A Robust PID Autotuning Method Applied to the Benchmark PID18

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Abstract: In this paper a proportional-integral-derivative (PID) autotuning control strategy is presented and applied to the benchmark system presented at the 3rd IFAC Conference on Advances in Proportional-Integral-Derivative Control (PID18). The automatic tuning of controller gains is based on a single sine test, with user-defined robustness margins guaranteed. Its performance is compared against a model based designed controller with computer-aided design tool based on frequency response (FRtool) and against the benchmark reference controller. The closed loop control simulations, applied on the benchmark, indicate that the method properly performed.

Keywords: KC autotuner, PID control, Multi-input and multi-output, Modulus margin, Refrigeration system.

1. INTRODUCTION

Refrigeration technology is widely used in our daily life, involved in a widely area such as food storage, generating comfortable artificial environment and industrial production and medical cryosurgery (Bejarano et al., 2017). The typical power ranges from less than 1KW to above 1MW (Rasmussen et al., 2005). A great deal of energy is consumed in these processes, therefore affecting the balance of plant-wide cost-energy savings (Buzelin et al., 2005). Hence, it is important to develop effective control strategies for accurate temperature control and energy savings.

Considering the difficulties existing in refrigeration systems such as strong nonlinearities, strong coupling between variables and dead time, many advanced control strategies have been developed to get better control effect. Multivariable H_∞ control is proposed in (Bejarano et al., 2015) where linear models are identified around different operating points. Model predictive control is proposed in (Razi et al., 2006; Sarabia et al., 2009; Ricker, 2010; Fallahsohi et al., 2010). Normalized decoupling method is applied to this strong coupling system (Shen et al., 2010), and then the PID control is designed to meet the performance objectives. Decentralized PID controllers are also studied to obtain better refrigeration performance (Wang et al., 2007; Marcinichen et al., 2008; Salazar and Mendez, 2014). However, these methods require a model of the refrigeration system, and identification is still a burden in real life applications.

To overcome the need for identification, a manifold of PID parameters autotuning methods have been proposed. One of the most used PID autotuner is Ziegler-Nichols (Z-N) method (Ziegler et al., 1942), which has good performance in disturbance rejection. However, Z-N method gives poor performance for processes with a dominant delay. Other PID autotuners such as Åström-Hägglund (AH) autotuner and Phase Margin (PM) autotuner (Åström et al., 1984, 2006; Hang et al., 1991) are based on the critical point of control system which is extracted from the traditional relay test. However, in the benchmark case there is no critical point. At the same time, from analysis reported in (De Keyser et al., 2010), it can be seen that these method are not good for all types of dynamic processes.

In this paper, a new type of PID autotuner named KC method is applied to the Benchmark system. The method is based on defining a ‘forbidden region’ in the Nyquist plane based on user-defined specs, which will guarantee the system margin requirements. Firstly, apply sine test on the system at a specific frequency. Then design the ‘forbidden region’ in the Nyquist plane. Finally, search the PID controller, which will guarantee the loop frequency response to be tangent to this ‘forbidden region’.

This paper is structured as follows. In section 2, the MIMO refrigeration control system is described. The detailed theory of KC method and FRtool is shown in the section 3. Finally, the simulation results and conclusions are given in section 4 and section 5 respectively.

2. DESCRIPTION OF THE REFRIGERATION SYSTEM

The refrigeration system is shown in Fig.1. The system mainly consists of condenser, compressor, evaporator and expansion valve. The objective of this cycle is to remove heat at the evaporator from its secondary flux and reject heat at the condenser by transferring it to the condenser secondary flux. This system works as follows. Firstly, the refrigerant enters the evaporator at low temperature and pressure, and it evaporates while removing heat from the evaporator secondary flux. Secondly, the compressor increases the refrigerant pressure and temperature and it enters the condenser. Thirdly, the refrigerant condenses and may become subcooled liquid while transferring heat to the condenser secondary flux. Finally, the expansion valve closes the cycle by upholding the pressure from the condenser to the evaporator (Bejarano et al., 2017).

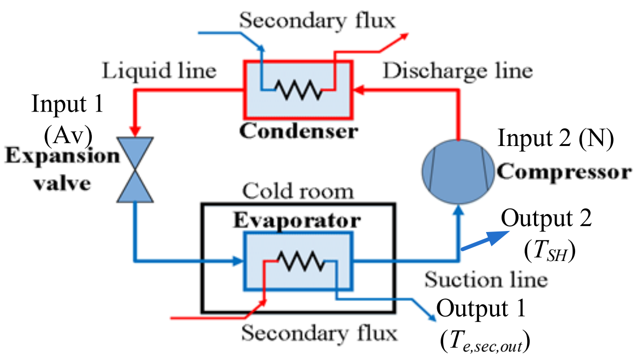

Fig. 1. Scheme of one-compression-stage, one-load-demand vapour- compression refrigeration cycle

Table 1. Variable ranges and operating point

Variables		Range	Operating point	Units
Input variables	A_v	[10-100]	≈50	%
	N	[30-50]	≈40	Hz
Disturbances	$T_{c,sec,in}$	[27-33]	30	°C
	$\dot{m}_{c,sec}$	[125-175]	150	g s^{-1}
	$P_{c,sec,in}$	—	1	bar
	$T_{e,sec,in}$	[-22 - -18]	-20	°C
	$\dot{m}_{e,sec}$	[55-75]	64.5	g s^{-1}
	$P_{e,sec,in}$	—	1	bar
	T_{surr}	[20-30]	25	°C
Output variables	$T_{e,sec,out}$	—	≈-22.15	°C
	T_{SH}	—	≈14.65	°C

In this benchmark process, there are two variables (the outlet temperature of the evaporator secondary flux $T_{e,sec,out}$ and the degree of superheating T_{SH}) that need to be controlled by manipulating two variables (the compressor speed N and the expansion valve opening A_v). The other variables are regarded as disturbances, such as i) inlet temperature of the condenser secondary flux $T_{c,sec,in}$ ii) mass flow of the condenser secondary flux $\dot{m}_{c,sec}$ iii) inlet pressure of the condenser secondary flux $P_{c,sec,in}$, iv) inlet temperature of the evaporator secondary flux $T_{e,sec,in}$, v) mass flow of the evaporator secondary flux $\dot{m}_{e,sec}$, vi) inlet pressure of the evaporator secondary flux $P_{e,sec,in}$ and vii) compressor surroundings temperature T_{surr}. The parameters used in this paper are shown in Table 1 (including variable ranges and initial operating point) obtained from (Bejarano et al., 2017).

3. CONTROL DESIGN

3.1 PID control automatic tuning method

Fig. 2 illustrates the main idea of this autotuner as to move a point B on the Nyquist curve of process *P(jω)* to another point A on the Nyquist curve of the loop *L(jω)=P(jω)C(jω)* through the PID controller indicated by *C(jω)*. Hence the system can have a good dynamic characteristic according to the system performance requirements, for example a specific robustness or loop modulus margin. The tuning procedure can be summarized as follows (De Keyser et al, 2017).

1) Select a frequency $\bar{\omega}$ ($\bar{\omega}$ is usually critical frequency, but might be different)
2) Perform sine tests on the benchmark system
3) Define a 'forbidden region' in the Nyquist plane according to the loop modulus margin
4) For each point on the region border, calculate PID controller
5) Find the point where the loop *L(jω)* is tangent to the 'forbidden region'
6) The controller corresponding to the point in step 5) is the final PID controller.

In order to have the loop *L(jω)* frequency response tangent to the 'forbidden region', the slope of 'forbidden region' and slope of loop *L(jω)* should be the same. In Fig. 2, the point D and point E are obtained according to loop modulus margin. D is the intersection of gain margin with negative real axis. E is the intersection of phase margin with unit circle. According to points D and E in Fig. 2, the circle can be calculated as:

$$Forbidden\ region:\ (\mathrm{Re}+\mathrm{C})^2+\mathrm{Im}^2=R^2 \tag{1}$$

$$\begin{aligned} &D \Rightarrow\ (-1/GM+C)^2=R^2 \\ &E \Rightarrow\ (-\cos PM+C)^2+(-\sin PM)^2=R^2 \end{aligned} \tag{2}$$

and the center and radius of the forbidden region are calculated as follows:

$$\mathrm{C}=\frac{GM^2-1}{2GM(GM\cos PM-1)};\ \mathrm{R}=\mathrm{C}-\frac{1}{GM} \tag{3}$$

The slope on the point A:

$$\left.\frac{\mathrm{d}\,\mathrm{Im}}{d\,\mathrm{Re}}\right|_{\alpha}=\frac{-\mathrm{Re}+C}{\mathrm{Im}}=\frac{\cos\alpha}{\sin\alpha} \tag{4}$$

In order to get the slope of loop *L(jω)*, the derivative from *L(jω)* to *ω* is calculated.

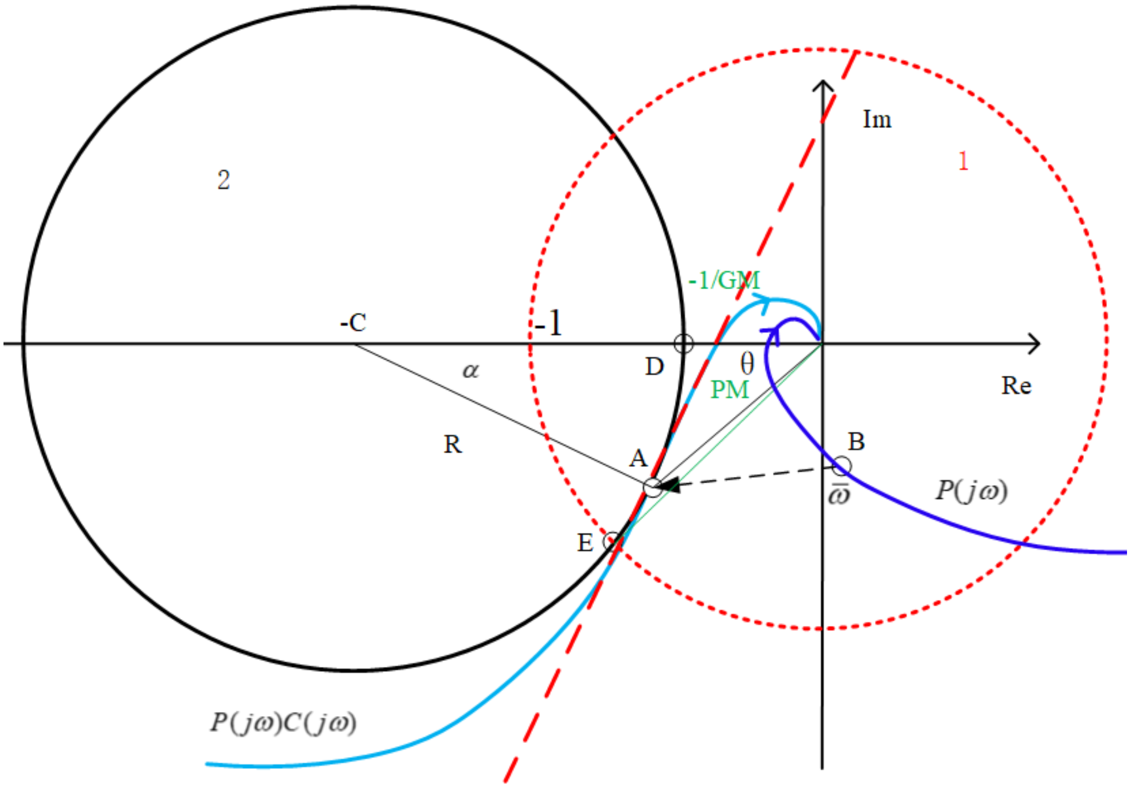

Fig. 2. Graphic illustration of autotuning principle. See text for description.

$$\frac{dP(j\omega)C(j\omega)}{d\omega} = P(j\omega)\frac{dC(j\omega)}{d\omega} + C(j\omega)\frac{dP(j\omega)}{d\omega} = \frac{d\,\mathrm{Re}_{PC}}{d\omega} + j\frac{d\,\mathrm{Im}_{PC}}{d\omega} \tag{5}$$

So $\left.\frac{d\,\mathrm{Im}_{PC}}{d\,\mathrm{Re}_{PC}}\right|_{\varpi}$ is calculated as the slope of loop $L(j\omega)$.

At point A, the following equation is obtained.

$$M_A e^{j\varphi_A} = M_{PC}(j\varpi)e^{j\varphi_{PC}(j\varpi)} \tag{6}$$

It can be rewritten as:

$$\begin{cases} M_A = M_{PC}(j\varpi) = M_P(j\varpi)M_C(j\varpi) \\ \varphi_A = \varphi_{PC}(j\varpi) = \varphi_P(j\varpi)+\varphi_C(j\varpi) \end{cases} \tag{7}$$

According to the typical form of PID controller

$$C(j\omega) = K_P(1+\frac{1}{T_i j\omega}+T_d j\omega) = K_P + jK_P\frac{T_d T_i \omega^2 -1}{T_i\omega} \tag{8}$$

The modulus and phase of the controller are as follows.

$$M_{C(j\omega)} = K_P\sqrt{1+(\frac{T_d T_i \varpi^2 -1}{T_i\varpi})^2} \tag{9}$$

$$\varphi_{C(j\omega)} = \mathrm{atan}(\frac{T_d T_i \varpi^2 -1}{T_i\varpi}) \tag{10}$$

From the point A on ‘forbidden region’, the modulus and phase can be calculated as follows.

$$M_A = \sqrt{R^2\sin^2\alpha + (C-R\cos\alpha)^2} = \sqrt{C^2+R^2-2CR\cos\alpha} \tag{11}$$

$$\tan(\varphi_C+\varphi_P) = \frac{R\sin\alpha}{C-R\cos\alpha} = \frac{\tan\varphi_C+\tan\varphi_P}{1-\tan\varphi_C\tan\varphi_P} \tag{12}$$

hence we have:

$$\tan\varphi_C = \frac{R\sin\alpha - \tan\varphi_P(C-R\cos\alpha)}{\tan\varphi_P R\sin\alpha + (C-R\cos\alpha)} \tag{13}$$

Let:

$$F = \frac{R\sin\alpha - \tan\varphi_P(C-R\cos\alpha)}{\tan\varphi_P R\sin\alpha + (C-R\cos\alpha)} \tag{14}$$

And considering the relationship of T_i=$4T_d$, the T_d can be calculated as:

$$T_d = \frac{F+\sqrt{F^2+1}}{2\omega} \tag{15}$$

Substituting T_d to equation(7), K_p can be obtained as:

$$K_p = \frac{M_A}{M_P(j\varpi)\sqrt{1+F^2}} \tag{16}$$

Therefore the item of $C(j\omega)$ and $\left.\frac{dC(j\omega)}{d\omega}\right|_{\bar{\omega}}$ can be calculated as follows:

$$C(j\omega) = K_p(1 + j\frac{T_d T_i \omega^2 - 1}{T_i \omega}) = \frac{M_A}{M_P(j\bar{\omega})\sqrt{1+F^2}}(1 + jF) \quad (17)$$

$$\frac{dC(j\omega)}{d\omega} = \frac{d(K_P(1 + \frac{1}{T_i j\omega} + T_d j\omega))}{d\omega} = K_p(-\frac{1}{jT_i\omega^2} + jT_d) \quad (18)$$
$$= jK_p(\frac{T_d T_i \bar{\omega}^2 + 1}{T_i \bar{\omega}}) = j\frac{M_A}{M_P(j\bar{\omega})\omega}$$

The *P(jω)* and $\frac{dP(j\omega)}{d\omega}$ can be obtained according to sine test (De Keyser et al., 2016). Hence, the $\left.\frac{d\,\mathrm{Im}_{PC}}{d\,\mathrm{Re}_{PC}}\right|_{\bar{\omega}}$ can be calculated with equation(5).

By finding the angle α which minimizes the error between slope of 'forbidden region' and slope of loop *L(jω)*, the PID parameters can be calculated as:

$$K_p = \frac{M_A}{M_P(j\bar{\omega})\sqrt{1+F^2}} \quad (19)$$

$$T_d = \frac{F + \sqrt{F^2+1}}{2\omega} \quad (20)$$

$$T_i = 4T_d \quad (21)$$

The autotuner method is directly applied on the benchmark refrigeration system, this implies the following iterative steps.

Step 1: Select a loop and apply a sine test on the selected loop while keeping another loop work at operating points. From this test, obtain the magnitude and phase for the selected loop.

Step 2: Compute the PID parameters for the selected loop.

Step 3: Apply the PID controller on the selected loop and keep it working at operating point. Perform sine test on the other loop.

Step 4: Repeat steps 2-3 for each loop until the output magnitude and phase do not change significantly between consecutive tests.

Step 5: The final PID parameters are obtained after step 4 is completed.

3.2 Computer Aided PID Design: FRtool

For validation of KC autotuner method, FRtool is applied to the benchmark system with full knowledge of the system (De Keyser et al., 2006). Firstly, it is necessary to get the model of the plant. Using the prediction error estimation algorithm, a linearized model of the refrigeration system is obtained around the normal operation points: expansion valve opening = 50% and compressor speed = 40Hz. The obtained continuous model is as follow:

$$G(s) = \begin{bmatrix} \frac{-0.2219s\ -0.004757}{s^2 + 5.834s + 0.2373} & \frac{-0.004638}{s^2+93.24s+3.802} \\ \frac{-2.425}{s^2 + 2.099s + 6.634} & \frac{1.208s + 0.03219}{s^2 + 6.743s + 0.1946} \end{bmatrix} \quad (22)$$

with transmission zeros :

$$z_1 = -93.198; \quad z_{2,3} = -1.0484 \pm 2.3526i$$
$$z_4 = -0.0408; \quad z_{5,6} = -0.0254 \pm 0.0022i \quad (23)$$

indicating that the process is minimum-phase. Secondly, based on decentralised approach, the RGA (Relative Gain Array) analysis of the multivariable process is realized.

$$\Lambda = \begin{bmatrix} 0.8815 & 0.1185 \\ 0.1185 & 0.8815 \end{bmatrix} \quad (24)$$

Since the main diagonal has positive values close to 1, the pairing 1-1/2-2 is suitable. Finally, the individual PID controllers are designed for each input-output pairing by neglecting the effect of the interaction loop.

4. SIMULATION RESULTS

In this section, the proposed PID autotuning method is compared with PID controller based on FRtool and the benchmark reference controller named Ref.PID. The following specification are applied during designing the PID parameters based on FRtool: overshoot $\%OS$ < 5%, robustness Ro > 0.5 and settling time T_s < 100 seconds for both outputs. Similarly, GM=2, PM=45° and $\bar{\omega}$=6rad/s are imposed for KC autotuning method to obtain similar specifications that FRtool for outputs $T_{e,sec,out}$ and T_{SH} respectively. Table 2 shows the PID parameters obtained with different tuning methods.

Table 2. PID Controller Parameters

Output	Tuning method	K_p	T_i	T_d
$T_{e,sec,out}$	FR tool	-47.23	3.98	0.53
	KC method	-29.87	0.8064	0.2016
T_{SH}	FR tool	6.44	1.24	0.31
	KC method	12.99	0.8088	0.2022

According to Table 2, it is important to note that the proportional-constant (K_p) of both controllers for output $T_{e,sec,out}$ is negative, due to the gain of transfer function is negative. On the other hand, the reference signals and performance indexes are all from the benchmark case. The performance indexes are shown in the Table 3. More information about the indexes can be found in paper (Bejarano et al., 2017).

Table 3. Performance indexes for the different controllers C_1= Ref. PID, C_2=FRtool, C_3=KC method

Indexes	C_1 vs C_2	C_1 vs C_3	C_2 vs C_3
$RIAE_1$	0.8854	0.3963	0.4476
$RIAE_2$	0.8708	0.5749	0.6602
$RITAE_1$	0.9381	0.2594	0.2765
$RITAE_2$	0.6025	0.1941	0.3221
$RITAE_2$	0.8583	0.4803	0.5596
$RITAE_2$	0.1975	0.0557	0.2822
$RIAVU_1$	3.5856	3.4119	0.9516
$RIAVU_2$	1.4560	0.9838	0.6757
J	0.8915	0.4527	0.4398

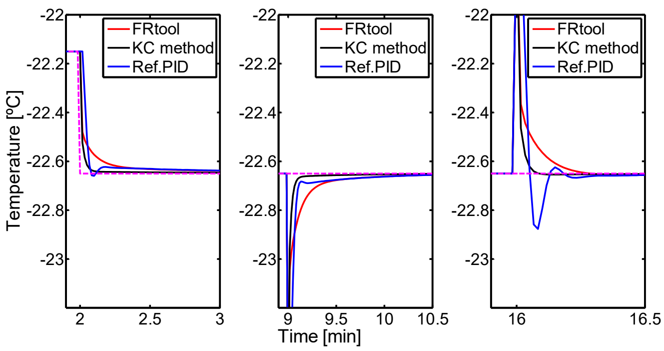

Fig. 3. Outlet temperature of the evaporator secondary flux ($T_{e,sec,out}$) with different PID controllers.

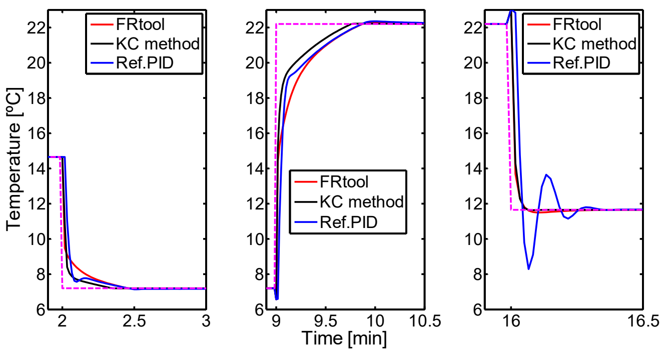

Fig. 4. Outlet temperature of the degree of superheating (T_{SH}) with different PID controllers.

According to the column of *C1* vs *C2* in Table 3, all indices that refer to output errors are less than unit, which means that the PID controller based on FRtool has a better performance than benchmark reference controller, The second comparison between the proposed method and benchmark reference controller has similar results with the first group, which indicates that the proposed method has a better performance than benchmark reference controller. In addition, the values are much lower than those calculated in the first comparison. According to the results from comparison between the proposed method and PID controller based on FRtool in the third group, the proposed method has better performance. It indicates that the proposed method achieves good load disturbance rejection, while maintaining a good reference tracking performance. The system outputs with different PID controller are show in Fig. 3 and Fig. 4. They also show that the KC autotuning method has best performance. This is because the KC autotuner method is based on defining a 'forbidden region' in the Nyquist plane based on user-defined specs, which will guarantee the system margin requirements. In (De Keyser et al, 2017) is reported the evaluation of this method to different type of systems obtaining good results.

The control effort of these method is shown in Fig. 5 and Fig.6 for valve opening (*Av*) and compressor speed (*N*) respectively. It can be seen the input of valve opening (*Av*) is higher in PID controller based on FRtool and proposed method, thus the relative Index $RIAVU_1$ is greater than one. However, KC method performs well in the input of *N*.

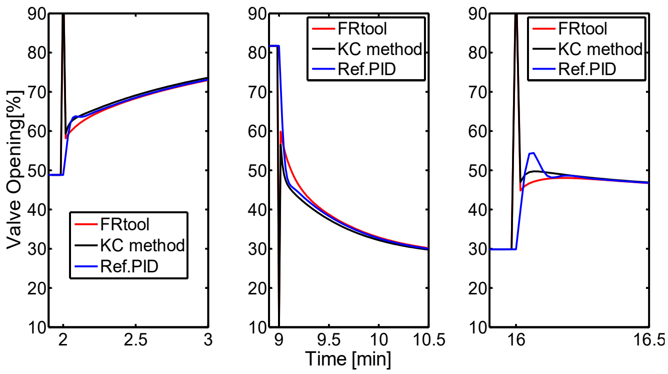

Fig. 5. Valve opening (Av) with different PID controllers.

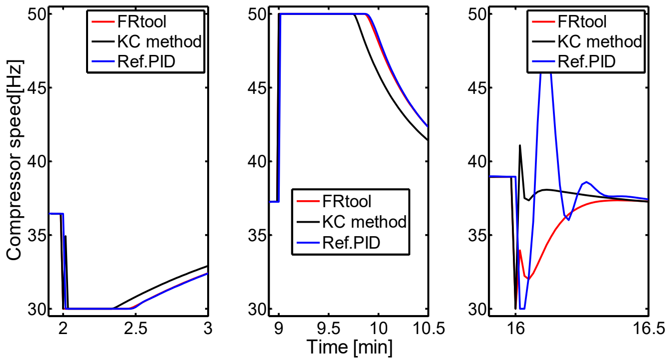

Fig. 6. Compressor speed (*N*) with different PID controllers.

5. CONCLUSIONS

In this paper, a robust PID autotuning method named KC autotuner is proposed. The method is based on defining a 'forbidden region' in the Nyquist plane based on user-defined specs, which will guarantee the system margin requirements. The proposed method is applied to the benchmark system presented at the 3rd IFAC Conference on Advances in Proportional-Integral-Derivative Control (PID18). The performance of the proposed method is compared against the PID controller based on FRtool with full knowledge of the system, also against the benchmark reference controller. The simulation results and numerical analysis show that the proposed method has better performance in disturbance rejection, while maintaining a good reference tracking performance. Further extension of this work could be the validation on other MIMO processes where the system modeling is a heavy task.

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