega_{\mathrm{x}} - bc\omega_{\mathrm{x}})}{A_m(c^2\omega_{\mathrm{x}}{}^2 + d^2)} \end{cases} \tag{9}$$

$$\begin{cases} K_P = \dfrac{\omega_{\mathrm{c}}\sin(\varphi_m)(ad - bc + c\omega_{\mathrm{c}}{}^2)}{c^2\omega^2 + d^2} - \dfrac{\cos(\varphi_m)(bd - d\omega_{\mathrm{c}}{}^2 + ac\omega_{\mathrm{c}}{}^2)}{c^2\omega^2 + d^2} \\ K_I = \dfrac{\omega_{\mathrm{c}}\sin(\varphi_m)(bd - d\omega_{\mathrm{c}}{}^2 + ac\omega_{\mathrm{c}}{}^2)}{c^2\omega_{\mathrm{c}}{}^2 + d^2} + \dfrac{\omega_{\mathrm{c}}\cos(\varphi_m)(ad\omega_{\mathrm{c}} - bc\omega_{\mathrm{c}} + c\omega_{\mathrm{c}}{}^3)}{c^2\omega_{\mathrm{c}}{}^2 + d^2} \end{cases} \tag{10}$$

Therefore, a proper region of K_P and K_I can be calculated by Eq(9) and Eq(10) to meet the requirements of stability margins.

A control loop should meet the stability requirements. Figure 4 shows the steps of BCS design in HENs based on frequency domain analysis.

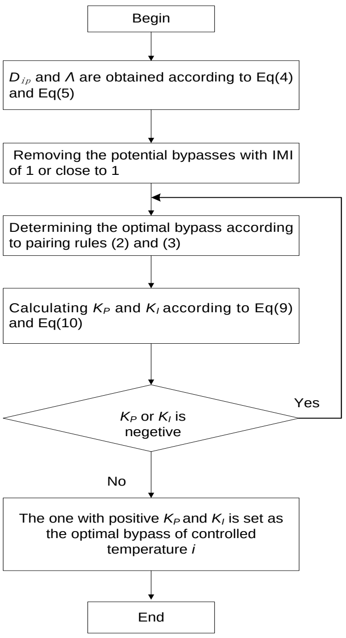


Figure 4: Control system process design of HENs

4. Case study

A simple HENs provided by Sun et al. (2011). The controlled target is the output temperature of hot stream and there are four potential bypasses in this HEN. The IMI in the frequency domain are shown in Table 2. According to pairing rules, Ns-RGA in the frequency domain described on the unit circle diagram are shown in Figure 5a. From the Figure 5a, the hot stream of heat exchanger 2 is the potential optimal bypass.

Table 2: IMI and ns-RGA in the frequency domain

Potential bypasses	Hot stream of heat exchanger 1	Cold stream of heat exchanger 1	Hot stream of heat exchanger 2	Cold stream of heat exchanger 2
IMI	0.6356	0.9623	0.4805	0.8886

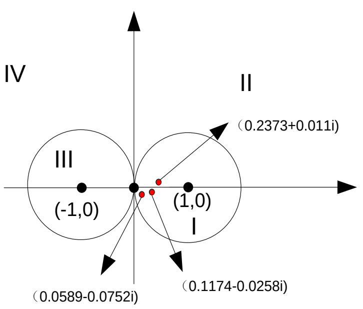


Figure 5a: Average ns-RGA in the frequency domain

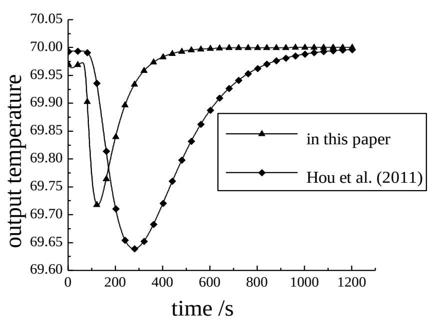


Figure 5b: Output temperature of hot stream

K_P and K_I are designed according to Eq(9) and Eq(10). When K_P and K_I is 0.5334 and 0.942, respectively, the gain margin and phase margin are 52db and 36°. K_P and K_I are non-negative. So the hot stream of heat exchanger 2 is the optimal bypass.

Hou et al. (2011) have studied structural controllability to design optimal bypass location and the result of optimal bypass is hot stream of heat exchanger 1 based on structural controllability. Therefore, when the input temperature of hot stream is changed from 190℃ to 185℃, the output temperature of hot stream under the control of Hou et al. (2011) and this paper is shown in Figure 5b. It can be concluded from Figure 5b that output temperature in this paper has faster response speed and smaller overshoot than the method in Hou et al. (2011); hence the control performance is better.

5. Conclusions

In this work bypass control system design based on frequency domain analysis considering stability margins has been addressed because previous studies only explored ns-RGA in the time domain using steady-state HENs. Then ns-RGA in the frequency domain is proposed to optimize potential bypasses. The main conclusions of this paper are as follows:

(1) It is proved that the flexible HENs is over stable, and stability margins should be considered when designing the control system.

(2) The IMI and ns-RGA in the frequency domain is used to analyze the optimal bypass combined the dynamic characteristics. On the basis of optimal bypasses and tuning strategies in PI controlled HENs, the control system will have a proper stability margins with gain margin of 3db-6db and phase margin of 30°-60°.

(3) This method will have a better control performance compared with other method based on ns-RGA in the time domain.

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