대한기계학회 2001년도 춘계학술대회논문집 B pp. 253~258 KSME 01S198

천연가스배관 내 피그흐름의 속도제어

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Speed Control of PIG Flow in Natural Gas Pipeline

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Key Words : Pipeline Inspection Gauge (PIG), Method Of Characteristic (MOC), Pipeline, Bypass Flow, Nonlinear Adaptive Control

Abstract

This paper introduces a simple nonlinear adaptive control method for pipeline inspection gauge (PIG) flow in natural gas pipeline. The dynamic behavior of the PIG depends on the different pressure across its body and the bypass flow through it. The system dynamics includes: dynamics of driving gas flow behind the PIG, dynamics of expelled gas in front of the PIG, and dynamics of the PIG. The method of characteristics (MOC) and Runger-Kuta method are used to solve the dynamics of flow. The PIG velocity is controlled through the amount of bypass flow across its body. A simple nonlinear adaptive controller based on the backstepping method is introduced. To derive the controller, three system parameters should be measured: the PIG position, its velocity and the velocity of bypass flow across the PIG body. The simulation has been done with a pipeline segment in the KOGAS low pressure system, Ueijungboo-Sangye line to verify the effectiveness of the proposed controller. Three cases of interest are considered: the PIG starts to move at its launcher, the PIG arrives at its receiver and the PIG restarts after stopping in the pipeline by obstruction. The simulation results show that the proposed nonlinear adaptive controller attained good performance and can be used for controlling the PIG velocity.

Nomenclatures

A	pipe cross section	$[m^2]$
c	wave speed	$[m/s]$
C_C	convection heat transfer coefficient	$[m^2]$
C	linear damping coefficient of PIG	$[Ns/m]$
d	internal diameter of pipeline	$[m]$
d_{valve}	bypass valve diameter	$[m]$
F_f	friction force per unit pipe length	$[N/m]$
F_{fp}	friction force between the PIG and pipe's wall	$[N]$
F_p	force due to different pressure acting on the PIG	$[N]$
g	gravity acceleration	$[m/s^2]$
h	opening height of bypass valve	$[m]$
K	wear factor of PIG	$[N/m]$
K_{SC}	sudden contraction loss coefficient	
K_{SE}	sudden expansion loss coefficient	
K_{total}	total loss coefficient of bypass system	
K_V	average-loss coefficient of valve	
L	length of pipeline	$[m]$
L_{PIG}	length of the PIG	$[m]$
m	hydraulic mean radius of pipe	$[m]$
M	mass of the PIG	$[kg]$
p	flow pressure	$[N/m^2]$
q	compound rate of heat inflow per unit area of pipe's wall	$[W/m^2]$
R	gas constant	$[J/kgK]$
S	perimeter of pipe	$[m]$
T	flow temperature	$[^0C]$
T_{ext}	seabed temperature	$[^0C]$
u	flow velocity	$[m/s]$
x_{PIG}	PIG position	$[m]$
v_{PIG}	PIG velocity	$[m/s]$
v_{ref}	reference velocity of PIG	$[m/s]$
v_V	absolute velocity of bypass flow	$[m/s]$

Greeks:

γ	the ratio of specific heat	
ν	kinetic viscosity of flow	$[m^2/s]$
ρ	flow density	$[kg/m^3]$

Subscripts:

$_{0},\ _{L}$	denote the points at inlet and outlet of pipeline
$_{u},\ _{d}$	denote the values of upstream and downstream flows

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1. Introduction

For many years on stream pigging was considered unavoidable. After construction cleaning and testing, if the pipeline would not pig on a regular basis, the efficiency of the lines decreased as the years passed. The decrease in efficiency relates to increased operational power costs, so the lines would be pigged to increase the efficiency. As pipelines get older, we see increased corrosion. To determine the amount of corrosion or metal loss in the pipeline, an in line inspection tool such as pipeline inspection gauge (PIG) is used. PIGs are often run to remove any water that has accumulated in the low spots of the pipeline and reduce corrosion. Other applications include running a Geometry PIG to determine if there are any dents or buckles in the line. All kinds of PIG are the most effective when they run at a near constant speed but will not be effective in case that they run at too high speed. Routine pigging operations such as batching, cleaning and liquid removal in gas pipelines, are done at normal operating velocities with the regular flow of product. This velocity is generally in the range of 1-5m/s in liquid pipelines, and 2-7m/s in gas pipelines. The optimal speed range for intelligent pigs is more defined, because for accurate data acquisition, the velocity of the tool must not exceed its "speed limit". Ranges of between 0.5-4m/s are recommended for corrosion tools, and slightly higher for caliper tools[14]. Hence estimate and control of the PIG velocity is very important when operating a pigging procedure in a pipeline.

Results of research on the dynamics of the PIG in pipelines are scarcely found in the literature. Some works relating to the estimation of the PIG dynamics have been reported. J.M.M. Out[12], 1993, used Lax-Wendroff scheme for the integration of gas equations with adaptation of finite difference grid. Azevedo et al.[7], 1996, simplified the solution with assumption of incompressible and steady state of flow in pipeline. P.C.R. Lima[6], 1999, solved the problem by using one-dimensional semi-implicit finite difference scheme. T.T. Nguyen et al.[1-4], 2000, treated the compressible, unsteady flow dynamic equations for flows in pipeline by using MOC and solved the PIG dynamic equation by using Runge-Kuta method.

The most basic method of reducing pig velocities is by use of pressure bypass ports in the PIG body. Once the pre-set different pressure is reached, the bypass port opens and the PIG velocity is reduced. This system is sufficient if the desired effect is to slow down the PIG without maintaining a desired speed. This kind of bypass ports can reduce speed, but do not offer the capability of adjusting for changes in flow conditions. It is general concept that we can adjust the PIG velocity by controlling the amount of bypass flow across the PIG body. *However, it is difficult to calculate the exact bypass volume* needed to sustain a given speed unless the pressure and flow remain constant throughout the pipeline. H.L. Wu et al.[8], 1996, carried out the test with bypass PIG for two-phase flow pipeline. By the mean of simulation and assumed friction behavior, they estimate the range of bypass fraction of a PIG for operation without the risk of standstill. With their test, the PIG with bypass openings up to 15% can operate without problems of stoppage in the gas pipeline of 20" diameter. D.J. Wilson and J.W. Yokota[10], 1994, proposed the speed control mechanism for 24" MFL PIG that was used in Tenneco filed. This speed control mechanism ran through a sequence of timed steps at 10% increment from 0% to 100% open. The spool valve was returned to fully closed position after each opening increment. The time the spool valve was stationary in the partially (or fully) open and closed positions was 30 seconds. This sequence was run three times. Although this speed control mechanism has attained good test performance, it seems to be trivial and loss generality. Apache Industries of Edmonton, Canada[13], 1992, used another method for the PIG velocity control problem. By regulating the amount of bypass through the PIG body, the speed of the vehicle can be controlled within a pre-set range. The PIG senses its velocity, compares this to a pre-set value, then controls the volume of bypass to maintain the required speed. The control system compares actual speed to a pre-set desired speed, and controls the motor driving the orifice plate. Effectively, this determines the amount of gas allowed to bypass, increasing flow if the PIG travels too fast, decreasing flow when speed is below the required value.

In the previous work[4], we proposed a simple nonlinear controller for regulating the PIG velocity using bypass flow. To derive such controller, all system parameters are assumed to know. However, in real system the friction force between pipe's wall and the cups of the PIG is changed depending on the PIG dynamics and the real conditions of the pipe's wall. To deal with this problem, in this paper we use an adaptive controller for controlling the PIG velocity when it flows in natural gas pipeline. The proposed nonlinear adaptive controller is derived from the Lyapunov function based on the back-stepping method[9]. The closed loop system is stable in the sense of Lyapunov stability. To derive the controller, three system parameters should be measured: the PIG position, its velocity and the velocity of bypass flow across the PIG body. The simulation has been done to verify the effectiveness of the proposed controller. Three cases of interest are considered: the PIG starts to move at launcher, the PIG arrives at its receiver and the PIG restarts after stopping in the pipeline. The simulation results show that the proposed nonlinear adaptive controller attained good performance and can be used for controlling the PIG velocity.

2. Modeling

The scheme of PIG with bypass flow control in natural gas pipeline can be described in Fig. 1.

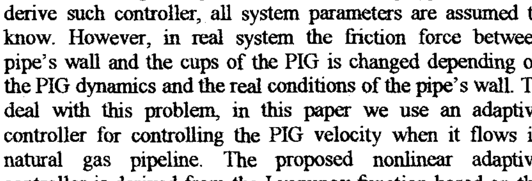

Fig. 1 PIG with bypass flow in natural gas pipeline

2.1 Gas Flow Model

We assume as the following:

i. the natural gas is ideal,
ii. flow is one phase,
iii. the pipeline diameter is constant,
iv. the friction factor is a function of wall's roughness and Reynolds number. Steady state values are used in transient calculations,
v. the flow is quasi-steady heat flow.

The unsteady flow dynamics can be modeled based on four fundamental fluid dynamic equations: continuity equation, momentum equation, state equation and energy equation as follows

$$\frac{\partial p}{\partial t}+u\frac{\partial p}{\partial x}+\gamma p\frac{\partial p}{\partial x}=\frac{\gamma-1}{A}\left(F_f\,u+qS\right) \tag{1}$$

$$\frac{\partial u}{\partial t}+\frac{1}{\rho}\frac{\partial p}{\partial x}+u\frac{\partial u}{\partial x}=-\frac{F_f}{\rho A} \tag{2}$$

$$\frac{\partial \rho}{\partial t}+\rho\frac{\partial u}{\partial x}+u\frac{\partial \rho}{\partial x}=0 \qquad (3)$$

The above equations are used to describe both upstream and downstream flows. They can be rewritten in as the following forms. For upstream flow

$$\frac{dX_u}{dt}+A_u\frac{dX_u}{dx}=B_u \qquad 0\le x\le x_{PIG}-L_{PIG} \qquad (4)$$

And for downstream

$$\frac{dX_d}{dt}+A_d\frac{dX_d}{dx}=B_d \qquad x_{PIG}\le x\le L \qquad (5)$$

where

$$X_*=\begin{bmatrix}p_*\\ u_*\\ \rho_*\end{bmatrix}\quad A_*=\begin{bmatrix}u_* & \gamma p_* & 0\\ \frac{1}{\rho_*} & u_* & 0\\ 0 & \rho_* & u_*\end{bmatrix}\quad B_*=\begin{bmatrix}\frac{\gamma-1}{A}\left(F_{f*}u_*+qS\right)\\ -\frac{F_{f*}}{\rho_* A}\\ 0\end{bmatrix}$$

* denotes u for upstream flow and d for downstream flow. Eqs. (4) and (5) must satisfy the following boundary conditions.

2.1.1 Boundary condition at pipeline inlet and outlet

The boundary conditions are given as pressure or flow rate and the temperature of flow as follows

$$\text{At inlet:}\quad \begin{cases}p_u(t,0)=p_0(t)\\ T_u(t,0)=T_0(t)\end{cases}\ \text{or}\ \begin{cases}Q_u(t,0)=Q_0(t)\\ T_u(t,0)=T_0(t)\end{cases} \qquad (6)$$

$$\text{At outlet:}\quad \begin{cases}p_d(t,L)=p_L(t)\\ T_d(t,L)=T_L(t)\end{cases}\ \text{or}\ \begin{cases}Q_d(t,L)=Q_L(t)\\ T_d(t,L)=T_L(t)\end{cases} \qquad (7)$$

2.1.2 Boundary condition at the tail and nose of the PIG

The boundary conditions at the PIG tail and nose depend on the amount of bypass flow through the PIG. The bypass flow through the PIG can be seen in Fig. 2. The amount of flow through the PIG depends on the opening height of valve, h, and the different pressure across its body.

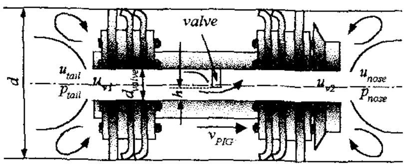

Fig. 2 Bypass flow through the PIG

When the velocity of natural gas in the range of 200m/s or its Mach number is less than 0.45, it can be treated as incompressible with an error less than 5%[10]. Hence in this paper, the pressure drop allows the bypass flow to be assumed as incompressible as it passes through the central bypass hole in the PIG. The bypass flow through valve causes the pressure drop across the PIG is given by:

$$p_u(t,x_{PIG}-L_{PIG})-p_d(t,x_{PIG})=K_{total}\frac{\left(v_V(t)-v_{PIG}(t)\right)^2}{2g} \qquad (8)$$

In Eq. (8), the pressure loss of valve depends on the structure of bypass system including the pressure loss of valve and the pressure loss caused by sudden contraction of flow at the tail of the PIG and sudden expansion of flow at the nose of the PIG.

$$K_{total}=K_{SC}+K_V+K_{SE} \qquad (9)$$

where

$$K_{SC}=0.42\left(1-\frac{d_{valve}^2}{d^2}\right),\ K_{SE}=\left(1-\frac{d_{valve}^2}{d^2}\right)^2,\ K_V=K_V(.)$$

The value of total pressure loss in Eq. (9) can also be obtained from experimental data in laboratory with the designed bypass valve system to be used.

The nonlinear hyperbolic partial differential equations (4)-(5) with the given boundary conditions (6)-(8) can be solved by transforming to ordinary differential equations using MOC which are presented in the previous works[1-3].

2.2 The PIG dynamic model

Forces acting on the PIG are shown in Fig. 1. The dynamic equation of the PIG can be applied from the Newton's Second Law as follows:

$$M\frac{d^2x_{PIG}(t)}{dt^2}+C\frac{dx_{PIG}(t)}{dt}+Kx_{PIG}(t)=F_p(t,x)-F_{fp}(x) \qquad (10)$$

In the Eq. (10), the driving force is derived from the different pressure at the tail and nose of the PIG that are calculated from upstream and downstream flow dynamics in each computational step. The friction force F_{fp}, the wear factor K and the linear damping coefficient C are measured from experiment.

3. Control of PIG

After rearrangement, Eqs. (8) and (10) can be rewritten in the forms

$$\dot{x}_{PIG}(t)=v_{PIG}(t) \qquad (11)$$

$$\dot{v}_{PIG}(t)=-\frac{K}{M}x_{PIG}(t)-\frac{C}{M}v_{PIG}(t)+\frac{A}{M}\frac{\left[v_V(t)-v_{PIG}(t)\right]^2}{2g}K_{total}(t)-\frac{1}{M}F_{fp}(t) \qquad (12)$$

or in the state space form

$$\dot{x}_p=A_px_p+B_p(.)u+\Gamma F_{fp} \qquad (13)$$

$$y_p=E_px_p \qquad (14)$$

where

$$x_p=[x_{PIG}\ v_{PIG}]^T,\ u=K_{total},\ y_p=v_{PIG}$$

$$A_p=\begin{bmatrix}[0\ \ 1]\\ A_2\end{bmatrix}=\begin{bmatrix}0 & 1\\ -\frac{K}{M} & -\frac{C}{M}\end{bmatrix},\ \Gamma=\begin{bmatrix}0\\ -\frac{1}{M}\end{bmatrix},$$

$$B_p(.)=\begin{bmatrix}0\\ B_2\end{bmatrix}=\begin{bmatrix}0\\ \frac{A}{M}\frac{(v_V-v_{PIG})^2}{2g}\end{bmatrix},\ E_p=[0\ \ 1]$$

The PIG velocity is controlled using a simple nonlinear adaptive controller. The control scheme can be seen in Fig. 3. The proposed controller is derived from the Lyapunov function based on the back-stepping method[9]. In the above Eq. (11), friction force $F_{fp}(t)$ is considered as an unknown parameter because we cannot measure exactly this value.

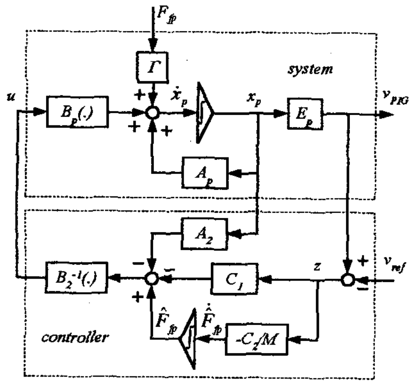

Fig. 3 The closed-loop adaptive system for the PIG velocity control problem

Define the error variable

$$z(t) \equiv v_{PIG}(t) - v_{ref} \tag{15}$$

Hence its derivative

$$\dot{z}(t) = -\frac{K}{M}x_{PIG}(t) - \frac{C}{M}v_{PIG}(t) + \frac{A}{M}\frac{[v_V(t)-v_{PIG}(t)]^2}{2g}K_{total}(t) - \frac{1}{M}F_{fp}(t) \tag{16}$$

Let $F_{fp}(t)$ be estimated by $\hat{F}_{fp}(t)$. The main reason for choosing $F_{fp}(t)$ as unknown factor is that this value cannot measure exactly and it changes depending on the PIG dynamics. If the control input $K_{total}(t)$ is chosen to satisfy

$$K_{total}(t) = \frac{2g}{A[v_V(t)-v_{PIG}(t)]^2} \times \left(Kx_{PIG}(t) + Cv_{PIG}(t) + \hat{F}_{fp}(t) - C_1 z(t)\right) \tag{17}$$

or

$$K_{total}(t) = \frac{2g}{A[v_V(t)-v_{PIG}(t)]^2} \times \left(Kx_{PIG}(t) + (C - MC_1)v_{PIG}(t) + \hat{F}_{fp}(t) + MC_1 v_{ref}\right)$$

Then Eq. (17) becomes

$$\dot{z}(t) = -C_1 z(t) - \frac{1}{M}\tilde{F}_{fp}(t) \tag{18}$$

where $\tilde{F}_{fp} = F_{fp} - \hat{F}_{fp}$ is the error of estimated friction force. The Lyapunov function's candidate is chosen as follows

$$V = \frac{1}{2}z^2 + \frac{1}{2C_2}\tilde{F}_{fp}^{\,2} \geq 0 \tag{19}$$

then $\dot{V} = -C_1 z^2 - \frac{1}{C_2}\tilde{F}_{fp}\left(\dot{\hat{F}}_{fp} + \frac{C_2}{M}z\right) \leq 0$ with the control law (17) and the updated law for $\hat{F}_{fp}$ as follows

$$\dot{\hat{F}}_{fp} = -\frac{C_2}{M}z \tag{20}$$

To derive the controller (17), we need to measure the PIG position $x_{PIG}(t)$, its velocity $v_{PIG}(t)$, and the velocity of bypass flow through the PIG $v_V(t) - v_{PIG}(t)$. The parameters $C_1 \geq 0$ and $C_2 \geq 0$ are used to adjust the performance of the closed loop system.

4. Simulation results

The simulation is performed with a pipeline segment in the Korea Gas Corporation (KOGAS) low pressure system, Ueijungboo-Sangye line. The numerical values using in this simulation are given in the Table. 1.

Table. 1 Numerical values for simulation

Parameters	Values	Units	Parameters	Values	Units
L	14800	m	ν	1.45e-5	m^2/s
d	0.7366	m	R	518.30	J/kgK
k	0.0450	mm	γ	1.40	
C_C	2	W/m^2s	M	2320	kg
T_{ext}	15	^0C	C	0.74	Ns/m
p_0	8	bar	K	0.00	N/m
Q_0	1.16	m^3/s	L_{PIG}	2.00	m
ρ_0	5.44	kg/m^3	v_{ref}	2.20	m/s
p_L	7.65	bar	F_{fpsta}	2.00	bar
Q_L	1.16	m^3/s	F_{fpdyn}	0.33	bar
ρ_L	5.20	kg/m^3	T	15	^0C
C_1	0.90		C_2	540000	

We choose the sampling time $\Delta t = 0.05s$, sampling distance $\Delta x = 40\ m$, and bypass valve diameter d_{valve}=0.1778m. The boundary condition of interest is used: constant flow rate at pipeline inlet $u_0(t,0) = u_0$, and constant pressure at pipeline outlet $p_L(t,L) = p_L$.

The first simulation has been done with the PIG when we launch it. The initial velocity is given to overcome the static friction force acing on the PIG. These simulation results are given in Figs. 4-7. The effect of proposed controller can be seen from Fig. 4: the PIG velocity with the proposed controller tracks well the reference velocity without oscillation. The different pressure acting on the PIG is given in Fig. 5. The total loss coefficient is considered as the control input to the system must be changed according to the value given in Fig. 6. The velocity of bypass flow across the PIG body is given in Fig. 7.

The second simulation has been done with assumption that the PIG was stopped at the one third of pipeline length by obstruction (debris or deposit). Getting the pig stuck rarely happens in a pipeline that is pigged routinely, however it can happen when pigging a pipeline which has been neglected or never been pigged before. After the PIG is stopped, the pressure at the tail of the PIG increased while the pressure at its nose decreased. As the result, the different pressure across the PIG is increased until overcoming both obstructions causing the stoppage and the static friction. Then, the PIG accelerates until the different pressure abates to a level required to overcome the static and dynamic friction. Once the PIG restarts, the friction force reduces from static value to dynamic value and the PIG velocity increases very fast. At this time, the bypass port must be opened to reduce the different pressure acting on the PIG and hence reduce its velocity. Fig. 8 shows the PIG velocity and Figs. 9 and 10 shows the different pressure acting on the PIG in the cases of control and no control. Fig. 11 shows the control law. With this control law, the PIG restarts with tracking well the reference speed.

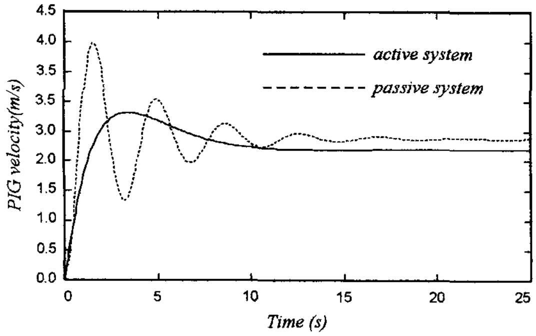

Fig. 4 The PIG velocity

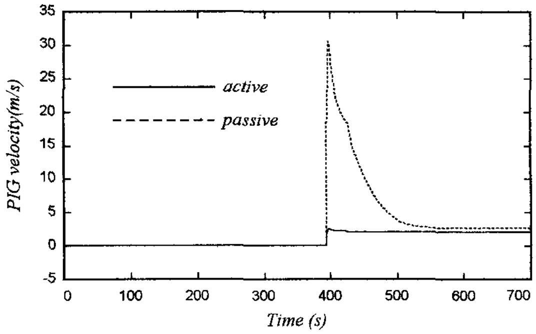

Fig. 8 PIG velocity after restart

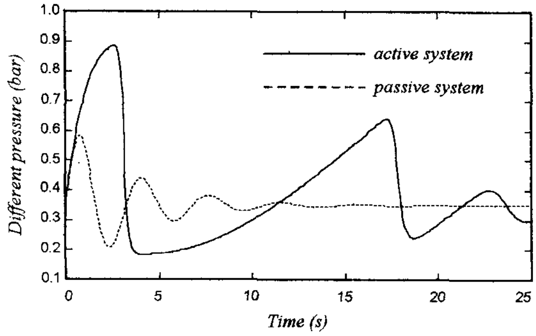

Fig. 5 Different pressure acting on the PIG

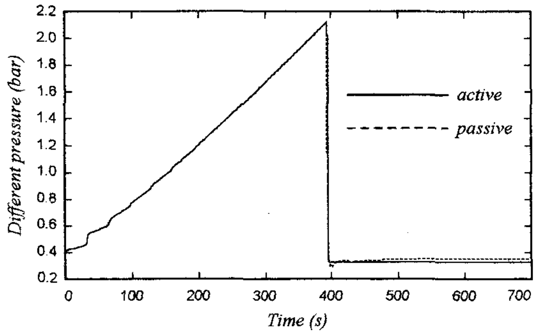

Fig. 9 Different pressure acting on the PIG

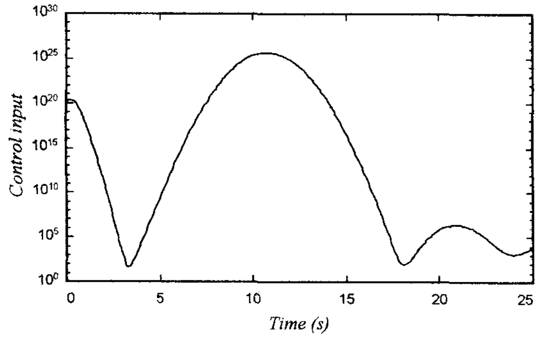

Fig. 6 Control law

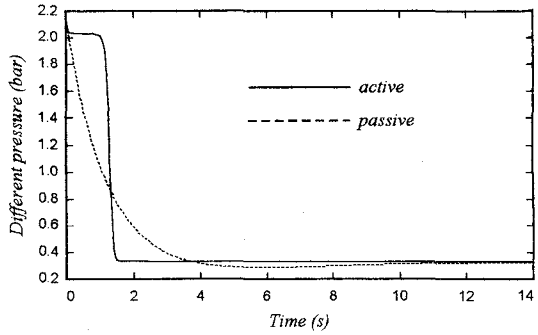

Fig. 10 Different pressure acting on the PIG after restarting

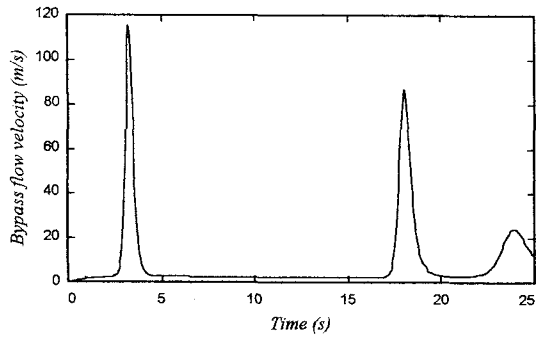

Fig. 7 Velocity of bypass flow across the PIG

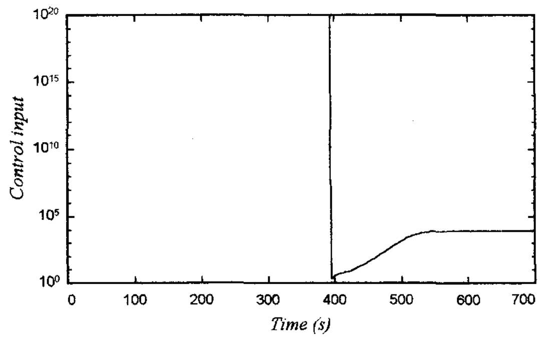

Fig. 11 Control law

The third simulation has been done for the PIG arrives at its trap barrel. Here the bypass port acts as a "brake" to stop the PIG when it is reaching to its trap barrel. Figure 12 shows the PIG velocity and the velocity of bypass flow after opening bypass port to reduce its speed. From this, we can use bypass flow to stop PIG without braking force harmful to the pipeline.

The different pressure acting on the PIG is given in Fig. 13. The different pressure first is reduced to slow down the PIG velocity and then to equal to friction force acting on the PIG. Fig. 14 shows the control law for this case. Fig. 15 shows the error of estimating of friction force in the above three simulations.

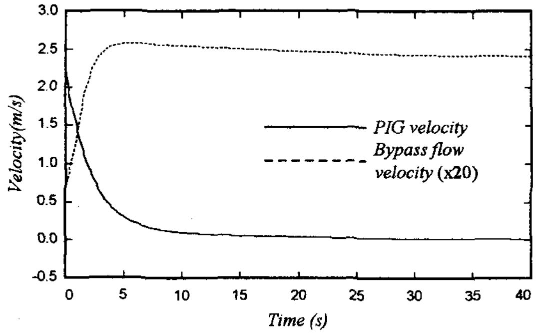

Fig. 12 PIG velocity when it is reaching to its receiver

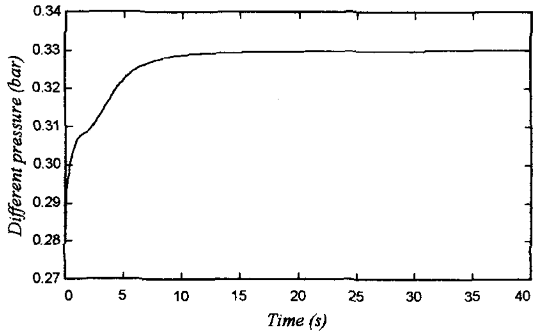

Fig. 13 Different pressure acting on the PIG

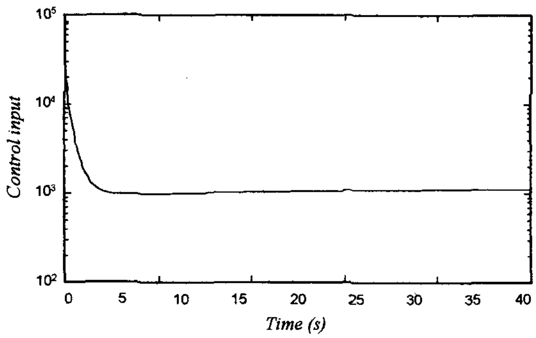

Fig. 14 Control law

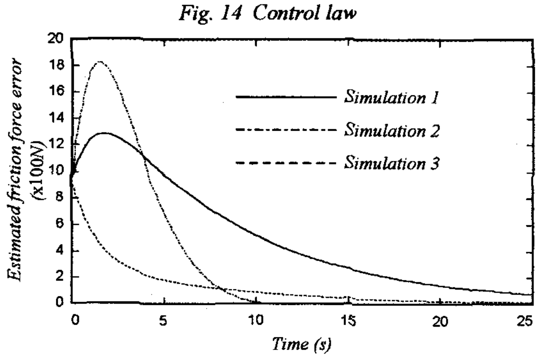

Fig. 15 Friction force estimate error

5. Conclusion

This paper proposes a simple nonlinear controller for controlling the PIG velocity. The unknown friction force is estimated using adaptive law. The closed loop system is stable in the sense of Lyapunov stability. To derive the controller, three system parameters are needed to measure: the PIG position, its velocity and the velocity of bypass flow across the PIG body. The simulation has been done in three cases: the PIG starts to move at its launcher, the PIG arrives at its receiver and the PIG restarts after stopping at the middle of pipeline. The simulation results show that with the proposed controller, the PIG can track well the reference speed when it runs in a natural gas pipeline.

Acknowledgment

This paper is a part of study results of "Modeling and Control of PIG Flow in Natural Gas Pipeline" which is studied by Korea Gas Corporation support. We gratefully acknowledge the contributions and suggestions of related persons.

References

(1) T.T. Nguyen, H.R. Yoo, Y.W. Rho, and S.B. Kim, "Modeling and Simulation for PIG Flow Control in Natural Gas Pipeline", *Proceedings of the 15th Korea Automatic Control Conference*, Yong-in, Korea, pp. 448-451, October 2000.

(2) T.T. Nguyen, H.R. Yoo, Y.W. Rho, and S.B. Kim, "Modeling and Simulation for PIG Flow Control in Natural Gas Pipeline", *KSME International Journal*, submitted.

(3) T.T. Nguyen, H.R. Yoo, Y.W. Rho, and S.B. Kim, "Modeling and Simulation for PIG with Bypass Flow Control in Natural Gas Pipeline", *KSME International Journal*, submitted.

(4) T.T. Nguyen, H.R. Yoo, Y.W. Rho, and S.B. Kim, "Speed Control of PIG Using Bypass Flow in Natural Gas Pipeline", *2001 IEEE International Symposium on Industrial Electronics*, June 12-16, 2001, Pusan, Korea.

(5) Korea Gas Corporation, *The First Stage of Development of Intelligent PIG for Low Pressure Pipeline*, March 2000.

(6) P.C.R. Lima, S.A. Petrobas, and H. Yeoung, "Modeling of Pigging Operations", *Proceedings of SPE Annual Technical Conference and Exhibition*, pp. 563-578, TX., USA, October 1999.

(7) L.F.A. Azevedo, A.M.B. Braga, A.O. Nieckele, M.F. Naccache, and M.G.F.M. Gomes, "Simple Hydrodynamic Models for the Prediction of Pig Motions in Pipelines", *Proceedings of the 1996 Offshore Technology Conference*, TX., USA, pp. 729-739, 1996.

(8) H.L. Wu, G. Van Spronsen, E.H. Klaus and D.M. Stewart," Bypass PIG for Two-phases Flow Pipelines", *Proceedings of the 1996 75th Annual Convention of the Gas Processors Association*, Denver, CO., USA, pp. 262-266, 1996.

(9) M. Krstic, I. Kanellakopoulos and P. Kokotovic, *Nonlinear and Adaptive Control Design*, John Wiley & Sons, Inc., 1995.

(10) D.J. Wilson and J.W. Yokota, *Speed Control Research and Development*, NOWSCO Pipeline Services, Alberta, November 1994.

(11) E. Benjamin Wylie, Victor L. Streeter and Lisheng Suo, *Fluid Transients in Systems*, Prentice-Hall, Inc., 1993.

(12) J.M.M. Out, "On the Dynamics of Pig-slug Trains in Gas Pipeline", OMAE, Vol. V, *Pipeline Technology*, ASME, pp. 395-403, June 1993.

(13) G.L. Smith, "Pigging Velocities and the Variable-Speed PIG", *Proceedings of Pipeline Pigging and Integrity Monitoring Conference*, Amsterdam, Netherlands, 28th September - 2nd October 1992.

(14) J.L. Cordell, "Pigging Research", *Proceeding of Pipeline Pigging and Inspection Technology Conference*, Houston, February 1991.