CRONE Control Strategy for Air Pressure System

V. Velmurugan, N. N. Praboo

Abstract: Pressure process in industry is inevitable and is considered with foremost importance in many processes like boilers, pressure vessels, reactors, closed vessels, steam drums and flash points. Pressure measurement and control is important requirements of all process, since it is related to safety of the human resources and equipment. So in this work an Air Pressure System (APS) is considered for investigation. Over the years an increasing attention made on fractional order controller and dynamic systems using fractional order calculus. Its theoretical and practical interests have been confirmed today, and its relevance to engineering society can be think carefully about as developing scientific avenue. This project discusses the design and implementation of generations of CRONE controller for APS. The Mathematical model of APS is determined from the various operating regions by using worst case modeling technique. The three generations of the strategy of CRONE control are designed based on worst case model. Simulation runs of set point tracking responses are documented. The time domain and integral error indices performances are obtained and compared on strategies of the generation CRONE controller. It is noticed that Third Generation CRONE (TGC) controller outperforms provide better performance than the other generations of CRONE controller.

Keywords: CRONE Controller, Air Pressure System, Control System Design (CSD), FGC, SGC, TGC, Black Locus, Non Linear Optimization.

I. INTRODUCTION

Manabe [1] initiated the idea of non integer order controller in the year 1960. Continuing his idea, Oustaloup investigated the fractional order control algorithms for the control systems. In addition he examine frequency domain on CRONE controller the year 1991. CRONE [2] is a acronym of “Commande Robuste d’Ordre Non Entier” which deals non integer order robust controller. There are three different CRONE controllers available in control environment namely First generation controller, Second generation controller and Third generation controller [3, 4, 5 and 6]. It is contemplated to be one of the evolved approaches to design robust and fractional order controllers [8-11 and 12]. In this paper worst case model is obtained for air pressure system depend on real time run parameters for different operating regions. All generations of CRONE controllers are designed based on the model. Real time servo run is carried out for the APS and the responses are recorded. The performances of all the generations of CRONE controllers are compared based on time domain criteria and integral error indices. The project is covered as follows: Section 2 presents complete information of the APS. The APS model parameters are determined in Section 3. In Section 4, Design of CRONE control strategies is depends on the worst case model. In Section 5, Implementation of CRONE controller based on CSD toolbox is discussed. The comparison of simulation outputs for the controller performances are provided in Section 6. Finally, declaring the remarks are given in Section 7.

II. DESCRIPTION OF THE PROCESS

A. Air Pressure System

Fig. 1 shows a schematic view of APS [7]. The pressure inside the process tank is to be controlled. The system consists of process tank, air filter regulator, pneumatic control valve and pressure transmitter. The air from the compressor is regulated to a certain range of pressure (0-75 psi) with the help of Air Filter Regulator (AFR) and the air is allowed to flow into the process tank. The piezoelectric transmitter is used to measure pressure in the process tank.

Fig. 1. Schematic view of Air Pressure System (APS)

The error deviation signal is generated by comparing the reference value with pressure in the tank. The error is processed in the controller to generate corresponding controller output (4-20 mA). The controller output is converted into pneumatic signal (3-15 psi) using Electric to Pressure (E/P) converter. The pressure signal is used to turn on the control valve to control the flow rate of air into the process tank. Thus the pressure in the process tank is regulated.
III. PROCESS MODEL IDENTIFICATION - APS

A. Determination of Worst Case Model Parameters

In real time platform, pressure inside the tank is retained at a stable state each of various operating points of 30%, 40%, 50% and 60%. The step input of ±10% pressure value for various operating point is applied and the dissimilarity of pressure in opposition to time for every operating point is observed separately until a new stable state is achieved shown in Fig 2 and 3. The model parameter such as time constant ($\tau_p$), time delay ($t_d$) and process gain ($K_p$) are determined and arranged in table 1 as per the recorded data.

From the Observation of table, the worst-case model parameters [9] such as smaller time constant ($\tau_p$), larger delay ($t_d$) and greater process gain ($K_p$) are considered and these parameters are taken for design of controllers.

Fig. 2. Open loop responses (10% Positive step changes) – APS

Fig. 3. Open loop responses (10% Negative step changes) - APS

<table>
<thead>
<tr>
<th>Operating Region %</th>
<th>$K_p$</th>
<th>$\tau_p$</th>
<th>$t_d$</th>
<th>$K_p$ (max)</th>
<th>$\tau_p$ (min)</th>
<th>$t_d$ (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 - 50</td>
<td>0.9</td>
<td>70</td>
<td>8</td>
<td>0.9</td>
<td>65</td>
<td>8</td>
</tr>
<tr>
<td>40 - 30</td>
<td>0.7</td>
<td>65</td>
<td>7.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 - 60</td>
<td>1.2</td>
<td>64</td>
<td>7.3</td>
<td>1.2</td>
<td>64</td>
<td>7.3</td>
</tr>
<tr>
<td>50 - 40</td>
<td>0.7</td>
<td>68</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Model identified to a wide region of 30 - 60 %

The identified worst case model of APS equation is,

$$G(s) = \frac{1.2}{64s + 1} e^{-8s}$$

Table- I: APS Worst case model parameters

By using the model equation, the designs of three generations of CRONE controllers are deliberated in next section.

IV. CRONE CONTROL STRATEGY

A. Design Procedure of First Generation CRONE Controller

The closed loop structure of the First Generation CRONE (FGC) control strategy is shown in Fig. 4.

$$C_F(s) = C_0 s^n , \text{ with } n \text{ and } C_0 \epsilon \Phi$$

In bode plot of “n” correlates to the integro – differentiator of open loop fractional order and $C_0$ is the gain of the FGC controller. The Bode plot of FGC controller is illustrated in Fig. 5. From the diagram it is noticed that the FGC controller confirms at a constant phase ($\pi n/2$) around the open loop gain crossover frequency $\omega_{cg}$. The FGC control strategy is particularly appropriate when the desired open-loop gain crossover frequency $\omega_{cg}$ is within a frequency range that has asymptotic response. In this band the nominal and perturbed plant phases are constant and the plant uncertainty is gain like. The controller $C_F(s)$ is defined within a frequency range $[\omega_A, \omega_B]$ around frequency $\omega_{cg}$ from the fractional transfer function of an order ‘$n$’ integro-differentiator:
The constant phase controller \( C_F(s) \) does not varied even variation of plant gain or plant corner frequency, therefore need to modify the phase margin. The gain crossover frequency \( \omega_c \) varies within the frequency range \([\omega_a, \omega_b]\). The FGC controller \( C_F(s) \) can also be defined by a band-limited transfer function on corner frequencies \( \omega_0 \) and \( \omega_h \) as,

\[
C_F(s) = C_0 \left( \frac{1 + s/\omega_0}{1 + s/\omega_h} \right)^n, \quad \omega_0 < \omega_A \quad \text{and} \quad \omega_h > \omega_B
\]  

(3)

The band limited fractional order transfer function of the FGC controller is serially connected with a low pass filter of order \( n_l \) and the band limited integrator of order \( n_i \) for acquiring desired control effort and avoid steady state errors. After the computation the transfer function of fractional order FGC controller is given by,

\[
C_F(s) = C_0 \left( \frac{\omega_l}{s} \right)^n \left( \frac{1 + s/\omega_0}{1 + s/\omega_h} \right)^n \frac{l}{(l + s/\omega_f)^n_F}
\]  

(4)

Here the conditions \( \omega_0 < \omega_l < \omega_c < \omega_h \) and \( \omega_0 \) and the integer orders \( n_i \) and \( n_l \) = 1. Where integrator used to reject the input disturbance and low pass filter used to avoid the amplification of the high frequency measurement noise.

B. Design Procedure of Second Generation CRONE Controller

The Second Generation CRONE (SGC) controller approach determines the transfer function of open loop \( \beta_s(s) \) in the frequency limit \([\omega_a, \omega_b]\) by the fractional integro-differentiator. The closed loop structure strategy of the SGC control is shown in Fig. 6.

![Fig. 6. Closed loop structure of SGC control strategy](image)

In this analysis, a SGC controller open loop fractional order transfer function \( \beta_s(s) \) is represented as,

\[
\beta_s(s) = C_S(s) G(s) = \left( \frac{\omega_c}{s} \right)^n, \quad n \in \{1, 2\}
\]  

(5)

The Nichols plane is plotted within the frequency range \([\omega_a, \omega_b]\) as shown in Fig. 7 of open loop fractional order transfer function \( \beta_s(s) \) of SGC controller. The vertical straight line \( \beta_s(s) \) of Nichols locus called frequency template. The phase location is decides by order \( n \) of frequency template, where \( n \) is order of controller around the open loop gain crossover frequency \( \omega_c \), the frequency template \( \beta_s(s) \) vertically by registering a constant phase around the reference open loop gain crossover frequency \( \omega_c \) based on plant parameters such as gain and frequency. This ensures the vitality of SGC controller.

![Fig. 7. Nichols locus of \( \beta_s(s) \) or Frequency template](image)
C. Design Procedure of Third Generation CRONE Controller

The structure of the strategy of TGC control is shown in Fig. 8. The TGC control design widens SGC controller by authorizing the handling of more common uncertainties.

\[
\beta_Y(s) = C_T(s) \cdot G(s) \cdot \beta(s)
\]

Where the transfer function of generalized template is band-limited, then it is changed by a conventional expression.

\[
\beta_Y(s) = e^{\theta_{RC}(b)} \left[ \frac{\omega_n^a}{s} \left( 1 + \frac{\omega_n^b}{s} \right)^a \right]^{\theta_{RC}(b)} \frac{1}{1 + \frac{s}{\omega_n^b}}
\]

Therefore the general equation of TGC Controller is,

\[
C_T(s) = \frac{\beta_Y(s)}{G(s)}
\]

It has eight high level parameters are there in open-loop complex fractional order integral transfer function \(\beta(s)\), they are \(n_l, n_h, a, b, \omega_0, \omega_m, C\). For which \(n_l\) and \(n_h\) are fixed by the control system designer. To obtain the tangency condition, \(\omega_0\) and \(C\) are declared. The four individualistic parameters of optimal template on nonlinear optimization algorithm to minimize the \(J\) cost function depend on resonant peak variations and achieve a set of shaping limitation.

\[
J = M_r_{\text{max}} - M_r
\]

The primary aim of the TGC control is the optimization of three liberated parameters (a tangency is obtuse) from the four high-level parameters \(a, b, \omega_0\) and \(\omega_m\) of template. The conventional form of TGC controller is given in (12). The equations (4), (7) and (12) are not in an implementable form, since it is having fractional order integro-differentiation terms. So it has to be converted into a rational form using recursive distribution technique. The recursive distribution of poles and zeros results in achievable rational order CRONE controller \(C_R(s)\) represented as

\[
\frac{C_R(s)}{G(s)} = \beta_Y(s)
\]

V. IMPLEMENTATION OF CRONE CONTROLLER USING CSD TOOLBOX

A. CRONE Controller parameters

The CRONE research group [5,6 & 8] is developed and managed the CRONE CSD toolbox. Which permit the user to lay down the elements such as plant parameters and its perturbations, frequency domain and time domain specifications, open loop tuned parameters and open loop fixed parameters etc. Therefore the APS plant information is set in the CRONE CSD toolbox for further analysis.
On following the design procedures given in section IV [4] with the help of CRONE CSD toolbox one can obtain all the three generations of rational order CRONE controllers are shown in Table III.

Table III: Rational Order CRONE Controller

<table>
<thead>
<tr>
<th>Controller Type</th>
<th>Nominal Specifications</th>
<th>Design Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rational First Generation CRONE (FGC) controller</td>
<td>$C_{FR}(s) = 1.539 \times \frac{s^3 + 0.1s + 0.7318s + 1.6110s + 3.5480}{s^3 + 0.5231s + 1.152s + 2.536}$</td>
<td>-</td>
</tr>
<tr>
<td>Rational Second Generation CRONE (SGC) controller</td>
<td>$C_{SR}(s) = 1.88 \times \frac{s^3 + 0.01754s + 0.7149s + 1.574}{s^3 + 0.5334s + 1.179s + 2.596}$</td>
<td>-</td>
</tr>
<tr>
<td>Rational Third Generation CRONE (TGC) controller</td>
<td>$C_{TR}(s) = 2.7229 \times \frac{1 + s/1.519}{1 + s/3.33} \times \frac{1 + s/0.555}{1 + s/0.4779}$</td>
<td>-</td>
</tr>
</tbody>
</table>

VI. RESULTS AND DISCUSSION

A. Servo Responses

The Simulation servo execution of all the three generation of crone controller are analysed and tabulated for APS. The servo response controller performances are analyzed based on error indices performance criteria viz. ISE and, IAE and the time domain performance measures viz. rise time ($t_r$) and settling time ($t_s$). The Simulation servo runs are conducted at 50% operating pressure. The set point change of ±5% and ±10% change in pressure is applied and is shown in Fig. 10, 11 & 12. The error and time performances are recorded in Table IV & V.
It is evident from the Table IV of error performances for the operating point of 50% pressure with the step change of ±5% and ±10%. The TGC is the extraordinary performer and stand in first position. The SGC is moderate performer to that of TGC controller. The FGC stays in last position by providing lesser ISE and IAE values of other controller.

From the Table V, it is acknowledged that the case of settling time TGC performs better than FGC and SGC and similarly in the performance of rise time TGC provide superior performance than TGC and FGC. Therefore, by considering controller performance and process output taken account of ISE, IAE and settling time values only with negligible of rise time to the controller.

**VII. CONCLUSION**

In this paper, worst case model parameters are obtained for APS from real time open loop test at different operating regions. By using the worst case model three generation of CRONE controllers are designed. The CRONE CSD toolbox used to implement the CRONE controllers are compared based on servo response error index and time domain analysis. Simulation servo runs are conducted at 50% operating pressure. Servo responses are computed and the performance manipulates are recorded. From the analysis the TGC controller better than other two generations of CRONE controllers.

**REFERENCES**

1. S. Manabe, The system design by the use of a model consisting of a saturation and non integer integrals, ETJ of Japan,8(3-4): 147-150,1963.
6. CRONE control design module user’s guide, CRONE research group,2010.
8. Ninteger,version 2.3, Fractional control toolbox for MATLAB.

**AUTHORS PROFILE**

V.Velmurugan was born in Cuddalore, India on 11th October 1984. He completed his Under Graduate Engineering degree with distinction in Electronics and Communication Engineering in the year 2006 from affiliated to Anna University, Dr.NNCE, Tholudur, Cuddalore, India and he acquired for his Master degree with distinction in specialization of Process Control and Instrumentation Engineering in the year 2012 in Annamalai University, Annamalainagar, India. He is presently working as Assistant Professor in the Department of Electronic and Instrumentation Engineering in Arunai Engineering College, Tiruvannamalai, India and also pursuing his research in the field of Process Control. His area of interest is on Fractional Order Robust Controller and Systems.

Dr.N.N.Praboo was born in Cuddalore, India on 10th December 1978. He graduated his Bachelor of Engineering degree in Electronics and Instrumentation in the year 2000 in Annamalai University, Annamalainagar, India. He further qualified himself for his Master degree in Engineering with the specialization in Process Control and Instrumentation Engineering in the year 2008 in the same institution. He received his Doctorate in Instrumentation Engineering at Annamalai University in the year of 2015. He is now Assistant Professor in the Department of Electronics and Instrumentation Engineering, Annamalai University, Annamalainagar, India. His area of interest is in Process Control and Instrumentation, Fractional Order Systems and Controllers.