Self-Tuning PID Control for a Continuous Dense Phase System

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Abstract— **This paper proposes a Self-Tuning PID controller for continuous dense phase (CDP) conveying systems, which are applied in the industry e.g. , the transportation of pet food where the shape of the final product is important. CDP systems are subject to parametric changes and external disturbances where online system identification is the best choice for startup tuning. Moreover, for this controller the mathematical model was developed considering that a total flow is calculated accounting the flow needed to transport the material at the desired convey velocity, plus the flow losses (airlock leakage flow, and future flow losses for wear). Additionally, the mathematical model is used to develop a self-tuning PIDcontroller, which will keep a main flow rate of the system based on the convey velocity set-point. Likewise, the controller will regulate the aperture of a valve to allow only the necessary air pass to form the slugs in a dense phase system. Furthermore, the coefficients of the mathematical model to fit a real system are estimatedusing Recursive Least Squares method. Finally, simulation tests are carried out to validate the proper functioning of the controller.**

Keywords— **PID controller; continuous dense phase system; airlock leakage; recursive least squares.**
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I. INTRODUCTION

Pneumatic conveying system is defined as the transport of various granular solids and dry powders using an air stream as a transportation media [1]. Recent developments shows the great advantages this type of system offers to factories, for that reason in the last years pneumatic system are chosen over mechanical transports. Some of the candidate industries for this type of transport are the folloging: agriculture, mining, chemical, pharmaceutical, paint manufacturing, food and metal refining and processing[2].

The pneumatic conveying systems can be classified based on the average particle concentration in the pipe and the air velocity:(1) dilute phase system where the mass flow ratio of 0-15 and high velocity: and (3) dense phase where flow ratio greater than 15 and low velocity[3].

The benefits of dense phase conveying over mechanical conveying are noticeably endless .The number one reason to apply this kind of system is when the product being handled is highly friable[4]. All the benefits are described : (1) Low air energy consumption; (2) Minimal material degradation; (3) Minimal material segregation; (4) Low pipeline and component wear: (5) Fewer maintenance points; (6) Capable of handling abrasive materials; (7) Capable of handling fragile materials; (8) Environmentally friendly; no material spillage, no dust emission, low noise emission; (9) Flexibility in routing; and (10) Ease of automation and control [3]

Because the dense phase pneumatic conveying moves the material in the pipe at low velocity, the particles of this material begin to fall to the bottom of the pipe. The technical term used to describe the velocity at which particles fall from airstream suspension is "saltation velocity".
Consequently, the main goal of a dense phase conveying system is to slow down the velocity of the product in the pipe. At low velocities, the product lies down for periods of time in the bottom of a horizontal line and it is blown under pressure to the discharge point in slugs or plugs.

Unfortunately, there is not enough research about dense phase systems, although the interest from factories is growing. Until now most of the designs of this type of system is purely mechanical, making this design highly sensitive to system disturbances and parametric changes that may arise. The implementation of feedback control to operate at low air flow rates without compromising reliability it becomes necessary.

Dense phase has so far not been successfully modelled in a way that would make those models applicable to clasical control design[1], [5]; consequently, other investigations [1] suggest intelligent controllers to stabilize kind of system using Artifical Neuroal Networks.

Hence, this paper proposes a self-tuning PID controller to solve the problem of parametric changes and disturbances in this system. This controller is based on online estimation of discrete data of a system applying recursive least squares programing method[6], [7]. Finally, using the pole placement method the parameters of the controller are adjusted to the online system to maintain its stability.

II. System Structure

A. Problem Structure

Most of the studies about dense phase systems with rotatory valves are more focused to find out the air leakage through the airlock. Rotatory valve air leakage is dependent on a number of issues, including system pressure, rotor clearances, material being handled, head of product above the valve and weather there is venting present [4].

The same concept used in Figure 1 to measure the air leakage also can be used to control the supply airflow that will move the material in the pipe. However, many other different modes of dense-phase have been developed to take advantage of the different properties and characteristics of bulk solid used in industry [5]. The actual methods for dense phase conveying systems control the airflow or pressure based on mechanical calculations, which require precise paraments. Consequently, the actual methods required a lot of testing to determine the value of the parameters. Therefore, due to the difficulty to measure some of the parameters and the change of the parameter's value because wearness on the equipment, this paper proposes a Self-Tunning PID controller for continuous dense phase conveying systems.

The main dis-advantage is the reliance upon empirical proce-dures for conveyer design, which in effect limitsthe design to a specific solid material. Relativelyminor changes in pipeline layout or operatingconditions can often result in unpredicted block-age problems. In addition, power consumption,wear rate, product degradation and particle sizeseparation can be major problem

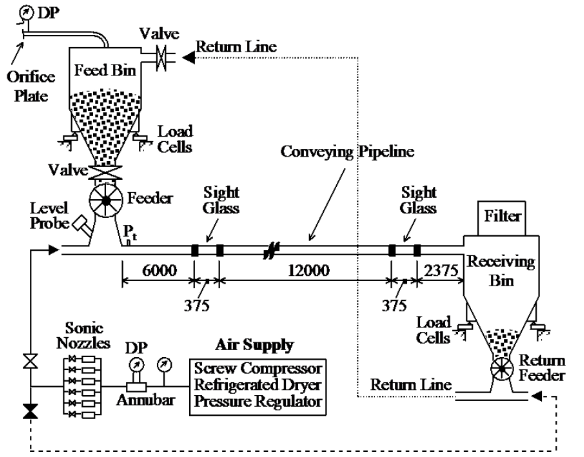

Fig. 1 Full-scale test ring to measure air leakage [4]

B. Mathematical Model of Continuous Dense Phase System

This paper analyzes a continues dense phase system which is conformed for the air supply provided by a blower, a valve to control the air flow going to the convey pipe, a rotatory valve which feeds the line, and the instrumentation to measure the airflow and pressures.

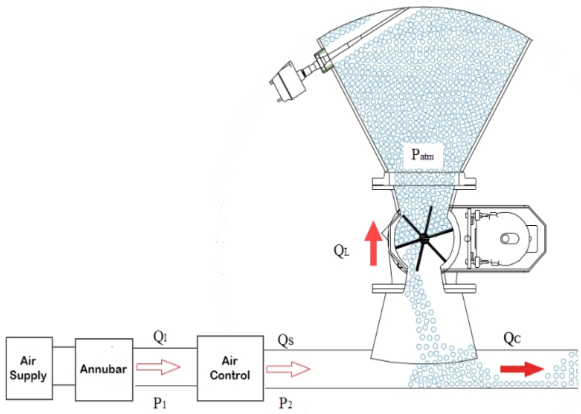

Fig. 2 A sample line graph using colors which contrast well both on screen and on a black-and-white hardcopy

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sacar teoria de como se hizo el modelo

todo de be ser muy generalized

$$\dot{Q}_s(t)=\frac{A_v(t)\,\zeta_3\chi_1\chi_2}{\zeta_1\sqrt{1-\left(\frac{A_v(t)\chi_2}{\zeta_1 A_p}\right)^2}}\sqrt{\frac{\zeta_2 R(P_1(t)-P_2(t))}{P_2(t)+P_{atm}}}\,T_1 \tag{1}$$

where T_1 It is a transformation that allows us to transform current flow to a standard flow.

$$T_1=\frac{P_2(t)+P_{atm}}{P_{std}}$$

$$\dot{P}_2(t)=\frac{P_1(t)\sigma_4+P_{atm}\sigma_4-\sigma_1+\sigma_3}{\sigma_2} \qquad (2)$$

where:

$$\sigma_1=A_p A_v(t)\zeta_1\zeta_2\zeta_3 P_{atm}^2 R T_s \chi_3\chi_4$$

$$\sigma_2=2A_p A_v(t)\zeta_1\zeta_2\zeta_3 P_{atm} R T_s \chi_5\chi_6$$

$$\sigma_3=A_p A_v(t)\zeta_1\zeta_2\zeta_3 P_1(t) P_{atm} R T_s \chi_7\chi_8$$

$$\sigma_4=\sqrt{\zeta_2 P_{atm} R T_s (4A_v(t)^2 N^2 P_{atm} RPM_{max}^2 T_s \chi_9^2\chi_{10}^2 \ldots}$$

$$\ldots-4A_p^2\zeta_1^2 N(t)^2 P_{atm} RPM_{max}^2 T_s \chi_{11}^2 \ldots$$

$$\ldots-4A_p^2\zeta_1^4\zeta_2 P_1(t) P_{std}\chi_{12}^2\chi_{13}^2 \ldots$$

$$\ldots 4A_v(t)^2\zeta_1^2\zeta_2 P_1(t) P_{std}\chi_{14}^2\chi_{15}^2\chi_{16}^2 \ldots$$

$$\ldots 8A_p^2\zeta_1^3 N(t) P_{atm} RPM_{max} T_s \chi_{17}^2\chi_{18}\sigma_5 \ldots$$

$$\ldots-8A_v(t)^2\zeta_1 N(t) P_{atm} RPM_{max} T_s \chi_{19}^2\chi_{20}^2\chi_{21}\sigma_5 \ldots$$

$$\ldots A_p^2 A_v(t)^2\zeta_1^2\zeta_2\zeta_3^2 P_{atm} R T_s \chi_{22}^2\chi_{23}^2$$

$$\sigma_5=\sqrt{\frac{\zeta_2 P_1(t) P_{std}}{P_{atm} T_s}}$$

$$\dot{P}_1(t)=N(t)^2\chi_{24}+N(t)\chi_{25}+A_v(t)\chi_{26} \qquad (3)$$

TABLE I
PARAMETERS OF DENSE PHASE SYSTEM

System	Parameter	Units
Q_s	Flow rate	$Scfm$
P_1	Presure before control valve	$\frac{lb_f}{\text{in}^2}$
P_2	Presure after control valve	$\frac{lb_f}{\text{in}^2}$
A_v	Control valve opening	$\%open$
N	Blower speed	$\%rpm$
ζ_1	Valve maximum open	$\%open$
ζ_2	Average temperature	^oF
ζ_3	Conversion Factor	
A_p	Pipe area	ft^2
R	Universal Gas Constant	$\frac{ft\, lb_f}{lb}$
P_{atm}	Atmospheric Presure	$\frac{lb_f}{\text{in}^2}$
P_{std}	Standard Presure	$\frac{lb_f}{\text{in}^2}$
RPM_{max}	Maximum blower revolutions per minute	rpm
T_s	Standard Temperature	^oR

C. *Mathematical Model Identification and Validation*

The identification and validation of the mathematical model (1), (2) and (3) that represents the behavior of the Dense Phase System is tested in this section. The main objective is to determine the value $\chi=[\chi_1 \ \ \chi_2 \ \ \ldots \ \ \chi_l]$ with $l=26$, which adjust the mathematical model with the real system. The differential equations (1), (2) and (3) are solved through Euler approximations (4), (5) and (6), where T_s is a sample time and $k\in 1,2,3,4,5..$, in orden the system can be simulated and the control algorithms can be tested.

$$Q_s(k+1)=Q_s(k)+\dot{Q}_s(k)T_s \qquad (4)$$

$$P_1(k+1)=P_1(k)+\dot{P}_1(k)T_s \qquad (5)$$

$$P_2(k+1)=P_2(k)+\dot{P}_2(k)T_s \qquad (6)$$

The identification of the dense phase system was carried out using optimization techniques, where an objective is to minimize a cost function (7), varying the values of the vector χ, where $\tilde{\boldsymbol{h}}(k)=[Q_{sr}(k)-Q_s(k) \quad P_{1r}(k)-P_1(k) \quad P_{2r}(k)-P_2]^T$ is the vector of errors between values of the real system and mathematical model, $Q_{sr}(k), P_{1r}(k), P_{2r}(k)$ are the values obtained from the real system finally $\boldsymbol{Q}$ is positive definite diagonal matrix that will weigh the vetor of errors.

$$\boldsymbol{J}=\sum_{n=k}^{k+1}\tilde{\boldsymbol{h}}(k)^T\boldsymbol{Q}\tilde{\boldsymbol{h}}(k) \qquad (7)$$

subject to equations (4) (5) and (6)

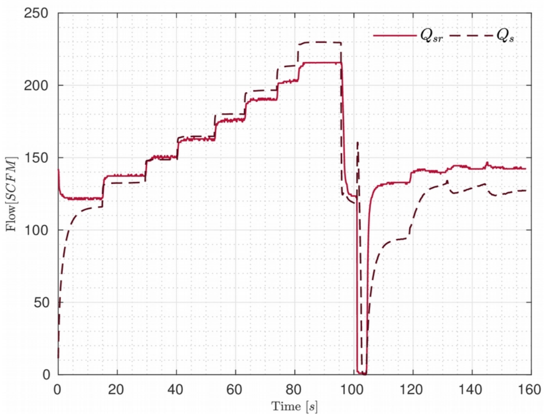
The parameters of the Dense Phase System are presents in the Table 2.

TABLE II
SYSTEM PARAMETERS OF DENSE PHASE SYSTEM

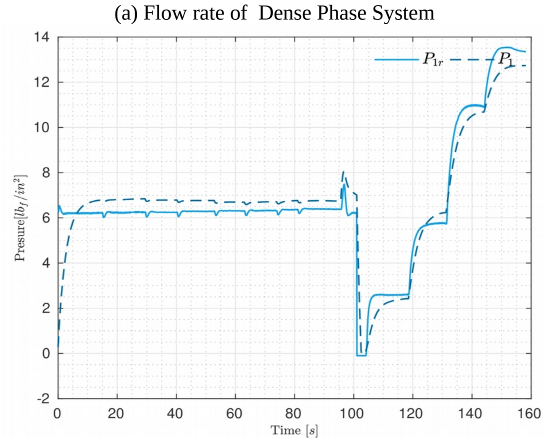
System	Parameters						
Flow System Q_s	χ_1	χ_2					
	2.59	0.013					
Presure 2 P_2	χ_3	χ_4	χ_5	χ_6	χ_7	χ_8	χ_9
	0.04	0.04	0.07	0.05	−0.03	−0.03	0.06
	χ_{10}	χ_{11}	χ_{12}	χ_{13}	χ_{14}	χ_{15}	χ_{16}
	0.06	0.01	0.05	0.04	0.04	0.05	0.02
	χ_{17}	χ_{18}	χ_{19}	χ_{20}	χ_{21}	χ_{22}	χ_{23}

	0.02	0.008	0.03	0.03	0.18	0.18	0.04
Presure 1 P_1	χ_{24}	χ_{25}	χ_{26}				
	0.02	0.2	0.06				

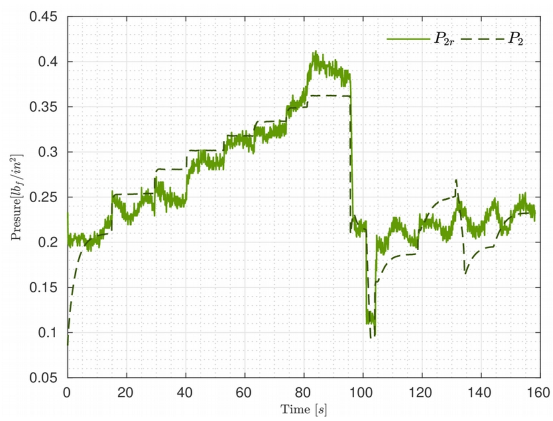
The experimental data for the validation procedures are shown in Fig. 3, where you can see the good performance of the proposed mathematical model.



(a) Flow rate of Dense Phase System



(b) Presure 1 of Dense Phase System



(c) Presure 2 of Dense Phase System

Fig. 3 Validation data of the proposed mathematical model of the Dense Phase System .

III. Controller Design

The proposed control scheme shows in Fig 4, allows that the flow rate of the dense phase system $Q_s(k)$ track a desired flow $Q_{sd}(k)$ in order to generates the slugs of specific material. This effect is produced by making variations in the $Q_{sd}(k)$ with respect to $P_2(k)$, this produces a saw-tooth-shaped set point.

The control objective is achieved through a designed a control system, which comprises 2 stages: (1) a *PID* controller that allows $P_1(k)$ tracking the desired pressure $P_{1d}(k)$ through variations in Blower Speed $N(k)$, which makes the system stable, (2) self tuning *PID* controller, that adjust the controller gains online achieving the smallest tracking error between $Q_{sd}(k)$ and $Q_s(k)$ through variations in control valve $A_v(k)$, this is achieved using recursive least squares and pole assignment methods.

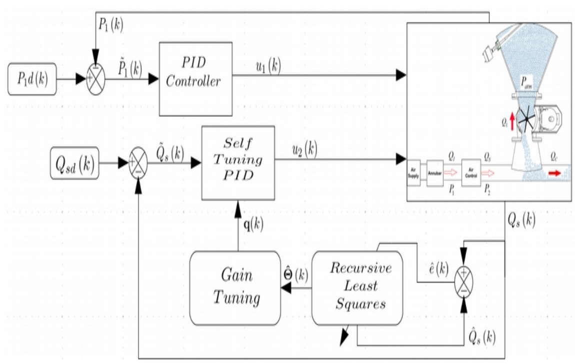


Fig. 4 Validation data of the proposed mathematical model of the Dense Phase System .

D. The PID controller for P_1

In real industrial applications, the recurrent algorithms are more suitable for practical use in this sense a PID controller with digital output can be applied, where main objective is calculate the increment change $\Delta N(k)$, obtained the following equations.

$$N(k)=\Delta N(k)+N(k-1) \quad (4)$$

$$\Delta N(k)=K_P(\tilde{P}_1(k)-\tilde{P}_1(k-1))+K_I(\tilde{P}_1(k))\ldots$$

$$\ldots K_D(\tilde{P}_1(k)-2\tilde{P}_1(k-1)+\tilde{P}_1(k-2)) \quad (5)$$

where $\tilde{P}_1(k)=P_{1d}(k)-P_1(k)$ is the error between the desired Pressure $P_{1d}(k)$ and the real Pressure $P_1(k)$, K_P it is known as the proportional gain, K_I is the integral gain and finally K_D .

To obtain better results in the PID controller, a saturation of the errors was added $y(k)=f(w,k_1,\tilde{P}_1(k))$, it is shown in the following equation (6).

$$y(k)=\left(\frac{w}{k_1+|\tilde{P}_1(k)|}\right) \quad (6)$$

This function allows to reduce large changes in the controller values that are produced by large variations in $P_{1d}(k)$.

E. The Self Tuning PID controller for Q_s

Due to the high non-linearity, parametric changes and external disturbances that occur in the dense phase system, becomes a complex system to control. In this sense the design of a self tuning PID is really necessary, because it is able to adapt the parameters of its controller in each time, it achieved a better performance even when there are changes in the system.

The general discrete transfer functions of a system is given by the following equations:

$$G_p(z)=\frac{B(z^{-1})}{A(z^{-1})} \tag{7}$$

where:

$$A(z^{-1})=1+a_1 z^{-1}+a_2 z^{-2}$$

$$B(z^{-1})=b_1 z^{-1}+b_2 z^{-2}$$

The general transfer function of a controller is ()

$$G_r(z)=\frac{Q(z^{-1})}{P(z^{-1})} \tag{8}$$

$$P(z^{-1})=1+(\gamma-1)z^{-1}-\gamma z^{-2}$$

$$Q(z^{-1})=q_0+q_1 z^{-1}+q_2 z^{-2}$$

Further, the following relation can be obtained for the control transfer function in closed loop

$$G(z)=\frac{B(z^{-1})Q(z^{-1})}{A(z^{-1})P(z^{-1})+B(z^{-1})Q(z^{-1})} \tag{8}$$

where the denominator of the equation (8) is known as the characteristic polynomial. In this sense this controllers based on desired a characteristic polynomial () that allows the close loop transfer function stable and capable to follow a desired set point

$$D(z^{-1})=1\sum_{i=0}^{n_d} d_i z^{-i} \tag{9}$$

$$A(z^{-1})P(z^{-1})+B(z^{-1})Q(z^{-1})=D(z^{-1})$$

$$\begin{bmatrix} b_1 & 0 & 0 & 1 \\ b_2 & b_1 & 0 & a_1-1 \\ 0 & b_2 & b_1 & a_2-a_1 \\ 0 & 0 & b_2 & a_2 \end{bmatrix}\begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ \gamma \end{bmatrix}=\begin{bmatrix} d_1+a-a_1 \\ d_2+a_1-a_2 \\ a_2 \\ 0 \end{bmatrix} \tag{10}$$

$$\boldsymbol{T}\boldsymbol{q}=\boldsymbol{D} \tag{11}$$

$$\boldsymbol{q}=\boldsymbol{T}^{-1}\boldsymbol{D} \tag{12}$$

where $\boldsymbol{q}=[q_0 \quad q_1 \quad q_2 \quad \gamma]$ a this vector y uses in the controller equation represented in equation ()

For implement self tuning controllers is necessary to use recursive identification methods which can perform the identification in real time

In conclusion the algorithm of recursive least squares is given by the following equations (7), (8), where $\hat{\boldsymbol{\Theta}}(k)=[a_1 \quad a_2 \quad b_1 \quad b_2]$ is the vector of parameters estimates is updated according to the recursive relation

$$\hat{\boldsymbol{\Theta}}(k)=\hat{\boldsymbol{\Theta}}(k-1)+\frac{\boldsymbol{C}(k)\boldsymbol{\phi}(k-1)}{1+\xi(k)}\hat{e}(k) \tag{7}$$

$$\xi(k)=\boldsymbol{\phi}(k-1)^T\boldsymbol{C}(k)\boldsymbol{\phi}(k-1) \tag{8}$$

$$\hat{e}(k)=Q_s(k)-\hat{\boldsymbol{\Theta}}^{\boldsymbol{T}}(k-1)\boldsymbol{\phi}(k-1) \tag{9}$$

$$\boldsymbol{C}(k)=\boldsymbol{C}(k-1)-\frac{\boldsymbol{C}(k-1)\boldsymbol{\phi}(k-1)\boldsymbol{\phi}^{\boldsymbol{T}}(k-1)\boldsymbol{C}(k-1)}{\varepsilon^{-1}(k)+\xi(k-1)} \tag{10}$$

$$\varepsilon(k)=\varphi(k)-\frac{1-\varphi(k)}{\xi(k-1)} \tag{11}$$

$$\varphi(k)^{-1}=1+(1+\rho)(\ln(1+\xi(k)))... \tag{12}$$

$$...+(\frac{(\upsilon(k)+1)\eta(k)}{1+\xi(k)+\eta(k)}-1)\frac{(\xi(k))}{1+\xi(k)} \tag{13}$$

$$\eta(k)=\frac{e^2\hat{}(k)}{\lambda(k)} \tag{14}$$

$$\upsilon(k)=\varphi(k)(\upsilon(k-1)+1) \tag{15}$$

$$\lambda(k)=\varphi(k)(\lambda(k-1)+\frac{\hat{e}^2(k)}{1+\xi(k)}) \tag{16}$$

IV. Results And Discussions

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Nomenclature

a	specific surface area	m^2m^{-3}
x	length co-ordinate	m

Greek letters

α	heat transfer coefficient	$Wm^{-2}K^{-1}$
τ	residence time	s

Subscripts

i	inlet

e equilibrium

V. Conclusions

Poner las conclusiones del trbajo bla bla blassssssssssssssssssssssssssssss

Acknowledgment

We would like to thank Causal Productions for permits to use and revise the template provided by Causal Productions. Original version of this template was provided by courtesy of Causal Productions (www.causalproductions.com).

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