A Design on New Error Compensator for Fractional PI Controller and Its Application

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Abstract: - Fractional-order controller was proven to perform better than the integer-order controller. However, the absence of a pole at origin in the approximated transfer function produced marginal error in fractional-order control system. This study demonstrated the design of an error compensator that comprises of a very small zero and a pole at origin to produce a zero steady-state error for the closed-loop system. Some modification on the error compensator was suggested for different order fractional integrator that can improve the overall phase margin. The proposed method can eliminate the steady-state error and additionally improved the percentage overshoot of the closed-loop response. The study was validated on steam temperature control of a steam distillation process that exhibits an s-shape step response. Hence, the PI controller was tuned using the Ziegler-Nichols rules and applied for both integer and fractional PI. Significant improvement of the fractional PI and the enhancement of the proposed error compensator was discussed evidently through simulation and supported by experimental applications.

Key-Words: - Fractional-order control; Fractional PI; Oustaloup's Recursive Approximation; Ziegler-Nichols tuning; steam temperature control; hydro-steam distillation.

1 Introduction

PID controller is still dominating the feedback control applications until today. The simple control strategy based on the accumulation over some operation on the error signal has made it easy to understand and robust enough to solve many industrial problems. That is why the research on optimizing the PID controller is still going on until today. The advancement of the three terms controller in the form of fractional PID (F-PID) control has becoming more popular since the last decade. This new technique is proven to provide more flexibility and ability to enhance modelling and control of systems' dynamics [1].

Integer-order approximation for fractional-order system had been investigated since 1960s in other research area such as chemistry and mechanical systems [2]. Some approximation techniques are based on continued fraction expansion (CFE), curve fitting or identification methods and power series expansion (PSE). Oustaloup's Recursive Approximation (ORA) is among the most popular approximation technique. The technique used recursive poles and zeros distribution within specified frequency range to assimilate the frequency response of the fractional-order transfer function.

Applications of fractional-order models in control theory had been considered only two decades after that. The idea of fractional-order controller was first proposed by Oustaloup in 1991 [3] through *Commande Robuste d'Ordre Non Entier* (CRONE) controller which means non-integer robust controller. Later on Podlubny [4] had initiated the fractional order PID in the form of $PI^{\lambda}D^{\mu}$ in 1999 involving an integrator of order λ and differentiator of order μ of less than 1. The generalization of the PID with fractional order of λ and μ was demonstrated by many researchers to give better performance compared to the integer PID. However, until now there is no systematic way to set the value for λ and μ [1].

Recently, more studies had been concentrated on the method for F-PID tuning [5][6]. Generally, the design specifications were looking for an infinite gain margin and constant phase margin around the cross-over frequency to gain robust control towards gain variations [7]. The solutions were then obtained by solving a linear numerical optimization problems as had been reported in [8], [9]. Another tuning approach was by utilizing the Ziegler-Nichols tuning rules based on information of its frequency and step response. The rules were successfully applied by [10]and [11] in their studies.

This paper investigates the application of fractional PI (F-PI) controller to control steam temperature of a steam distillation process. The steam was applied for essential oil extraction which needs to be regulated around 85ºC to preserve the quality of yield. Ziegler-Nichols tuning rule was applied for the PI controller's gain and the fractional order was adjusted for the F-PI based on frequency response specification and steady-state error requirement.

The main issue that will be discussed in this paper is on the steady-state error compensation technique that is necessary when implementing the fractional controller. The approximation of fractional terms for integrator using ORA technique missed a pole at the origin as opposed to the integer PI controller. Its absence in the F-PI controller has become disadvantage despites of its advantages. Previously, two error compensator schemes had been introduced by Feliu et al.[8] and Axtell [10] and was popularly applied ever since. This paper discussed on the application of both schemes and proposed some modification for improvement.

This paper is organized as follows: Section 2 outlines the Oustaloup's approximation for fractal operators used to implement the F-PI. Section 3 described briefly on the hydro-steam distillation for essential oil extraction system and its modelling. Section 4 discussed on the design on the error compensator. Section 5 presents the experimental results and demonstrates the efficiency of the proposed method. Finally, conclusions were drawn in section 6 for the issue being discussed.

2 Fractional PI Controller Approximation

The implementation of fractional controller involved the technique of approximating the integer order systems to represent the fractional order system. Some of the techniques normally applied are continued fraction expansion (CFE), curve fitting or identification methods and power series expansion (PSE). These techniques had been discussed and demonstrated in [2]. In identification methods, the approximation was analyzed in frequency domain to obtain a rational function whose frequency response fits the frequency response of the irrational function. This method was derived by Oustaloup himself and known as Oustaloup's recursive approximation (ORA). This method is based on the approximation of a function in the form:

$$H(s) = s^m, m \in \Re \tag{1}$$

This function can be approximated by series of rational function synthesized as follows:

$$\hat{\mathbf{H}}(s) = k\prod_{n=1}^{N}\frac{1+ s/\omega_{z,n}}{1+ s/\omega_{p,n}} \tag{2}$$

However, the approximation of H(s) denoted in this paper as $\hat{H}(s)$ is only valid within the boundary of low cut-off and high cut-off frequency defined as $[\omega_l : \omega_h]$. Referring to equation 2, N represents the number of poles and zeros which should be chosen beforehand. High value of N permitted good approximation but increased the computational complexity. On the other hand, low value will results in simpler approximation but could cause appearance of ripple in gain and phase behavior. Proper rules for selecting these parameters was discussed in [12]. The assignment of low and high frequency band limitations could somehow avoid the use of infinite numbers of rational transfer function besides limiting the high frequency gain of the derivative effect[13].

The poles and zeros of the approximated function are calculated using the recursive equations given in equation 3:

$$\begin{aligned} &\omega_{z,1} = \omega_l\sqrt{\eta} \\ &\left.\begin{aligned}\omega_{p,n} &= \omega_{z,n}\alpha \\ \omega_{z,n+1} &= \omega_{p,n}\eta\end{aligned}\right\}, n = 1...N \end{aligned} \tag{3}$$

where

$$\alpha = \left(\frac{\omega_h}{\omega_l}\right)^{\mu/N} \text{ and } \eta = \left(\frac{\omega_h}{\omega_l}\right)^{1-\mu/N}$$

The transfer function of F-PID is given by

$$C(s) = K_p\left(1 + \frac{1}{T_i s^{\lambda}} + T_d s^{\mu}\right) \tag{4}$$

where K_p, T_i, and T_d are controller gain while λ and μ are the integral and differential power in real number. Fractional PID is the generalization of integer PID such that

- If λ =1 and μ=1, we obtain a classical PID.
- If λ=1 and μ=0, we obtain a PI controller.
- If λ=0 and μ=1, we obtain a PD controller.
- If λ=0 and μ=0, we obtain a P controller

Hence, if λ and μ were set to arbitrary value between 0 and 1, the controller can be configured to behave within these four possibilities [6], [10], [14].

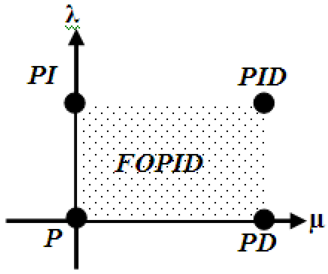

Fig. 1 Fractional PID control space

This is the main advantage of the F-PID. Other than that, F-PID was acknowledged by many researchers to provide better control especially to a class of fractal system. Furthermore, F-PID is less sensitive to changes in process parameters and the controller parameters itself. There were five parameters that can be tuned instead of three in the conventional version and thus, more design specifications can be achieved from the λ and μ adjustment [5].

The frequency response for differentiator and integrator using ORA was shown in Fig.2 and Fig.3 respectively. The magnitude and phase of each function related to fractional power m is given by,

$$\left.\begin{aligned} 20\lg\left|\hat{s}^m\big|_{s=j\omega}\right| &= 20m\lg(\omega)dB \\ \angle\hat{s}^m\big|_{s=j\omega} &= \frac{\pi m}{2} \end{aligned}\right\}\omega_l \le \omega \le \omega_h \tag{5}$$

where m represents the magnitude of λ and μ and will be used throughout this paper. The gain and phase can be adjusted between ±20 dB/dec and ±90º. This characteristic enables more accurate design of the PID controller.

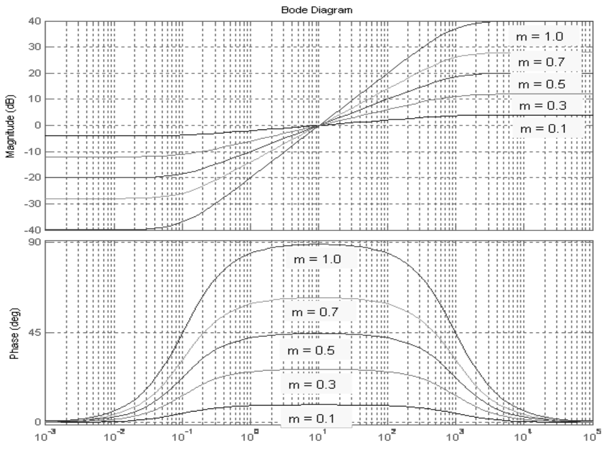

Fig. 2 Bode diagram of ORA on s^m

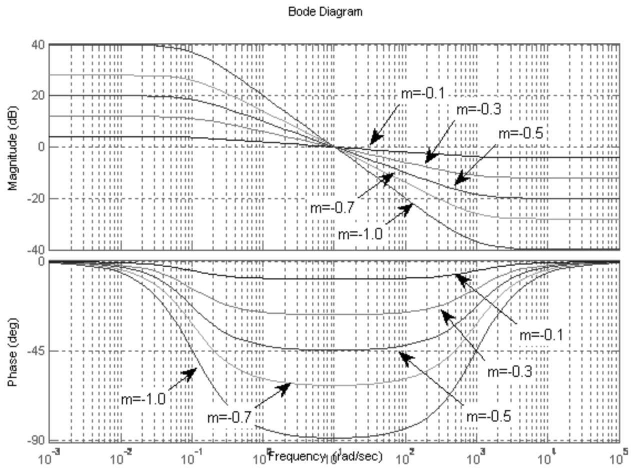

Fig. 3 Bode diagram of ORA on s^{-m}

3 Hydro-steam Distillation for Essential Oil Extraction Process

Generally, essential oil was extracted using distillation method. There are varieties of distillation methods available but common methods applied in the industries are hydro distillation, hydro-steam distillation and steam distillation. Distillation process separates the chemical constituents according to its boiling point in the form of oil vapours and steam mixture. Monoterpene hydrocarbons and oxygenated constituents have lower boiling point than phenols, ethers, or sesquiterpenes [15] and hence, will be released during lower temperature. The vapours are converted into liquid form through condensation process and can be separated from water using appropriate instruments.

In hydro distillation, the botanic materials are completely immersed in water and bring to boil. During the process, the materials are always in direct contact with heat and exposed to thermal degradation. Oxygenated components such as phenols get partially dissolved in the water and normally have to be redistilled in order to recover the lost compounds. However, redistilling process will increased operational cost and hence, was sometimes omitted [16]. Due to these reasons, the oils produced using hydro distillation is usually lower in quality compared to other distillation methods.

The most popular method used in industries is the steam distillation [17]. In proportion, almost 93% of essential oils were extracted using steam distillation [16]. This method was preferred by aromatic industries because it was cheap [18] compared to other advanced methods such as supercritical fluid extraction (SFE) or solvent extraction. In steam distillation, the dry steam was supplied from satellite boiler unit into the vessel holding the botanic material. The advantage of this technique is that the amount of steam can be controlled to minimize thermal degradation. However, the application was only affordable by large-scale essential oil industries because the cost of the equipments is very high and need to be operated by qualified personnel.

The practical alternative for rural industries is called the hydro-steam distillation. The equipment for this method is very much similar to the hydro distillation except that the botanic material was situated above the boiling water. Hence, it was prevented from being in direct contact with the boiling water. In this method, the steam was generated inside the same vessel instead of being supplied from external boiler. The advantages of this method over hydro distillation are: 1) It produces higher yield, 2) Oil components are less susceptible to hydrolysis and, 3) The process is faster. On the other hand, this method is much cheaper and simpler than the large-scale steam distillation plant.

The main problem encountered in this method is the uncontrolled steam temperature during the extraction process which leads to uncertain quality of the yield. The idea was to regulate the steam temperature by manipulating the water temperature inside the tank. This can be done by applying an electrical heater and then manipulating the power supplied to the heater in order to maintain the steam at a specified set point. Regulating the steam temperature in this manner was not easy since the dead-time is very large. Other than that, the response is very non-linear and slowly varying towards the actuating signal.

A hydro-steam distillation plant has been developed for this study. The plant was developed from a stainless steel tank and connected to a single-tube copper condenser at the top. The steam was generated by boiling the water in the same tank. A perforated tray was installed above the boiling water to support the raw material. The plant was equipped with temperature sensors of RTD PT100 type for continuous steam temperature monitoring during closed-loop control. The electrical heater was manipulated using STOM-1 power controller in burst mode control. Figure 4 shows a schematic diagram of the proposed system together with a photograph of the real plant.

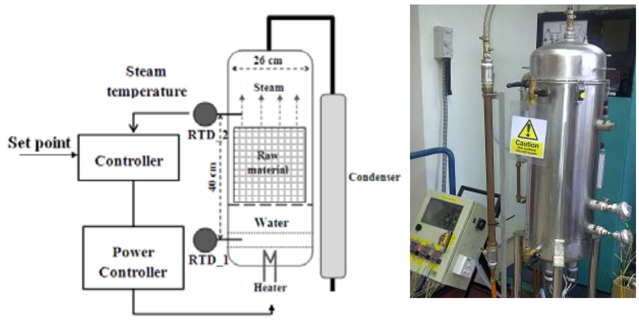

Fig.4 Schematic and photo of the hydro-steam distillation plant

3.1 Steam Temperature Model for Control

Steam temperature is a self-regulating process and has wide operating range. But, for this application, the operating range was limited from 80ºC to 100ºC. The process dynamics depend on the volume of water loaded into the tank. This variable has great impact especially on the dominant time constant of the process model.

Experiments of step input were carried out in order to obtain a mathematical model that describes its behaviors during nominal operating conditions. The specified conditions are listed below:

Input range: 0 – 5 volt
Output range: 80ºC - 100ºC
Nominal set point: 85ºC
Nominal water volume: 10 liters

Two sets of input-output data were considered. Each dataset was assigned as Z1 and Z2 with the following settings:

Z1: Input : 3.0 - 3.5 volt

Output : 73ºC - 100ºC
Z2: Input : 3.0 - 4.0 volt
Output : 83ºC - 100ºC

Both datasets are shown in Figure 5 and 6 respectively.

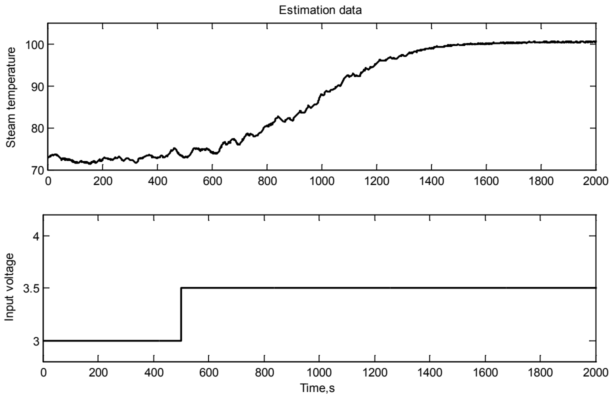

Fig.5 Z1 dataset

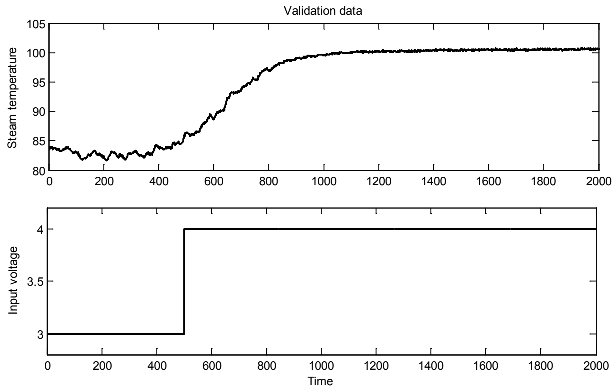

Fig.6 Validation dataset (Z2)

The dynamics of steam temperature within the specified range can be represented by a second-order transfer function. The approximate model can be determined using MATLAB System Identification Toolbox which requires two input-output datasets. The first dataset (Z1) was used for estimation and another one (Z2) for validation. Model validation was based on measurement of best fit between validation data and simulated data out of the estimated model. Formula of best fit is given by equation 6.

$$\% fit = 100\left[1 - \frac{norm(\hat{y} - y)}{norm(y - \bar{y})}\right] \qquad (6)$$

where
y = true value
$\hat{y}$ = estimated value
$\bar{y}$ = mean value

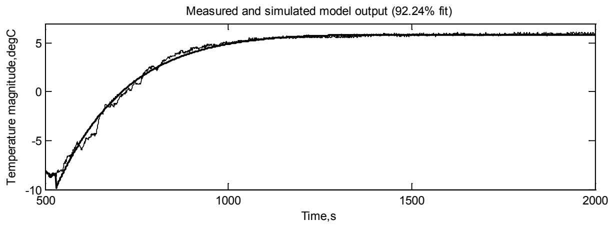

Fig.7 Validation of estimated model

The estimation produced an estimate transfer function as given in equation 7 with best fit of 92.24%.

$$G(s) = \frac{0.000366}{(s + 0.011)(s + 0.0074)} \qquad (7)$$

3.2 PID Tuning with Ziegler-Nichols Rules

This study applied Ziegler-Nichols PID tuning based on a process reaction curve. It should be noted that, these rules were only accurate for a process with an s-shaped step response or otherwise will not produce satisfactory response. The PID parameters can be acquired easily from the step response test and no process model is required. The tuning rules are listed in Table 1.

Table 1 Ziegler-Nichols PID tuning rules from FOPDT

	K_c	T_i	T_d
P	$\left(\frac{1}{K}\right)\left(\frac{\tau}{\theta}\right)$	-	-
PI	$\left(\frac{0.9}{K}\right)\left(\frac{\tau}{\theta}\right)$	3.3θ	-
PID	$\left(\frac{1.2}{K}\right)\left(\frac{\tau}{\theta}\right)$	2.0θ	0.5 θ

Information about the process gain (K), process dead-time (θ), and process time constant (τ) can be obtained from the process reaction curve. These parameters are described in Fig. 8.

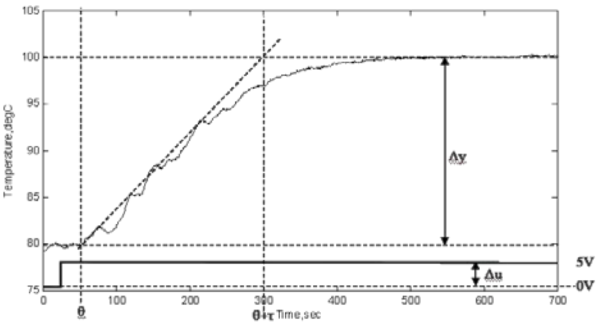

Fig. 8 Process reaction curve of steam temperature in hydro-steam distillation process.

The controller parameters are then calculated according to the rules listed in Table 1 for K=4.5, θ=25 sec, and τ=280 sec. For the standard PID structure, the following PI controller was obtained;

$$C(s) = 2.19\left(1 + \frac{0.027}{s}\right) \tag{8}$$

4 Error Compensator Design for Fractional PI

Applying ORA to an integrator never generates a pole at the origin and hence, the controller will not be able to track the set point without steady-state error [12]. The approach currently used to resolve this matter was by introducing a pure integrator and split the fractional integrator into two parts. This method was introduced by Axtell [10] and described by Eq. 9.

$$\frac{1}{s^{\lambda}} = s^{1-\lambda} \times \frac{1}{s} \tag{9}$$

The ORA was then applied to the fractional function of $s^{1-\lambda}$. This approach was used by Ramiro [10] but conversely, Farshad [19] has proved that this approach produced inaccurate results. Applying a pure integrator will modify the overall frequency response and thus, the output will not be as expected and may cause instability. Alternatively, the steady-state error can be improved by increasing the system's type by introducing Eq. 10 as proposed by Feliu-Batlle et al. [8]

$$G_e(s) = \frac{s+n}{s} \tag{10}$$

where n being a small value so that high frequency specifications were maintained and the system gain will not altered drastically. This approach was applied in this research for steady-state error compensation but with some modifications. The effect of each steady-state error compensation technique discussed above was described through Bode plots of the integrator terms and the composite PI controller. Figure 9 represents the effect from error compensator described by Eq.9 while Fig.10 represents Eq.10. Both conditions were simulated for m=-0.5.

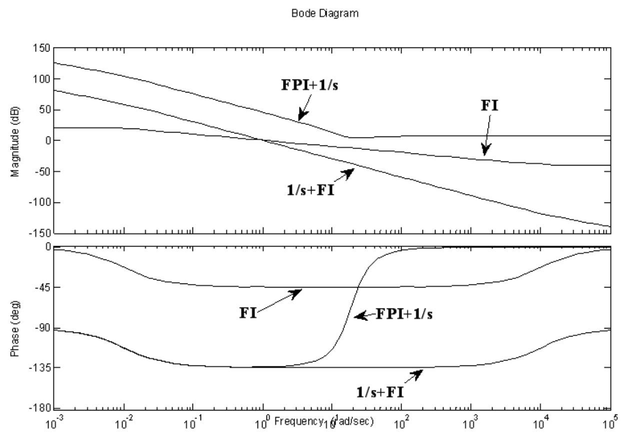

Fig. 9 Bode plot of FO-PI with error compensation in Eq. 9 when m=-0.5.

When the pure integrator was cascaded to the fractional integrator (FI), both magnitude and phase characteristics were totally altered for the whole frequency range. The phase was shifted down and reduced the phase margin. Consequently, the overshoot will increase. The phase was no more maintained around the crossover frequency and hence, gain changes will not be tolerated. On contrary, using the second method just increased the system's type and maintains all other behaviors around specified frequency range. The overall magnitude specifications can be achieved by a simple gain adjustment.

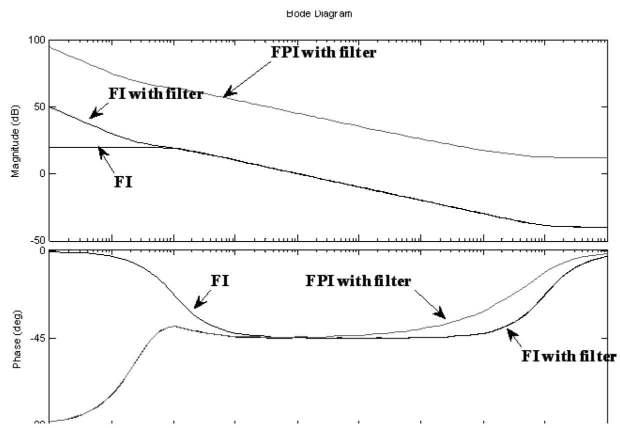

Fig. 10 Bode plot of F-PI with error compensation in Eq. 10 when m= -0.5

The results were based on simulation study of the second-order model given by Eq.7. PI parameters were obtained using the Ziegler-Nichols rules and were compared with the F-PI having the same controller settings. The integrator was approximated using ORA with N = 4, ω_L=0.01 rad/s and ω_H=10000 rad/s. The approximate transfer function was multiplied with gain, k so that the Bode magnitude crossed 0 dB (unity gain) at 1 rad/s.

4.1 F-PI without Error Compensation

The first experiment was implemented without any error compensator for the F-PI. The objective here was to get the idea on the effect of F-PI and to gauge its limitation. The controllers were compared for temperature regulation at 85ºC. The result for I-PI was given in Table 2. The response has high overshoot but zero steady-state error. The settling time reported in this paper includes the input offset of 10s which should be subtracted from the reported value.

Table 2 I-PI Closed-loop Performances

Rise time, (s)	Settling time, (s)	OS (%)	Steady-state error (ºC)
20	314	74.53	0

The F-PI was implemented with the same controller settings. The integral term was varied for integer order, m = -0.1, -0.5, and -0.9. For each case, the gain k was adjusted accordingly as mentioned in previous section. The output response together with the output from I-PI was shown in Fig.11 and the performance criterions were given in Table 3.

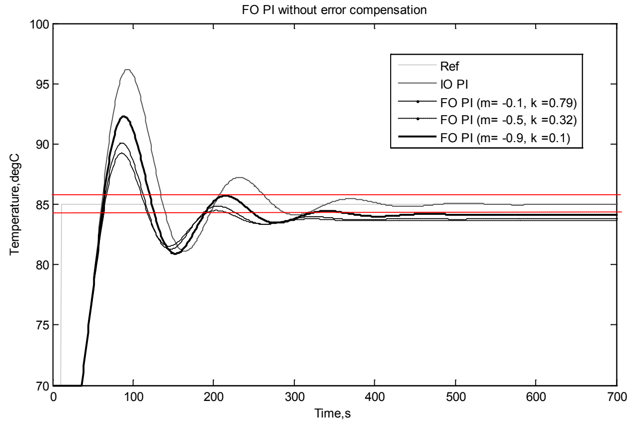

Fig. 11 F-PI closed-loop responses without error compensation.

In terms of overshoot, the F-PI version was better than the I-PI. The overshoot was reduced with the fractal power. But, none of the F-PI output can regulate the temperature at the set point and not even settled within the ±5% (±0.75ºC) boundary. This was due to the absence of pole at the origin as discussed previously.

TABLE 3 F-PI (WITHOUT ERROR COMPENSATION) CLOSED-LOOP PERFORMANCES.

m	k	OS (%)	Steady-state error (ºC)
-0.1	0.79	28.27	1.33
-0.5	0.32	33.93	1.21
-0.9	0.1	48.50	0.87

4.2 F-PI with fixed error compensation

The next stage of evaluation accommodated an error compensator described by Eq.10. The compensator was design for m=-0.5 where n will remain fixed at 0.03 rad /s. The fractional power was varied for m= -0.1, -0.5 and -0.9. The incompetency of the compensator can be observed in Fig.12. The output performance was given in Table 4.

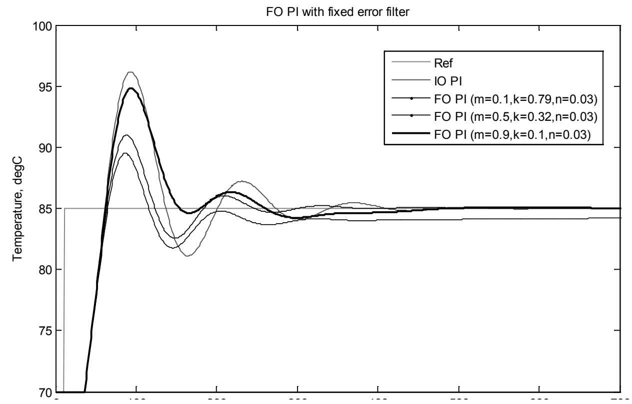

Fig. 12 F-PI closed-loop responses with fixed error compensation.

The overall transient was a bit different from the results obtained in section 4.1. Obviously, steady-state error was improved and eliminated for m=-0.5 and -0.9. The error when m=-0.1 was reduced. However, overshoot in the output was worse for every order of m but the settling time was improved compared to I-PI.

Table 4 F-PI (with Fixed Error Compensation) Closed-Loop Performances.

m	k	n	Settling time (s)	OS (%)	Steady-state error (ºC)
-0.1	0.79	0.03	-	30.07	0.84
-0.5	0.32	0.03	224	40	0
-0.9	0.1	0.03	294	65.47	0

4.3 F-PI with error compensation of variable n

From the results obtained in section 4.1 and 4.2, it can be concluded that the zero of the error compensator had some impact on the overall system's response and should be adjusted to get better response for different order of m. So, this study proposed an adjustable n which is the zero of the error compensator transfer function.

The movement of zero had significant impact on the phase margin especially when m=-0.5 and -0.9 while for m=-0.1, the presence of the filter was very dominant due to small magnitude and phase of the fractional integrator. For m=-0.9, great improvement in %OS was observed when n= 0.03 compared to n=0.003. The overall results were presented in Fig.13 and closed-loop performance was given in Table 5.

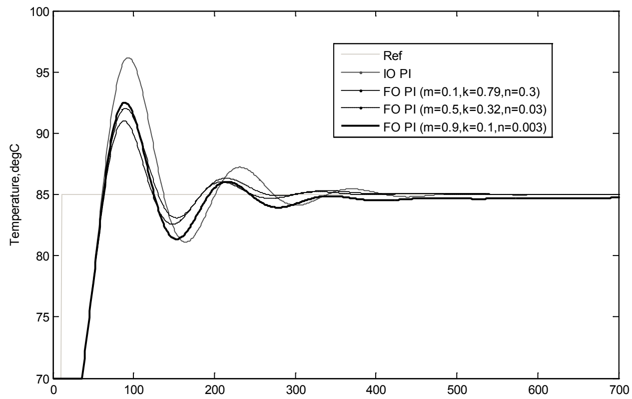

Fig. 13 F-PI closed-loop responses with variable error compensation.

Table 5 F-PI (with variable error compensation) closed-loop performances

m	k	n	Settling time (s)	OS (%)	Steady-state error (ºC)
-0.1	0.79	0.3	239	46.93	0
-0.5	0.32	0.03	225	40.00	0
-0.9	0.1	0.003	301	50.07	0

5 Experimental Results

The simulation results were validated on a hydro-steam distillation process. For real-time implementation, the approximated transfer function of the integrator was discretized using Tustin method with sampling time of 1 sec. The real-time control was performed using MATLAB Real-time Workshop interfaced with PCI 1711 data acquisition card from Advantech Automation.

The first result was used to validate the data from Table 5. The real-time response was slower than the simulation because the actuator saturation was neglected during simulation. However, the closed-loop responses of F-PI were significantly improved the overshoot of the steam temperature produced by the PI controller. The efficiency of the proposed error compensator was proven in this experiment whereby all responses of F-PI produced no steady-state error. Figure 14 presents the real-time F-PI with the same setting listed in Table 5.

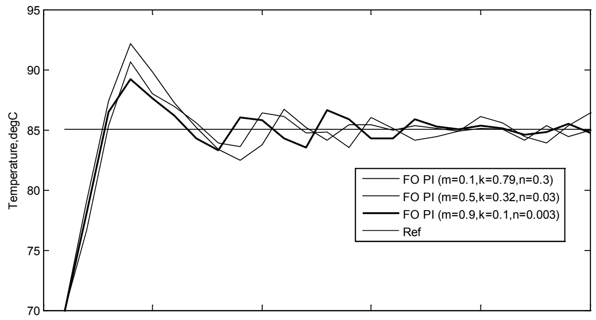

Fig. 14 F-PI setting from Table 5 compared with I-PI.

However, the overshoot can be further improved by adjusting the value of n to increase its phase margin as had been presented in the previous section. This is obvious for the case when m is set to 0.1 and n is dominating the frequency response of the overall system. The overshoot of this case can be significantly reduced by letting n = 0.03 and the output still saturates without steady-state error.

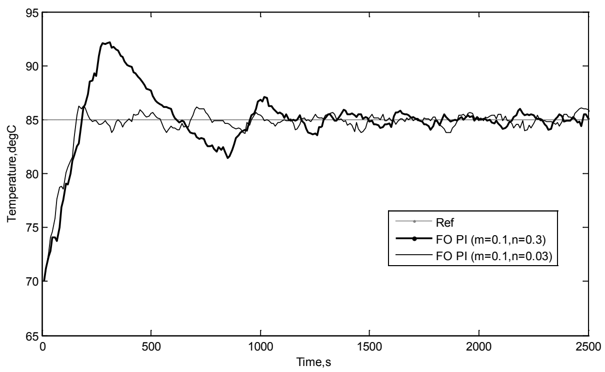

Fig. 15 F-PI with m=-0.1 and adjustable n.

The same situation can be demonstrated to the case when m=0.9. The overshoot was significantly improved for n = 0.003 compared to n = 0.03.

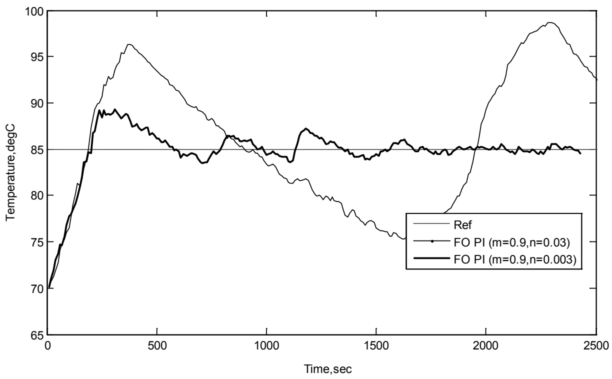

Fig.16 F-PI with m=-0.9 and adjustable n.

Conclusion

This study demonstrated the improvement of fractional PI over the integer PI. The inherent steady-state error was eliminated using an error compensator comprised of a very small zero and a pole at origin. This study also show that the compensator was not generalized for every order of the fractional integrator but should be tuned for better phase margin that can improve the output's overshoot. Another observation was that the error compensator is dominating the closed-loop response for cases when fractional-order is less than 0.5. The results were comprehensively explained by simulation and verified experimentally.

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