Real Time Implementation of Third Generation CRONE Control Strategy for Air Pressure System

V. Velmurugan, N. N. Praboo

Abstract: ***The primary objectives of this research work are design and implementation of Third Generation CRONE controller for Air Pressure System (APS). The mathematical modeling is determined using worst case modeling technique for different operating regions. The design and implementation of CRONE control strategy through worst case modelling and examined in real time. The performances of Third Generation CRONE (TGC) controller is compared with ZN-PI controller and the results are tabulated in terms of time domain and error indices. It is validated that the TGC controller gives better performances than ZN-PI controllers.***

Keywords: Mathematical modelling, CRONE Controller, ZN-PI controller, Air Pressure System, Nichols Plot, Non Linear Optimization.

I. INTRODUCTION

Podlubny [1] presented important studies on fractional order control strategies, which established the starting point in fractional order calculus on automatic control applications. CRONE is a acronym of “Commande Robuste d'Ordre Non Entier” which means non integer order robust controller. In the process environment, there are available three categorized CRONE controllers namely First generation CRONE controller [2], Second generation CRONE controller [3] and the Third generation CRONE controller [4,11,13]. Jocelyn Sabatier [6] in their work extended the second generation CRONE control to have the control of linear time periodic systems. A.Morand [7] dealt with car longitudinal control performed by cruise control system using CRONE approach. Duarte Valerio [10] described a method to identify a digital model for a plant from its frequency data.

In this paper worst case model is obtained for Air Pressure System (APS) depend on real time run parameters for different operating regions. Third generation CRONE controller is designed based on the model. Real time servo run is carried out for the APS and the responses are recorded. The performance of all Third generation CRONE controller is compared with ZN-PI controller based on time domain criteria and integral error indices.

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The 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 based on the worst case model. In Section 5, Implementation of CRONE controller using CSD toolbox is discussed. The comparison of the real time outputs for the controller performances are provided in Section 6. Finally, remarks are given in Section 7.

II. DESCRIPTION OF THE PROCESS

A. Air Pressure System

Fig. 1 shows the functional block representations of air pressure system [8,9].The main objectives of this work is to control and maintain the pressure in the process tank. It consists of process tank, pneumatic control valve, pressure transmitter and Air Filter Regulator (AFR).

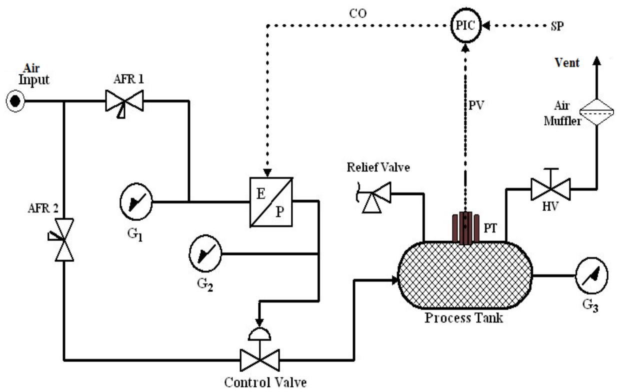

Fig. 1. Schematic view of Air Pressure System (APS)

The process tank is filled by the air from the compressor with help of air pressure regulator at the range of (0-75 psi). The pressure in the process tank is measured through piezoelectric transmitter. The measured signal is compared with desired set point to obtain the error signal.

Further the error signal is applied to controller to generate the output (4-20 mA). The electrical controller output is converted into the pneumatic signal at the range of (3-15 psi) to regulate the control valve. The pressure signal can actuate the control valve to maintain desired value of pressure inside the process tank. The real time experiment setup is shown in fig. 2. It consist of air tank,

air filter regulator, E/P converter, I/V converter, V/I converter, pressure transmitter, pneumatic control valve, VMAT01 DAQ card and pressure gauges.

The source of compressed air regulated by means of air filter regulator and sent to the process tank using the Air to Open (ATO) pneumatic control valve. The air pressure is measured using piezoelectric transducer. The I/V converter used to convert the current from the sensor into A/D of VMAT01 card.

The output signal of VMAT01 card is applied to a controller and compared with predefined reference value to generate the controller output. The controller output is feed to the D/A of VMAT01 card. The analog signal is converted into pneumatic signal at rate of (0-15 psi), which is said to be input of final control element to maintain desired value of pressure in the process tank.

Fig. 2. Experimental setup 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 pneumatic signal is used to turn on the control valve to control the flow rate of air into the process tank. Thus the pressure inside the process tank is regulated.

III. PROCESS MODEL IDENTIFICATION - APS

A. Determination of Worst Case Model Parameters

In real time platform, pressure in the tank is kept at a steady state each of different operating points of 30%, 40%, 50% and 60%. A step size of ±10% pressure value for each operating point is applied and the variation of pressure against time for each operating point is recorded separately until a new steady state is attained shown in Fig 3 and 4.

From the recorded data, the model parameters such as process gain (K_p) time constant (τ_p) and time delay (t_d) are computed and tabulated in Table I.

From the table, the worst case model parameters [14 and 15] such as larger process gain (K_p), smaller time constant (τ_p) and larger delay (t_d) are considered and these parameters are taken for design of controllers.

Table- I: APS Worst case model parameters

Operating Region %	K_p	τ_p	t_d	$K_{p(max)}$	$\tau_{p(min)}$	$t_{d(max)}$
40 - 50	0.9	70	8	0.96	68	7
	6					
40 - 30	0.7	68	7.3			
50 - 60	1.2	64	7.3	1.2	64	6.8
50 - 40	0.8	70	7.2			
Model identified to a wide region of 30 - 60 %				**1.2**	**64**	**7**

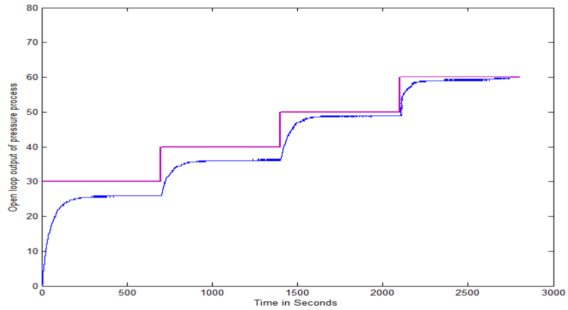

Fig. 3. Open loop responses

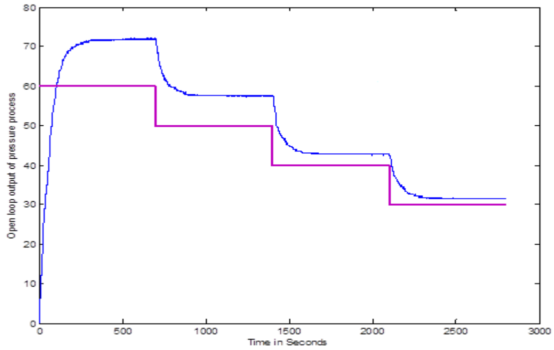

Fig. 4. Open loop responses

(10% Positive step changes) – APS (10% Negative step changes) – APS)

The identified worst case model of APS equation is,

$$G(s) = \frac{1.2}{64s+1} e^{-7s} \quad (1)$$

By using the model equation, the designs of Third generation of CRONE controllers is deliberated in next section.

IV. CONTROL STRATEGY

A. Third Generation CRONE (TGC) Controller

The closed loop of TGC controller strategy [4] is exhibited in Fig. 5. The TGC controller design widens the previous generations of CRONE by allowing to handle more general uncertainties.

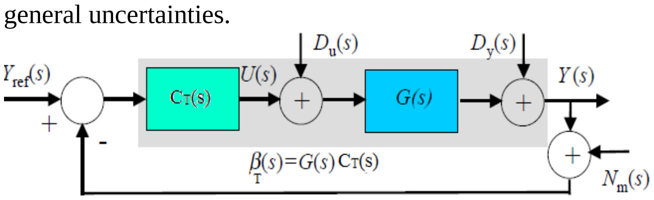

Fig. 5. Closed loop structure of TGC controller strategy

Y_{ref}(s) – input reference signal, **C_T(s)** - CRONE controller, **G(s)** - process transfer function, **Y(s)** - plant output, **U(s)** - controller output, **D_u(s)** – i/p disturbance, **D_y(s)** – o/p disturbance,

N_m(s) - sensor disturbance, **β_T(s)** – transfer function of open loop fractional order TGC

The design of TGC controller strategy having three stages namely generalized template, optimal template and optimization of open loop behavior. The general unity feedback structure is given in Fig. 5. The design of control strategy is based on the definition of a generalized template (Fig. 6), which is to be described in the black locus (Nichols chart) by every direction straight line segment around open loop gain crossover frequency ω_{cg}. From the Nichols chart, the real order value *a*, decides the phase location of the frequency template and the imaginary order value b, determines its angle to the vertical. The complex fractional order integral transfer function is:

$$\beta_T(s) = C_T(S)G(s) = \left(\cosh\left(b\frac{\pi}{2}\right)\right)^{sign(b)} \left(\frac{\omega_{cg}}{s}\right)^a \left(\cos\left(b \ln\left(\frac{s}{\omega_{cg}}\right)\right)\right)^{-sign(b)} \quad (2)$$

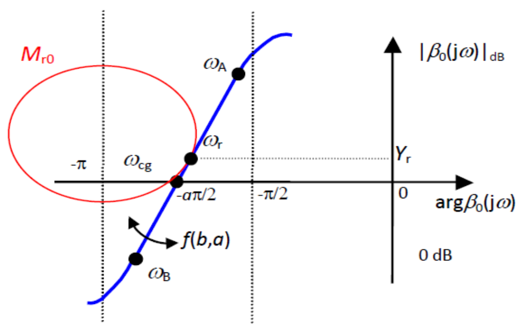

Fig. 6. Black Locus of Generalized template (Nichols plane)

From the derivatives of the β (jω) magnitude and phase at frequency ω_{cg}, the angle of the generalized template to the vertical can be expressed as a function of *a* and *b*:

$$\frac{d\left(|\beta_T(j\omega)|_{db}\right)}{d\left(phase\,\beta_T(j\omega)\right)} = \frac{-20\,a\,sign(b)}{\ln(10)\,b\tanh(b\frac{\pi}{2})} \quad (3)$$

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

$$\beta_T(s) = C^{sign(b)}\left(\frac{\omega_l}{s}+1\right)^{n_l}\left(\alpha_0\frac{1+s/\omega_h}{1+s/\omega_l}\right)^{a} \times \left(Re/_i\left(\alpha_0\frac{1+s/\omega_h}{1+s/\omega_l}\right)^{ib}\right)^{-q\,sign(b)}\left(\frac{1}{(1+\frac{s}{\omega_h})^{n_h}}\right) \quad (4)$$

Therefore the third generation fractional order CRONE controller is,

$$C_T(s) = \frac{\beta_T(s)}{G(s)} \quad (5)$$

There are eight high level parameters are there in open-loop complex fractional order integral transfer function β(s), they are n_l, n_h, a, b, ω_l, ω_h, ω_r and C. In which n_l and n_h are fixed by the control system designer. In order to obtain the tangency condition, ω_r and C are mentioned. A nonlinear optimization algorithm based on optimal template for the four independent parameters which minimizes the cost function J based on the resonant peak variations and fulfils a set of shaping constraints.

$$J = M_{r\,max} - M_{ro} \quad (6)$$

Synthesizing such a template through the optimization of three independent parameters ω_l, ω_h and ω_r leads to parameterization of three dependent parameters a, b and C shown in Fig. 7. The general form of TGC controller is given in (5). The equation (5) is not in an implementable form, since it is having fractional order integro-differentiation terms. So it has to be changed into a rational form using recursive distribution technique. The achievable rational order CRONE controller $C_R(s)$ by recursive distribution method represented as.

$$C_R(s) = \frac{\beta_R(s)}{G(s)} \quad (7)$$

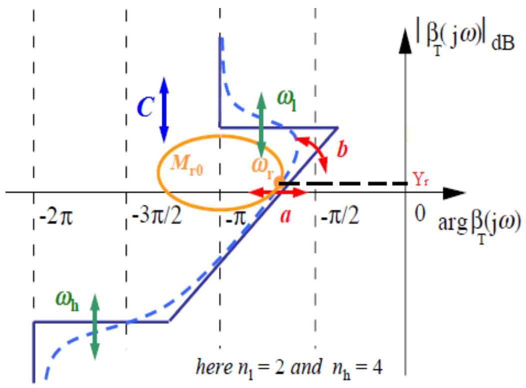

Fig. 7. Asymptotic Nichols locus- effect of parameters

B. ZN - PI Controller

The most famous tuning methodology was first proposed by Ziegler and Nichols in the year of 1942, who were engineers for a major control hardware company in United States. Based on their experience with the transients from many types of processes, they developed a closed loop tuning method still used today in one form or another.

The method is described as a closed loop method because the controller remains in the loop as an active controller in automatic mode. PID controllers online auto tuning that is based on ZN tuning method. The ZN- PI controller[12] is to control the plant or system with respect to set point and process variable and independent of nature of the system or plant.

Ziegler-Nichols tuning rule was the main such exertion to give a useful way to deal with tune a PID controller. Based on the worst case model of the Air Pressure System (APS), The Zeigler Nichols (ZN) – PI controller is designed. The Controller is given as

$$C(s) = K_C + \frac{K_C K_I}{s} = 6.857 + \frac{0.2938}{s} \quad (8)$$

Where,

$$K_C = \frac{0.9\tau}{K_P \times t_d} \quad \text{and} \quad K_I = \frac{1}{\tau_I} = \frac{1}{3.33 \times t_d}$$

V. IMPLEMENTATION OF CRONE CONTROLLER USING CSD TOOLBOX

A. CRONE Controller parameters

The CRONE Control System Design (CSD) toolbox is developed and managed by CRONE research group [5]. It allows the user to set the basic elements like plant parameters and its perturbations, time domain and frequency domain specifications, open loop fixed parameters and open loop tuned parameters etc.

Thus the APS plant model information is set in the CRONE CSD toolbox for further computation. Its plant perturbations are also considered. The plant gain is perturbed to a range of ±20%, since a bigger range of perturbation is considered to incorporate robustness to the controller and are in the range of $0.88 < 1.1 < 1.32$.

The user defined CRONE controller design specifications are open loop gain cross over frequency ω_{cg}, required phase margin P_m, etc. The user defined values for the system considered in the present work is reported in Table II.

Table- II: User defined CRONE Controller Design Specifications

Required nominal open loop - ω_{cg}	3	ω_A / ω_l - ratio	10
Required nominal phase margin - P_m	54.91	ω_h / ω_B - ratio	10
Integral order - n_i	1	ω_{AB} / ω_{cg} - ratio	1
Low-pass filter order - n_f	1	ω_{cg} / ω_i - ratio	30
Rational Approx. cell no. N	5	ω_f / ω_{cg} - ratio	30
Fractional effect width - ω_A / ω_B ratio - 0.8379			

On following the design procedures given in section IV [5] with the help of CRONE CSD toolbox one can obtain the Third generation rational order CRONE controllers are shown in Table III.

Table- III: Controller Design Parameters

Rational ZN-PI controller
$C(s) = \dfrac{6.857s + 0.2938}{s}$
Rational Third Generation CRONE (TGC) controller
$C_{TR}(s) = \dfrac{2.8}{s} \dfrac{(1 + \frac{s}{1.612})}{(1 + \frac{s}{16})} \dfrac{(1 + \frac{s}{0.57})}{(1 + \frac{s}{0.5})}$

VI. RESULTS AND DISCUSSION

A. Servo Responses

The real time servo run of TGC controller and ZN-PI controller are conducted and recorded for Air Pressure System (APS). The servo response performances are analyzed based on error indices performance criteria viz. Integral Square Error (ISE), Integral Absolute Error (IAE) and the time domain performance measures viz. settling time (t_s), rise time (t_r). The real time servo runs are conducted at 40%, 50% and 60% operating pressure. A set-point change of ±5% and ±10% change in pressure is applied and is shown in below figures. The error performances are presented in Table IV.

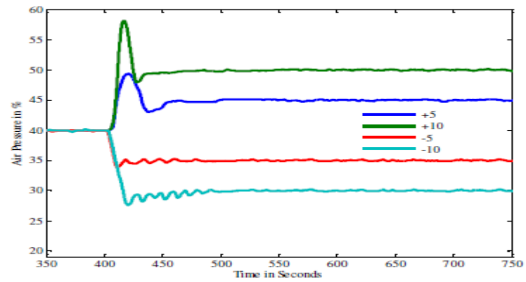

Fig. 8. Set point tracking at 40 % pressure using ZN-PI controller

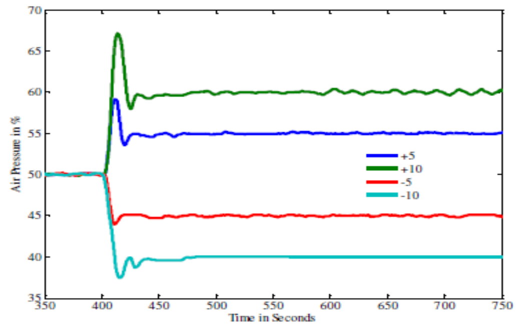

Fig. 9. Set point tracking at 50 % pressure using ZN-PI

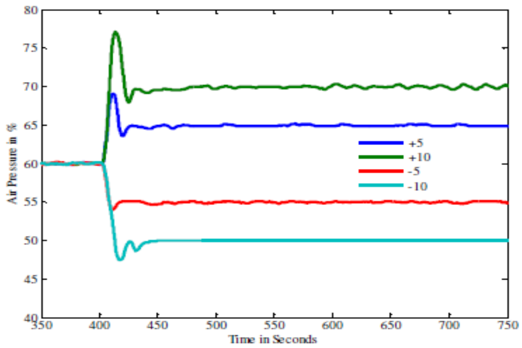

Fig. 10. Set point tracking at 60 % pressure using ZN-PI controller

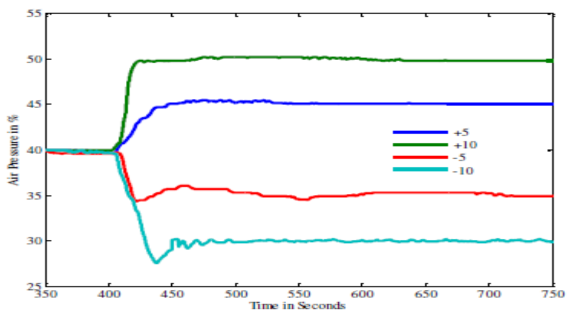

Fig. 11. Set point tracking at 40 % pressure using TGC Controller

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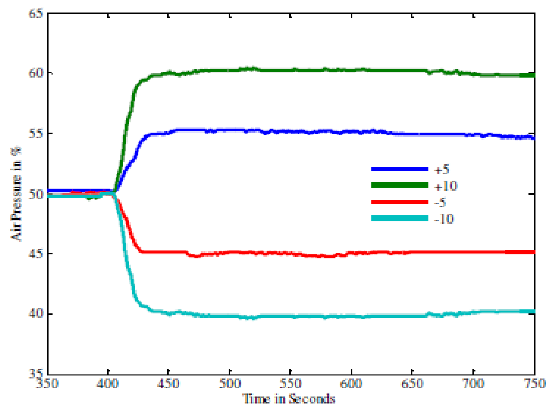

Fig. 12. Set point tracking at 50 % pressure using TGC controller

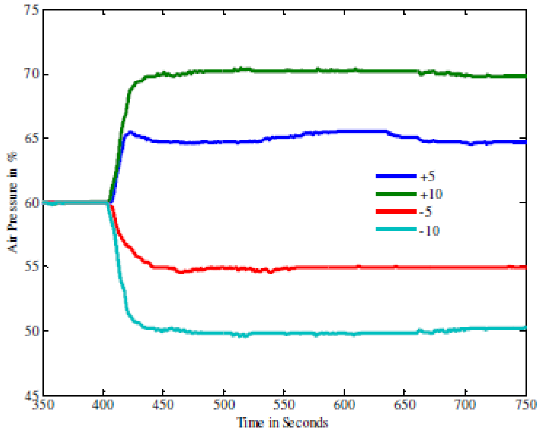

Fig. 13. Set point tracking at 60 % pressure using TGC Controller

Table- IV: APS – Set point tracking –Error performances

Operating Point	Step Change	ZN-PI		TGC	
		ISE	*IAE*	*ISE*	*IAE*
40%	+10%	8900	920	5279	567
	+5%	3300	450	1690	330
	-5%	3255	475	1800	328
	-10%	8570	940	5352	561
50%	+10%	9000	930	5300	580
	+5%	3450	470	1700	340
	-5%	3300	480	1750	335
	-10%	8670	960	5350	575
60%	+10%	8850	935	5325	560
	+5%	3400	460	1698	337
	-5%	3350	485	1720	330
	-10%	9050	945	5280	579

Table- V: APS – Set point tracking – Time domain performance

Operating Point	Step Change	ZN-PI		TGC	
		t_s	t_r	t_s	t_r
40%	+10%	180	20	140	60
	+5%	160	19	130	50
	-5%	160	18	130	30
	-10%	180	20	140	60
50%	+10%	160	13	90	32
	+5%	150	11	80	30
	-5%	150	11	80	30
	-10%	160	13	90	32
60%	+10%	160	13	90	40
	+5%	150	11	80	30
	-5%	150	11	80	30
	-10%	160	13	90	40

From the table IV, It is visualized error performances for the operating point of 40%, 50% and 60% of pressure with the step change of ±5% and ±10%. The TGC controller provides extremely better performance compare to ZN-PI controller in the view of ISE and IAE. Similarly it is observed from the Table V, The TGC controller is the extraordinary performer and stands in first position in terms of settling time with negligible of rise time to the controller.

VII. CONCLUSION

In this paper, worst case model parameters are obtained for Air Pressure System (APS) from real time open loop test at different operating regions. From the worst case model TGC controller and ZN-PI controller are designed. The CRONE CSD toolbox used to implement the CRONE controllers and is compared with ZN-PI controller based on servo response error indices and time domain analysis. Real time runs are recorded at 40%, 50% and 60% operating pressure and its performances are computed. From the analysis, it is concluded that the TGC controller performs far better than ZN-PI controllers.

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