Effect on Gain & Phase Margin Based Stability Analysis and Stability Region in Control Parameter Space of Temperature Control System with Constant Time Communication Delays

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Abstract:-In this article, a comprehensive analysis of the Temperature Control System (TCS) with time-invariant communication delays. The first method, a precise approach, taking an account of gain and phase margin (GM &PM) respectively is introduced to determine the stable/delay margin based on TCS parameters. The technique implements a deletion process to change the Transcendental Characteristic Equation (TCE) into a novel polynomial root of the crossing frequency in a complex plane. The positive or real roots of the polynomial equation rightly equivalent with completely complex roots of the original system characteristic equation. The second technique, a graphical approach is executed to resolve the stabilizing province of controlled parameters for a given delay. The technique is fundamentally an extracting stable province and stability frontier line (SFL) in the control parameter space having user-evident gain & phase margin (GMPM). The extensive simulation analysis that the proposed techniques give an optimized performance of a thermal control system with time-invariant communication delays.

Keywords: Delay-dependent stability, thermal control system, time-invariant delay, gain margin and phase margin, stability region.

1. INTRODUCTION

The heat exchanger is a mechanical device which allows an exchange/transfer the thermal energy from one medium (a liquid or gas) to another medium (liquid or gas) without coming into direct contact (Ramesh, K et. al (2003)). However, heat exchangers is not only applicable to heating the medium, but are also used for cooling purposes (Ramesh, K et. Al (2003), Donald R (2009)). We can view the heat-exchanger in all kinds of locations, generally working to heat or cool for engines and machines to work considerable efficiency. Different categories of heat exchangers can be classified based on their applications. They are (a) shell & tube heat-exchanger, (b) plate heat-exchanger, (c) plat & shell heat-exchanger, (d) Helical-coil heat-exchanger, (e) pillow plate heat exchanger, (f) Adiabatic wheel heat exchanger, (g) Plate fin heat-exchanger, (h) Spiral heat exchanger, (i) fluid heat exchanger, (j) waste heat recovery units. A shell & tube heat-exchanger is the very most common type of unit which the name is derived from construction (G, M, Sarabeevi., M, LailaBeebi, (2016)). The heat exchanger device is very essential in all industries such as, (1) marine applications (Propulsion Plant (PP), Starting Air System (SAS), Fuel Injection System (FIS), Refrigeration System (RS), A.C system, fresh water system, and steam turbine unit), (2) Electrical applications (solar water heating, transformer oil cooler, generators and motors coolers, Air blast cooler for application HVDC, radiating cooler, nuclear power plant, thermal power plant, process air heat batteries), (3) bioprocess applications (heating or cooling of liquid foods, freezing & evaporation of fluids for the making of ice creams, sorbet and fruit based Juices) (Padmakshi et al(2014)), (4) medical applications (In this era, high-technology medical apparatus are required more effective controlling the temperature. As continuously increasing the heat load, So much more OEM's are changes to liquid cooling to heat loads for medical lasers, imaging equipment. Recirculation chillers, cold plates, ambient cooling systems, liquid to liquid cooling systems are the cooling techniques used in medical systems, Cardioplegia apparatus), (5) Heat exchanger applications not only in the above said but also in pharmaceutical industry, alcohol production, metallurgical process, petroleum refinery process and biochemical processing.

The mission of networked based TCS is to get the value of sensor measurement from the shell & tube heat exchanger and control signal/information from a controller, to terminate and to implement obligatory control measures for adjusting the outlet temperature (Venkatachalam Veeraragavan et al. (2017)). The TCS needs a dedicated network for communication to obtain measured data and to transmit signals from the outlet of the heat exchanger unit to the controller; as a consequence, delays get introduced in the feedback loop (Venkatachalam V et al. (2017)).

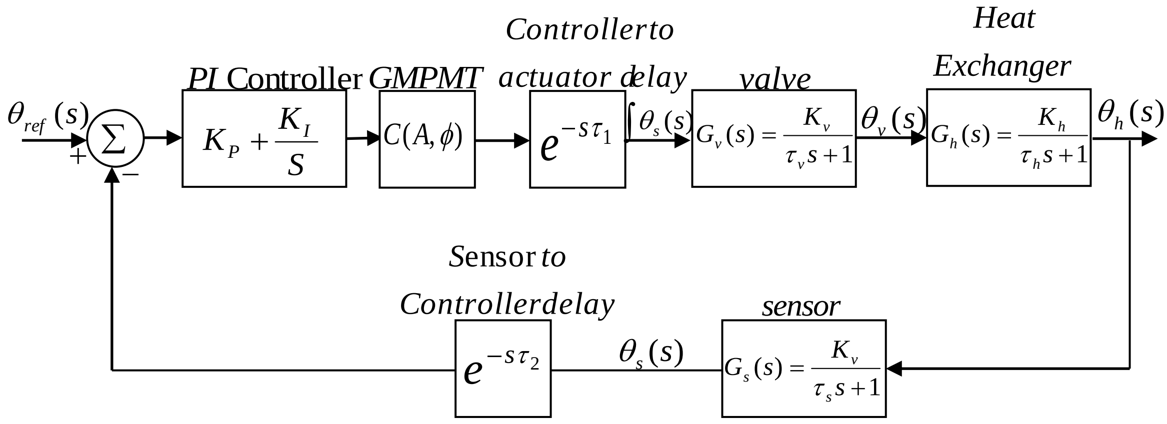

Fig s1 Closed loop TCS with GMPMT

Stability criteria basically have a necessary conditions are involvedto obtain the delay margin within which TCS controlled via a remote operator station (centre) is asymptotically stable (Sahin, Sonmez & Saffet, Ayasun (2017), Hakan et al. (2017)). In inclusion to stability analysis, other relative stability specifications, performance such as GMPM that gives assurance of desired performance may also consider into account in a delay margin computation process (Sahin, Sonmez & Saffet, Ayasun (2017), Hakan et al. (2017)). The impact of GMPM on the stability is ascertained through a detailed analysis.

2. TIME-DELAYED MODEL OF TCS

The linear state-space model of TCS is used to analyze the performance and to design a controller (Venkatachalam Veeraragavan et al. (2017), Chhaya, Sharma et al. (2011)). Fig.1 represents the closed loop thermal control system with network-induced delay with GMPM. The user described GMPMT as a ‘virtual compensator’ is incorporated to TCS in the feed forward path as depicted in Fig.1. The GMPMT is frequency independent as represented below (Sahin, Sonmez & Saffet, Ayasun (2016), Sahin, Sonmez., Saffet, Ayasun (2016), K. Ramakrishnan & N. Swarnalakshmi, (2018), Sahin Sonmez & Saffet Ayasun (2019)),

$$C(A,\emptyset) = Ae^{-j\emptyset} \quad (1)$$

where A and $\emptyset$ is marked as (GMPM), respectively. The original characteristic of the thermal control system without a GMPMT is first received (Sahin Sonmez & Saffet Ayasun (2019), Chang CH & Han KW (1990), Hamamci SE & Koksal M (2010), Olgac N & Sipahi R (2002)) .

$$\Delta(s, \quad \tau) = P(s) + Q(s)e^{-s\tau} = 0 \quad (2)$$

where, the coefficients of $P(s)$ and $Q(s)$are:

$$\left.\begin{aligned} P(s) = p_3s^4 + p_2s^3 + p_1s^2 + p_0s^1 \\ Q(s) = q_1s + q_0 \end{aligned}\right\} \quad (3)$$

with

$p_3 = T_VT_HT_F;\quad p_2 = T_VT_F + T_VT_H + T_HT_F;$

$p_1 = T_V + T_F + T_H;\quad p_0 = 1;$

$q_1 = K_PK_VK_FK_H;\quad q_0 = K_IK_VK_FK_H;$

The new polynomial equation (1) of the modified TCS with GMPMT depicted in Fig. 1 is then obtained (V. Venkatachalam et al (2019), V. Venkatachalam & D. Prabhakaran (2018)).

$$\Delta(s, \quad \tau') = P'(S) + Q'(S)e^{-s\tau'} = 0 \quad (4)$$

where

$$\left.\begin{aligned} P(s) = P'(s) = p_3s^4 + p_2s^3 + p_1s^2 + p_0s^1 \\ Q'(s) = AQ(s) = Aq_1s + Aq_0 = q_1's + q_0' \end{aligned}\right\} \quad (5)$$

An exponential term in equation (4) is $e^{-s\tau'}$ in lieu of $e^{-s\tau}$ as in equation (4). It will get by adding $e^{-s\tau}$& $e^{-j\emptyset}$ into a single form for $s = j\omega_c$ that is polynomial roots (4) on the $j\omega - plane$. The correlation between τ' and τ is shown below

$$\tau' = \tau + \frac{\emptyset}{\omega_c} \quad (6)$$

In equation (6), τ' represents the stable margin of the modified TCS with GMPMT and τ represents the time-invariant delay for which the TCS without GMPMT (Sahin Sonmez & Saffet Ayasun (2019), Chang CH & Han KW (1990), Hamamci SE & Koksal M (2010), Olgac N & Sipahi R (2002), V. Venkatachalam et al.(2019)).

3. COMPUTATION OF DELAY MARGIN WITH GMPMT

It should be stressed; the maximum value of delay at which equation (4) of modified TCS roots on the $j\omega - axis$, the maximum value of stable margin of the GMPM based TCS (Chang CH & Han KW (1990), Hamamci SE & Koksal M (2010)). Therefore, to determine the purely $j\omega$ −roots of the modified TCS equation at $s = \pm j\omega_c$ and the corresponding value of maximum τ'Then, apply these values, the delay margin for the original TCS would have liked gain (A) & $phase$ ($\emptyset$) could be simply obtained (Chang CH & Han KW (1990), Hamamci SE & Koksal M (2010)).

The stability of GMPM based thermal control system is evaluated by the location of modified system characteristic equation roots as given in (4). For a system to be asymptotically stable. All roots are ought to contain in the left half of $j\omega$ −plot for a stated maximum time-invariant delay. Note that in (4) is a TCE due to term $e^{-j\omega_c\tau'}$. As a consequence of transcendental character, the modified equation (4) has infinitely much finite value of roots and to be quite difficult the determination of the roots. Nevertheless, the main task is to obtain the maximum delay value for which the GMPM based characteristic equation (CE) roots on $j\omega -$ axis. Let Consider the $\Delta(j\omega_c, \quad \tau') = 0$ has a polynomial roots locate on the line of the imaginary axis at $s = j\omega_c$, for some limited values of τ' and same for the $\Delta(-j\omega_c, \ \tau') = 0$. As a consequence, the problem of determining the delay margin τ' such that both $\Delta(j\omega_c, \ \tau') = 0$ and $\Delta(-j\omega_c, \ \tau') = 0$ have the same value of roots at $s = j\omega_c$ (Sahin, Sonmez & Saffet, Ayasun (2017), Hakan, Gunduz et al. (2017), Chhaya, Sharma et al. (2011), Sahin, Sonmez & Saffet, Ayasun (2016)). These results could be stated as

$$\left.\begin{aligned} P'(j\omega_c) + Q'(j\omega_c)e^{-j\omega_c\tau'} = 0 \\ P'(-j\omega_c) + Q'(-j\omega_c)e^{j\omega_c\tau'} = 0 \end{aligned}\right\} \quad (7)$$

In (7), the two equations are possibly one could remove effortlessly $e^{-j\omega_c\tau'}$ and $e^{j\omega_c\tau'}$ terms, to be obtain a modified new polynomial equation not including any transcendental terms as follows

$$W(\omega_c^2) = P(j\omega_c)P(-j\omega_c) - Q(j\omega_c)Q(-j\omega_c) = 0 \quad (8)$$

By substituting the $P'(s)$ and $Q'(s)$ polynomials given in (5) into (7), the new polynomial equation of the modified thermal control system with GMPMT is determined in terms of system parameters as given below

$$W(\omega_c^2) = t_4\omega_c^8 + t_3\omega_c^6 + t_2\omega_c^4 + t_1\omega_c^2 + t_0 = 0 \quad (9)$$

where

$$t_4 = p_3^2; \quad t_3 = p_2^2 - 2p_3p_1; \quad t_2 = p_1^2 - 2p_2p_0; \ t_1 = p_0^2 - {q_1'}^2; \ t_0 = -{q_0'}^2;$$

It clearly shows, do not use any approximation to deletion process of the exponential terms. Therefore, real positive roots in equation (9) exactly coincide with the imaginary roots in (4). Based on the positive roots in (9), the following two possible categories of stability as described below:

1. In equation (9) does not have an any real positive root of all finite value of delay $\tau' \geq 0$, then the GMPM based thermal control system is said to be delay-independent stable, indicating that all the roots of original characteristic equation (4) lie in the left of the s-plane (Sahin Sonmez & Saffet Ayasun (2019)).
2. In equation (9) has at least one real positive root, then the GMPM based thermal control system is said to be delay-dependent stable. In the presence, some roots in equation (4) transverse the $j\omega-$axis at $s = j\omega_c$ for a finite value of communication delay τ', is called as the stable delay margin (Sahin Sonmez & Saffet Ayasun (2019)).

If found the real positive root in equation (9), the corresponding delay margin of GMPM based thermal control system is obtained by using equation (4) as given below) (Sahin Sonmez & Saffet Ayasun (2019), Chang CH & Han KW (1990), Hamamci SE & Koksal M (2010), Olgac N & Sipahi R (2002), V. Venkatachalam et al.(2019)).

$$\Delta(j\omega_c, \ \tau') = P'(j\omega_c) + Q'(j\omega_c)e^{-j\omega_c\tau'} = 0$$

$$e^{-j\omega_c\tau'} = \cos(\omega_c\tau') - j\sin(\omega_c\tau') = -\frac{P'(j\omega_c)}{Q'(j\omega_c)} \quad (10)$$

$$\cos(\omega_c\tau') = Re\left\{-\frac{P'(j\omega_c)}{Q'(j\omega_c)}\right\}; \ \sin(\omega_c\tau') = Im\left\{\frac{P'(j\omega_c)}{Q'(j\omega_c)}\right\}$$

$$\tau' = \frac{1}{\omega_c}Tan^{-1}\left(\frac{Im\{P(j\omega_c)/Q(j\omega_c)\}}{Re\{-P(j\omega_c)/Q(j\omega_c)\}}\right) + \frac{2\pi r}{\omega_c}; \quad (11)$$

$$\tau' = \frac{1}{\omega_c}Tan^{-1}\left(\frac{a_5\omega_c^5 + a_3\omega_c^3 + a_1\omega_c^1}{a_4\omega_c^4 + a_2\omega_c^2 + a_0\omega_c^0}\right) + \frac{2\pi r}{\omega_c}; \quad r = 0,1,2,\dots,\infty \quad (12)$$

where the respective coefficients are given below:

$a_0 = 0$; $a_1 = -p_0q_0'$; $a_2 = p_0q_1' - p_1q_0'$; $a_3 = p_2q_0' - q_1'$; $a_4 = p_3q_0' - p_2q_1$; $a_5 = p_3$

It should be clearly expressed that the modified new polynomial equation given in (9) may have more than one real positive root whose set is given by

$$\{\omega_c\} = \{\omega_{c1}, \omega_{c2}, \dots, \omega_{cq}\} \quad (13)$$

To determine the corresponding value of delay by employing (12) for each positive root $\omega_{cm}, m = 1,2,\dots,q$. These values of maximum delay will be set of delay margins which are interval spaced and defined asshows the repeated period.

$$\{\tau_m'\} = \{\tau_{m1}', \tau_{m2}', \dots, \tau_{m\infty}'\}, \ m = 1,2,\dots,q \quad (14)$$

where

$$\tau_{m,r+1}' - \tau_{m,r}' = \frac{2\pi}{\omega_c} \quad (15)$$

Eventually, the minimum of $\tau_m', m = 1,2,\dots,q$ is stable delay of the GMPM based TCS.

$$\tau' = min(\tau_m') \quad (16)$$

3. The GMPM based TCS, it could easily obtain the time-delay of TCS without GMPM will have the desired gain margin and phase margin as follows (Sahin Sonmez & Saffet Ayasun (2019)).

$$\tau = \tau' - \frac{\emptyset}{\omega_c} \quad (17)$$

4. DETERMINATION OF STABILIZING REGION WITH GMPM'S

To determine the stable frontier line for a given constant delay τ' and desired GMPM, let substitute $s = j\omega_c$ with $\omega_c > 0$ into the modified characteristic equation (4).

$$\Delta(j\omega_c, \ \tau') = p_3(j\omega_c)^4 + p_2(j\omega_c)^3 + p_1(j\omega_c)^2 + p_0j\omega_c + (q_1'j\omega_c + q_0')e^{-(j\omega_c)\tau'} = 0 \quad (18)$$

Substituting $e^{-j\omega_c\tau'} = \cos(\omega_c\tau') - j\sin(\omega_c\tau')$ into equation (18) and divide (K_P, K_I) controller gains the following equation is given below (Olgac N & Sipahi R, (2002), V. Venkatachalam et al. (2019)):

$$\Delta(j\omega_c, \ \tau') = p_3\omega_c^4 - jp_2\omega_c^3 - p_1\omega_c^2 + p_0j\omega_c + jq_1'\omega_c\cos(\omega_c\tau') + q_1'\omega_c\sin(\omega_c\tau') + q_0'\cos(\omega_c\tau') - jq_0'\sin(\omega_c\tau')$$

$$\Delta(j\omega_c, \ \tau') = [p_3\omega_c^4 - p_1\omega_c^2 + q_1'\omega_c\sin(\omega_c\tau') + q_0'\cos(\omega_c\tau')] + j[-p_2\omega_c^3 + p_0\omega_c + q_1'\omega_c\cos(\omega_c\tau') - q_0'\sin(\omega_c\tau')] \quad (19)$$

Equating the real and imaginary section of $\Delta(j\omega_c, \ \tau')$ equal to zero and we get the following equation

$$\left.\begin{aligned} K_PA_1(\omega_c) + K_IB_1(\omega_c) + C_1(\omega_c) = 0 \\ K_PA_2(\omega_c) + K_IB_2(\omega_c) + C_2(\omega_c) = 0 \end{aligned}\right\} \quad (20)$$

where

$$A_1(\omega_c) = q_1'\omega_c\sin(\omega_c\tau'); B_1(\omega_c) = q_0'\cos(\omega_c\tau'); \ C_1(\omega_c) = p_3\omega_c^4 - p_1\omega_c^2$$

$$A_2(\omega_c) = q_1'\omega_c\cos(\omega_c\tau'); \ B_2(\omega_c) = -q_0'\sin(\omega_c\tau'); \ C_2(\omega_c) = -p_2\omega_c^3 + p_0\omega_c$$

To solve the equation (20) and to identify stable frontier locus (K_P, K_I, ω_c) on (K_P, K_I)plane.

$$K_P = \frac{B_1(\omega_c)C_2(\omega_c) - B_2(\omega_c)C_1(\omega_c)}{A_1(\omega_c)B_2(\omega_c) - A_2(\omega_c)B_1(\omega_c)}$$
$$K_I = \frac{A_2(\omega_c)C_1(\omega_c) - A_1(\omega_c)C_2(\omega_c)}{A_1(\omega_c)B_2(\omega_c) - A_2(\omega_c)B_1(\omega_c)} \quad (21)$$

It must be noted that the line $(K_I = 0)$ is also in a frontier curve because a positive root of $\Delta(j\omega_c, \ \tau') = 0$ in equation (18) can cross the imaginary castle at $s = j\omega_c = 0$ for $K_I =$

0 (V. Venkatachalam & D. Prabhakaran (2018), Sahaj Saxena & Yogesh V. Hote (2018), Saffet Ayasun (2008)). As a result, the frontier locus (K_P, K_I, ω_c) and the line $K_I = 0$ split (K_I, K_P) −plane into two territories which is unstable and stable respectively. This area of the frontier locus is known as Real Root frontier (RRF) and also obtained in (21) is described as Complex Root Frontier (CRF) of the stability regions (Sahin, Sonmez & Saffet, Ayasun (2016), Sahin, Sonmez & Saffet, Ayasun (2016)). That's refers the real root crossing over the imaginary axis at $s = \infty$ might be noticed depending on the delayed system characteristics equation.

5. RESULTS AND DISCUSSIONS

5.1 GMPM Based Delay Margin Computation

In this division, the delay τ' for stability of various sets of (K_I, K_P) and GMPMs is computed by using (12). Theoretical values of delay are verified by LMI tool in MATLAB/Simulink (V. Venkatachalam et al. (2019)). The parameters of TCS as given below (Venkatachalam Veeraragavan et al. (2017), Venkatachalam V & Prabhakaran D (2017), V. Venkatachalam & D. Prabhakaran (2018)).

Table 1 Parameters values of the TCS

System	**Gain**	**Time-Constant**
Heat Exchanger	$K_H = 34$	$T_H = 30$
Valve	$K_V = 1.25$	$T_V = 3$
Sensor	$K_F = 0.08$	$T_F = 2$

Table 2 Maximum value of delay τ' when $A = 0.5$; and $\emptyset = 0$

K_I	$A = 0.5;\ \emptyset = 0$					
	$K_P = 0.5$	$K_P = 1.0$	$K_P = 1.5$	$K_P = 2.0$	$K_P = 2.5$	$K_P = 3.0$
0.02	42.3595	30.6206	18.8219	12.7610	9.3543	7.2192
0.04	20.2379	20.5495	15.7720	11.5785	8.7669	6.8760
0.06	12.3346	14.6560	13.0438	10.3769	8.1565	6.5200
0.08	8.2501	10.9378	10.7937	9.2267	7.5419	6.1567
0.10	5.7525	8.4044	8.9780	8.1664	6.9385	5.7917

Table 3 Maximum value of delay τ' when $A = 1$; and $\emptyset = 0$

K_I	$A = 1;\ \emptyset = 0$					
	$K_P = 0.5$	$K_P = 1.0$	$K_P = 1.5$	$K_P = 2.0$	$K_P = 2.5$	$K_P = 3.0$
0.02	20.5495	11.5785	6.8760	4.5766	3.2630	2.4252
0.04	10.9378	9.2267	6.1567	**4.2533**	3.0816	2.3092
0.06	6.5747	7.2104	5.4294	3.9208	2.8958	2.1909
0.08	4.1169	5.6017	4.7283	3.5858	2.7072	2.0710
0.10	5.2470	4.3355	4.0745	3.2540	2.5175	1.9500

Table 4 Maximum value of delay τ' when $A = 2.0$; and $\emptyset = 0$

K_I	$A = 2.0;\ \emptyset = 0$					
	$K_P = 0.5$	$K_P = 1.0$	$K_P = 1.5$	$K_P = 2.0$	$K_P = 2.5$	$K_P = 3.0$
0.02	9.2267	4.2533	2.3092	1.3704	0.8591	0.4806
0.04	5.6017	3.5858	2.0710	1.2490	0.7550	0.4304
0.06	3.3311	2.9304	1.8284	1.1257	0.6800	0.3796
0.08	1.8620	2.3202	1.5859	1.0014	0.6045	0.3286
0.10	0.8534	1.7709	1.3470	0.8768	0.5285	0.2773

Table 5 Maximum value of delay τ' when $A = 3$; and $\emptyset = 0$

K_I	$A = 3;\ \emptyset = 0$					
	$K_P = 0.5$	$K_P = 1.0$	$K_P = 1.5$	$K_P = 2.0$	$K_P = 2.5$	$K_P = 3.0$
0.02	6.9385	2.9891	1.5201	0.8106	0.4009	0.1371
0.04	4.3571	2.5175	1.3430	**0.7176**	0.3430	0.0973
0.06	2.5707	2.0483	1.1632	0.6234	0.2846	0.0572
0.08	1.3487	1.6006	0.9830	0.5285	0.2258	0.0170
0.10	0.4827	1.1858	0.8045	0.4335	0.1608	*

Table 6 Maximum value of delay τ' when r $A = 0.5$; and $\emptyset = 5$

K_I	$A = 0.5;\ \emptyset = 5$					
	$K_P = 0.5$	$K_P = 1.0$	$K_P = 1.5$	$K_P = 2.0$	$K_P = 2.5$	$K_P = 3.0$
0.02	39.5693	28.8741	17.6766	11.9007	8.6541	6.6211
0.04	18.3234	19.0543	14.6734	10.7296	8.0705	6.2794
0.06	10.7836	13.3411	12.0015	9.5449	7.4661	5.9259
0.08	6.6099	9.7527	9.8066	8.4147	6.8592	5.5669
0.10	4.5539	7.3171	8.0414	7.3760	6.2649	5.2051

Table 7 Maximum value of delay τ' when $A = 0.5$; and $\emptyset = 10$

K_I	$A = 0.5$; $\emptyset = 10$					
	$K_P = 0.5$	$K_P = 1.0$	$K_P = 1.5$	$K_P = 2.0$	$K_P = 2.5$	$K_P = 3.0$
0.02	36.7790	27.1275	16.5312	11.0404	7.9540	6.0229
0.04	16.4089	17.5591	13.5747	9.8807	7.3742	5.6829
0.06	9.2326	12.0263	10.9591	8.7128	6.7757	5.3319
0.08	5.5697	8.5677	8.8195	7.6027	6.1765	4.9754
0.10	3.3553	6.2298	7.1048	6.5855	5.5913	4.6186

Table 8 Maximum value of delay τ' when $A = 1$; and $\emptyset = 5$

K_I	$A = 1$; $\emptyset = 5$					
	$K_P = 0.5$	$K_P = 1.0$	$K_P = 1.5$	$K_P = 2.0$	$K_P = 2.5$	$K_P = 3.0$
0.02	19.0543	10.7296	6.2794	4.1014	2.8588	2.0680
0.04	9.7527	8.4147	5.5661	3.7797	2.6780	1.9521
0.06	5.5640	6.4417	4.8477	3.4497	2.4931	1.8343
0.08	3.2195	4.8748	4.1576	3.1180	2.3058	1.7150
0.10	1.7305	3.6461	3.5159	2.7903	2.1178	1.5947

Table 9 Maximum value of delay τ' when $A = 1$; and $\emptyset = 10$

K_I	$A = 1$; $\emptyset = 10$					
	$K_P = 0.5$	$K_P = 1.0$	$K_P = 1.5$	$K_P = 2.0$	$K_P = 2.5$	$K_P = 3.0$
0.02	17.5591	9.8807	5.6829	3.6262	2.4547	1.7107
0.04	8.5677	7.6027	4.9754	3.3060	2.2744	1.5951
0.06	4.5533	5.6731	4.2660	2.9786	2.0905	1.4777
0.08	2.3222	4.1479	3.5869	2.6503	1.9045	1.3590
0.10	0.9140	2.9567	2.9573	2.3267	1.7187	1.2395

Table 10 Maximum value of delay τ' when $A = 2$; and $\emptyset = 5$

K_I	$A = 2$; $\emptyset = 5$					
	$K_P = 0.5$	$K_P = 1.0$	$K_P = 1.5$	$K_P = 2.0$	$K_P = 2.5$	$K_P = 3.0$
0.02	8.4147	3.7797	1.9521	1.0720	0.5666	0.2429
0.04	4.8748	3.1180	1.7150	0.9509	0.4926	0.1927
0.06	2.6747	2.4713	1.4741	0.8281	0.4179	0.1421
0.08	1.2599	1.8715	1.2338	0.7045	0.3426	0.0912
0.10	0.2936	1.3332	0.9976	0.5807	0.2671	0.0401

Table 11 Maximum value of delay τ' when $A = 2$; and $\emptyset = 10$

K_I	$A = 2$; $\emptyset = 10$					
	$K_P = 0.5$	$K_P = 1.0$	$K_P = 1.5$	$K_P = 2.0$	$K_P = 2.5$	$K_P = 3.0$
0.02	7.6027	3.3060	1.5651	0.7736	0.3041	0.0052
0.04	4.1479	2.6503	1.3590	0.6528	0.2303	*
0.06	2.0182	2.0122	1.1198	0.5305	0.1558	*
0.08	0.6577	1.4228	0.8816	0.4076	0.0808	*
0.10	*	0.8955	0.6481	0.2847	0.0056	*

Delay margin that assure the desired GMPM are computed by using (12) to (17) for a various sets of control parameter and for various GMPM. Table 2 provides a delay margin for $A = 1$ and $\emptyset = 0$. Corresponds to this case, the conventional method of delay margin analysis, where the GM & PMs are not included. Therefore $\tau' = \tau$ since $\emptyset = 0$ as refer in equation (5). That results mention at a fixed value of K_P and τ' decreases as K_I increases. It refers to it increases as K_I results would be less stable system. As a result of K_P on τ'has two kinds of forms for a standard K_I. Note that a fixed K_I and τ' is decreases for every K_P. However, τ' is increasing when K_P is $(0 - 0.5)$ in range and $\tau'$is decreases when the K_P in the range of 0.5-8.50 and for a fixed value of$K_I = 0.02$.

Next, the GMPM are elected as $A = 0.5$; $\emptyset = 0$, $A = 1$; $\emptyset = 0$; $A = 2$; $\emptyset = 0$ and $A = 3$; $\emptyset = 0$ to analyze the effect of GM alone on the stable delay margin. The related results are depicted in Table 2- 5 respectively. It obviously shows that the addition of GM notably delay margin has reduced for all value of control parameter as tabulated (Table 2-Table 5). The delay reduces becomes significant increases of gain margin A. In graphical representation effect of gain margin with various values of phase margin are depicted as Fig.2.From Fig. 2, it is very easy to infer the power of time-delay on the stability of TCS (Venkatachalam V et al. (2017)) and Fig.3 vice versa.

The effect of PM ($\emptyset$) is also analyzed in Table 5-11 gives the results of delay margin for $A = 0.5, \emptyset = 5; A = 0.5, \emptyset = 10;$ $A = 1, \emptyset = 5;$ $A = 1, \emptyset = 10;$ $A = 2, \emptyset = 5$ and $A = 2$ $\emptyset = 10$ respectively. Same as in GM (A) case, the analytical results clearly bring out that the maximum delay margin reduces as for all (K_P *and* K_I)control parameters when the PM($\emptyset$) is considered. Although, the delay reduces is less than that of the GM case as tabulated (Table 6 - 11). Finally, both GMPMs are incorporated in the analytical computation of delay margin. The maximum delay margin for various values of GMPMs with $K_P = 0.5;$ $K_I = 0.02$. It is clearly indicates the integrated effect of GMPM on maximum delay are more notably than their separate impacts as shown in Fig 4. Simulation results are presented to demonstrate the causes of GMPM should be considered in the computations of delay margin. In Fig. 5 shows the step response of thermal system for $A = 1, \emptyset = 0; A = 1, \emptyset = 10$ & $A = 2, \emptyset = 20$ when the control parameters $K_p = 2.0, K_I = 0.04$. From the Table 3, observe that stable delay is found to be $\tau = 4.2533$.

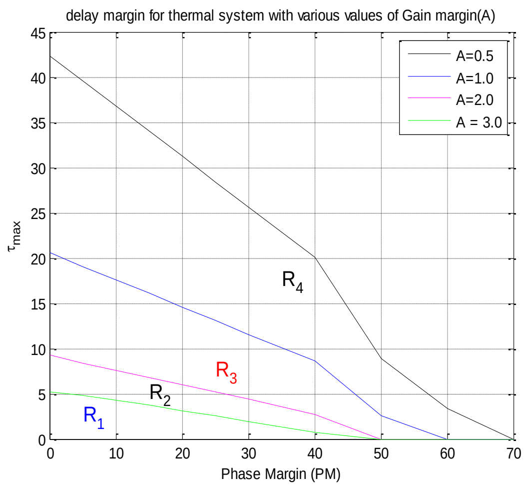

Fig 2 Deviation of Network Delay versus Gain Margin

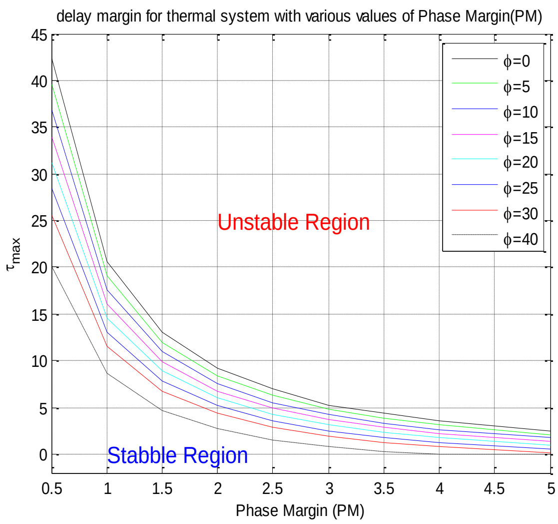

Fig 3 Delay margin for various values of Phase Margin (PM)

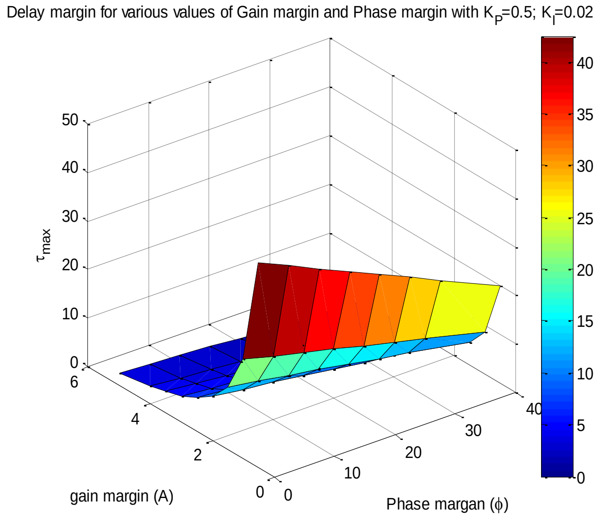

Fig 4 Delay margin for various values of GMPM with $K_p = 0.5;$ $K_I = 0.02$

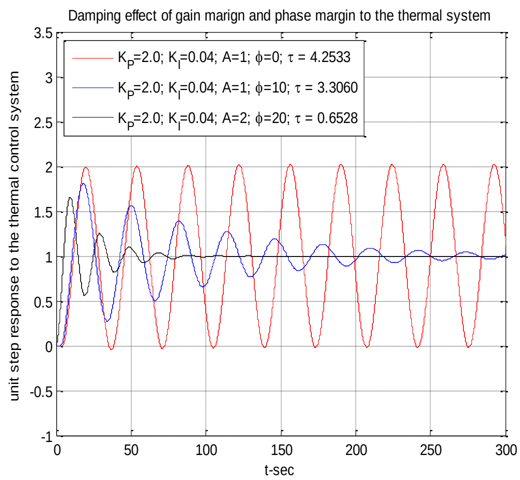

Fig 5. Damping effect of GMPM to the thermal control system

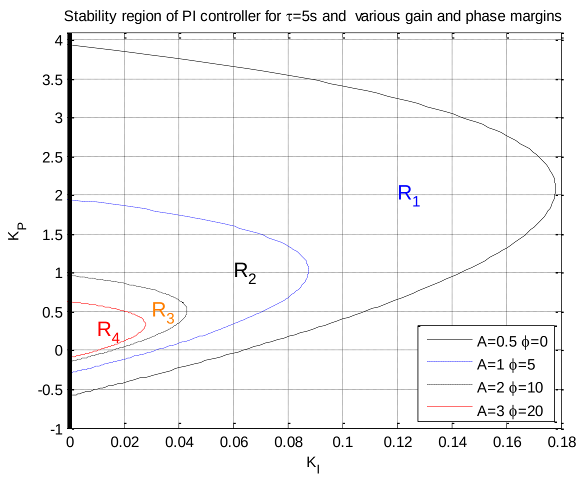

Fig 6 Stability Region for various values of gain margin (GM) and phase margin (PM).

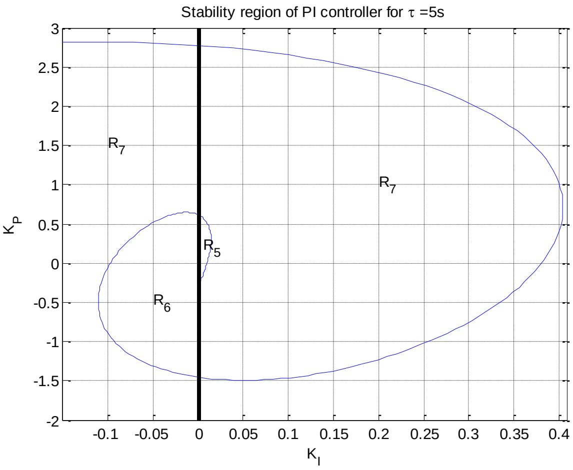

Fig 7a Stability region for without considering GMPMs

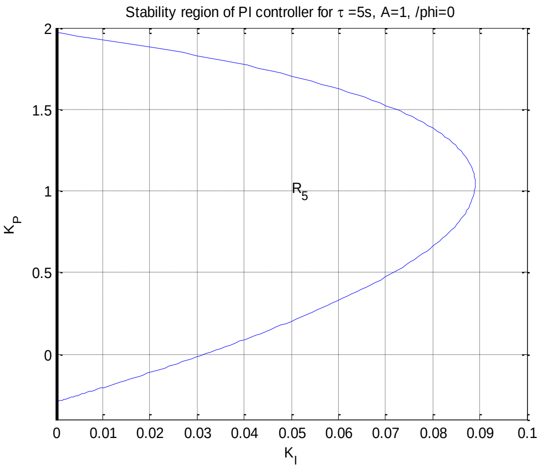

Fig 7b Stability region for without considering GMPMs

As seen in Fig. 5, TCS shows the sustained oscillations for the maximum delay value. However, such sustained oscillations in the output response are not considerable for operational overview. To reduce such an unpleasant oscillation, we have to refer GMPM in computation process. As can be found in Table 9 & 11, delay bound based on GMPM is computed as $\tau = 3.3060$ for $A = 1\ \emptyset = 10°$ and $\tau = 0.6528$ for $A = 2\ \emptyset = 20°$. As compared with $A = 1\ \emptyset = 0°$, it shows clear from Fig. 5 that the output response quickly shrinking for $\tau = 0.6528$ when $A = 2\ \emptyset = 20°$ is examined. These results clearly represent GMPM must be incorporated into a computation process to need better dynamic response of TCS.

5.2 Stability Regions Based on GMPM

The networked-delay is elected as $\tau = 5\ secs$ and crossing frequency ω_c range is elected as $\omega \in [0,\ \ 5]$ for Stability frontier locus (SFL). The first task is to analyze the stabilizing values of controller gains K_P and K_I such that modified characteristic equation (4) with (5) should be Hurwitz stable with GMPM. Suppose our desired GMPM are $A = 0.5, 1, 2, 3$ and $\emptyset = 0°, 5°, 10°, 20°$ respectively, then put $A = 3$ and $\emptyset = 20°$ in equation (19) to (21) and could obtain the SFL as shown in Fig. 6. The corresponding region is marked on R_4. Consequently, by putting various gain and phase margins it is indicated as R_1, R_2, R_3 respectively. Finally, the stable region of PI parameter without considering GMPM is obtained by putting $A = 1$ and $\emptyset = 0°$in equations (19) to (21). The stability region is represented in Fig. 7a and 7b. Notice that relative stability curve with desired GMPM, R_2, R_3, R_4 much smaller and R_1 much greater.

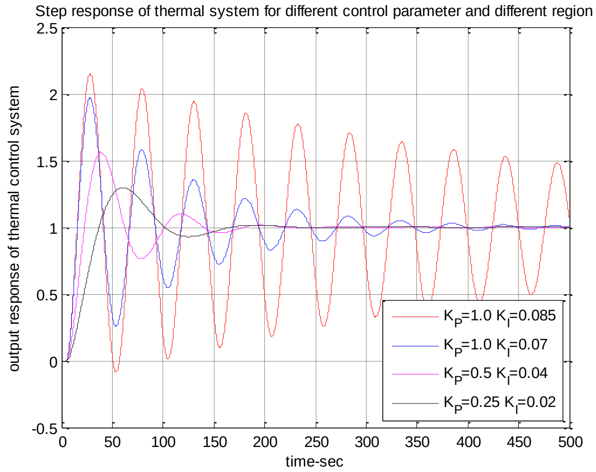

Fig 8. Step response of TCS with GMPM

Next, three points are selected, ($K_P = 1;\ K_I = 0.085$) in R_5 (without considering GMPM case) ($K_P = 1;\ K_I = 0.07$) in R_2, ($K_P = 0.5;\ K_I = 0.04$) in R_3, ($K_P = 0.25;\ K_I = 0.02$) in R_4 regions respectively. Fig. 8 depicts the performance of the TCS. It is clearly, defined the output responses are stable. Anyhow, the step functions for ($K_P = 1;\ K_I = 0.085$) carries undesirable performance as compared to other responses. The controlling and operating point of view, such unpleasant deviations are not acceptable. It is obviously showing the dynamic performance of TCS is rapid without oscillatory for control parameter (K_p, K_I) elected from the regions R_3, and R_4 with desired GMPM.

6. CONCLUSION

In this article, the networked-controlled TCS with delays has been investigated. The impact of GMPM of the stability margin of TCS is ascertained as an employed conventional TCE method. The delay almost takes places in the system feedback path owing to the uses of pneumatic valve, sensors, employment of data communication links for exchanges. The time-delay unchanged exerts an instability effect onto the overall system performance. That the implications of time delays on TCS stability can be obtained by employing the proposed criteria. The results drawn can be employed for guidelines for compilation control parameters for the networked TCS.

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