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Morphological Adaptation for Speed Control of Pipeline Inspection Gauges MC-PIG

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Abstract

Passive and active hybrid pipeline inspection gauges (PIGs) have been used for in-pipe inspection. While a passive PIG cannot control its speed, the hybrid version can achieve this by using an integrated valve specifically designed and embedded in the PIG. This study proposes a generic new method for speed adaptation in PIGs (called MC-PIG) by introducing a generic, modular, controllable, external valve unit add-on for attaching to existing conventional (passive) PIGs with minimal change. The MC-PIG method is based on the principle of morphological computation with closed-loop control. It is achieved by regulating/computing the PIG's morphology (i.e., a modular rotary valve unit add-on) to control bypass flow. Adjustment of the valve angle can affect the flow rate passing through the PIG, resulting in speed regulation ability. We use numerical simulation with computational fluid dynamics (CFD) to investigate and analyze the speed of a simulated PIG with the valve unit adjusted by proportional-integral (PI) control under various in-pipe pressure conditions. Our simulation experiments are performed under different operating conditions in three pipe sizes (16″, 18″, and 22″ in diameter) to manifest the speed adaptation of the PIG with the modular valve unit add-on and PI control. Our results show that the PIG can effectively perform real-time adaptation (i.e., adjusting its valve angle) to maintain the desired speed. The valve design can be adjusted from 5 degrees (closed valve, resulting in high moving speed) to a maximum of 45 degrees (fully open valve, resulting in low moving speed). The speed of the PIG can be regulated from 0.59 m/s to 3.88 m/s in a 16″ pipe at 4.38 m/s (in-pipe fluid velocity), 2500 kPa (operating pressure), and 62 °C (operating temperature). Finally, the MC-PIG method is validated using a 3D-printed prototype in a 6″ pipe. Through the investigation, we observed that two factors influence speed adaptation; the pressure drop coefficient and friction of the PIG and pipeline. In conclusion, the results from the simulation and prototype show close characteristics with an acceptable error.

Introduction

In the oil and gas industry, pipelines are primarily used to transport fluids, and it is therefore critical that pipeline systems are cost-effective, efficient, and secure during transportation. However, corrosion, natural disasters, geological movements, and other factors frequently cause leaks and cracks in underground and marine pipelines. Pipeline system leaks and cracks can result in massive economic loss, environmental disaster, and even endanger human life. Thus, they must be inspected on a regular basis, which is typically done using a pipeline inspection gauge (PIG). PIGs are usually launched at the inlet of the pipeline and received at the outlet, or PIG receiver. The fluids transported through the pipeline, as well as the higher pressure behind them, are the driving force of the PIG operation. However, fluid fluctuation can affect PIG velocity, causing it to malfunction. During cleaning and inspection, PIGs may experience higher or lower speeds than desired, affecting the cleaning results or creating inaccurate inspections. This can result in re-pigging, false crack detection, or odometry errors. In addition, the pipeline operation for fluid transportation must be temporarily halted to implement the PIG, thereby affecting the rate of production.

Several studies have been carried out over recent decades to investigate and develop adaptive speed control of PIGs. The analysis and simulation of PIG motion have been comprehensively investigated for motion efficiency and safety improvement [1–4]. One of the most common solutions is to use a bypass valve. The valve controls the bypass flow of the PIG, leading to speed control regulation. For example, Nguyen et al. [5–7] investigated the use of a PIG in a natural gas pipeline with bypass flow control, presenting system modeling, simulation results, and dynamic flow of the PIG's surroundings. The dynamic flow includes not only the PIG dynamics but also those of driving gas behind, in front, and inside the bypass flow. Their study introduces a simple nonlinear speed control scheme with the modeling of PIG flow based on compressible, unsteady flow realized using a method of characteristics (MOC). Guibin et al. [8] defined the dynamic model of a bypass valve for PIG speed control, based on both theoretical and experimental analysis. Zhu et al. [9] extended their investigation [8] to the dynamic characteristics of a rotatable bypass valve for PIG speed control in a gas pipeline, using an experimental approach to identify the relationships between torque, the bypass-valve opening area, and differential pressure over the bypass valve, as a potential reference for developing a PIG speed control algorithm. Although all of these studies [1–9] propose and demonstrate PIG speed control methods, they are all limited to specific pipe sizes. Their solutions are designed for specific PIGs, requiring significant PIG modifications, and resulting in a great deal of adjustment (i.e., hardware modifications) and a lack of generalization (i.e., transferable to other PIGs).

To achieve a flexible, practical, and transferable solution for adaptive PIG speed control in various PIGs and different pipe sizes, we propose here a generic new method for the speed adaptation of PIGs (called morphological adaptation for speed control of PIGs or MC-PIG). This is achieved by a generic, modular, controllable, external rotary valve unit add-on with sealing parts and closed-loop valve control. The modular unit is designed to be attachable (plug and play) to existing conventional (passive) PIGs on the market with minimal modification. The closed-loop control can regulate the pressure between upstream and downstream by bypassing the flow through the unit (Fig. 1). Furthermore, this unit is capable of operating in various pipelines by changing the size of the sealing parts according to the pipe size.

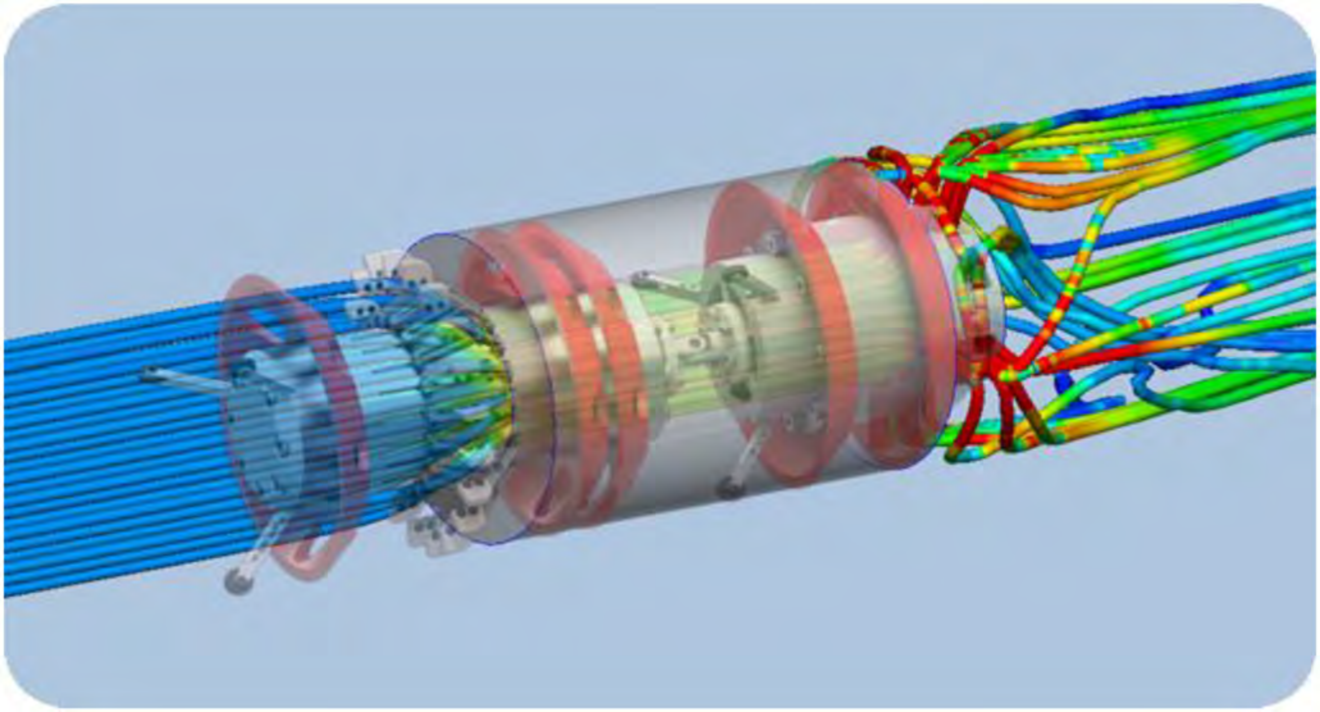

Fig. 1—The conceptual design of the MC-PIG unit with an adjustable rotary valve (right) attached to a PIG (left). It is simulated under an operating condition using computational fluid dynamics (CFD). The MC-PIG system moves from left to right.

In this work, our MC-PIG design methodology consists of four main processes or tasks (as shown in Fig. 2): 1) dynamic model realization, 2) CFD modeling, 3) numerical simulation, and 4) prototype validation. Our simplified dynamic model (i.e., equation of motion) describes and illustrates the motion of the MC-PIG. Based on the dynamic model, CFD is used to calculate the design parameters for numerical simulation, positioning, speed observation, and prediction of the MC-PIG. Finally, we fabricated the MC-PIG prototype for testing and then compared and evaluated the results of physical testing with those of simulation.

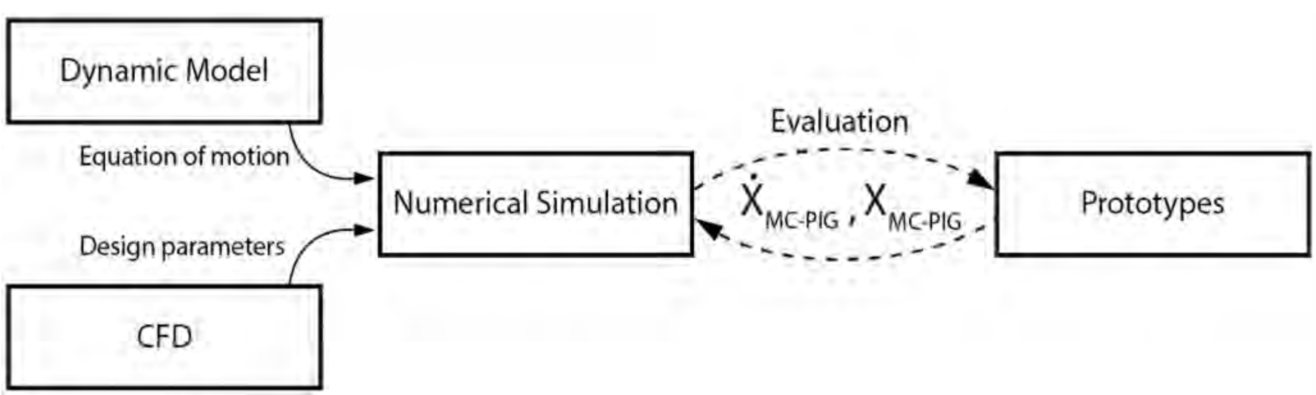

Fig. 2—Four main processes/tasks of the MC-PIG design methodology in the workflow. The tasks are described in the following sections: dynamic model, CFD, numerical simulation, and prototype with different opening angle modules

Dynamic model

The motion of the MC-PIG is derived from the interactive forces between the external fluid and the MC-PIG.According to its free body diagram (Fig. 3), the motion of the MC-PIG can be described from a combination of forces derived from the pressure difference (F_p), change in momentum of the external fluid (F_m), and frictional force (f). The equation of motion is given as follows:

$$m\ddot{x} = F_p + F_m - f. \tag{1}$$

From Eq. 1, the force from the pressure difference can be calculated in terms of the pressure loss coefficient (k), which depends on the MC-PIG morphology. The momentum force is expressed as a velocity function of the MC-PIG $(\dot{x})$ and the velocity of the external fluid (V_F). The frictional force is assumed to be constant. As a result, Eq. 1 can be reformulated as:

$$m\ddot{x} = \frac{1}{2}k\rho V_{BP}^2 A + \rho A\left(V_F - \dot{x}\right)\left(\dot{x} + \frac{V_F}{2}\right) - f, \tag{2}$$

Where m, $\dot{x}$, $\ddot{x}$, and A are the mass, velocity, acceleration, and cross-sectional area of the MC-PIG, respectively. ρ is the external fluid density. It is assumed to be an incompressible flow. Based on the continuity equation under constant fluid density assumption, we can simply calculate the bypass velocity of the fluid (V_{BP}) as follows:

$$V_{BP} = \frac{\left(V_F - \dot{x}\right)}{d^2} D^2, \tag{3}$$

where D *and* d are the inner diameters of the pipe and bypass area of the MC-PIG, respectively. In this study, m, A, ρ, d, D are assumed to be constant. According to Eq. 2, the momentum force is so small as to be negligible. Therefore, we can estimate the final or terminal velocity $(\dot{x}_T)$ by setting $\ddot{x} = 0$ as:

$$\dot{x}_T \approx V_F - \frac{d^2}{D^2}\sqrt{\frac{2f}{k\rho A}} \tag{4}$$

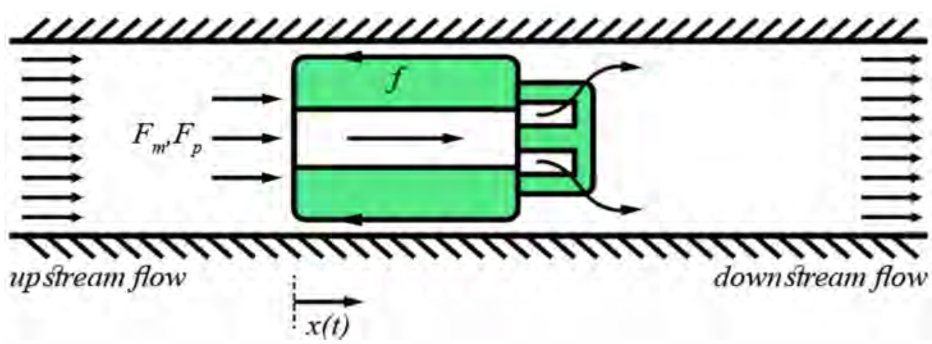

Fig. 3—Free body diagram of the MC-PIG demonstrating the interaction forces between the MC-PIG and its surroundings in the pipe.

Computational fluid dynamics

Computational fluid dynamics (CFD) are widely used in various industrial applications to simulate and analyze fluid and hydro-mechanic behaviors. In this study, Autodesk CFD 2021 is utilized to visualize and characterize the MC-PIG's behavior and find the pressure loss coefficient value (k, see Eqs. 2 and 4) for numerical simulation. The Reynolds-averaged Navier-Stokes (RANS) with K-omega turbulence model is used for model approximation to solve the flow inside the pipe. However, this method only solves a portion of the Navier-Stokes equation and models other medium and small eddies as an approximation to reduce computational power and time. Table 1 shows the simulation environment and settings used in the simulation. It is worth noting that the operating conditions are derived from the actual industrial pipeline data.

Table 1—Parameters and settings for the CFD simulation. *Some parameters were estimated and simplified as a single phase flow.

	Pipe 16″	Pipe 18″	Pipe 22″
Pipe diameter	40.64 cm	45.72 cm	55.88 cm
Density of fluid*	14.78759 kg/m³	18.579057 kg/m³	20.760746 kg/m³
Viscosity of fluid*	0.00012654 Pa s	0.0001274 Pa s	0.00011814 Pa s
Inlet velocity of fluid	4.3877 m/s	7.9403 m/s	3.3857 m/s
Outlet pressure at the end of the pipe	0 barg	0 barg	0 barg
Operating temperature	62°C	60°C	30°C

The CAD models of the MC-PIG with different opening angles of the rotary valve module are created for the three pipe diameters (16″, 18″, and 22″). For each pipe, five different models with opening valve angles of 5, 15, 25, 35, and 45 degrees are used to perform qualitative simulation and analysis. The model geometry is shown in Table 2 and Fig. 4. The maximum bypass area of a fully opened valve (45 degrees) is equal to the inner bypass area of the MC-PIG. The other parameters obtained during the design of the fabrication process and other components, such as motors, controllers, and batteries, will be added in the future.

Table 2—Design parameters of the MC-PIG.

Dimension	Value
PIG outer diameter (*D*)	16″, 18″, 22″
PIG bypass inner diameter (*d*)	0.52D
PIG bypass length (*L*)	1.42D
Number of bypassing holes (*n*)	4
Rotary valve outer diameter (*b*)	d +15 mm
Rotary valve length (l)	0.5d
Rotary valve thickness (t)	0.05*D*

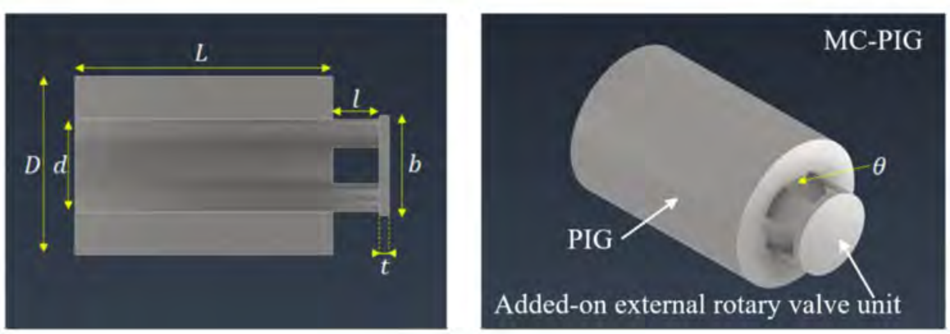

Fig. 4—Geometry of the MC-PIG model. The MC-PIG consists of the PIG body and the external rotary valve unit add-on. The valve unit can be controlled by adjusting its opening valve angle for speed control.

The CFD results show that the MC-PIG with a small opening angle has higher differential pressure and turbulence between the front and rear (Fig. 5). As can be observed, the 5-degree-opening angle valve shows red and yellow areas at the rear, indicating higher velocity than the blue and light blue areas. Fig. 5 is the result of an 18″ pipe, while the other sizes also have the same characteristics (not shown). The images on the right show the particle traces, visualized as fluid passing through the MC-PIG. Obviously, the high turbulence occurs in small opening angles (i.e., 5, 15, and 25 degrees).

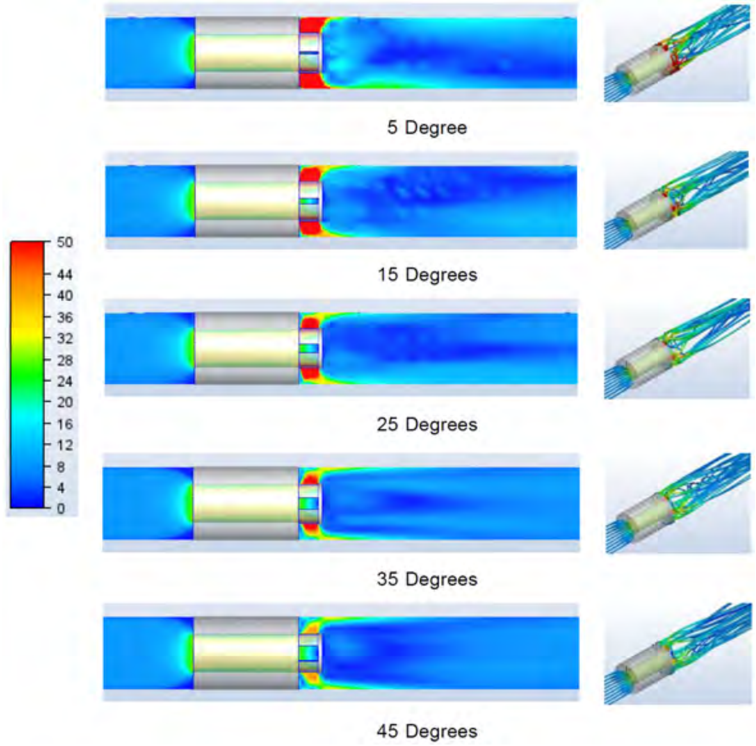

Fig. 5—Fluid velocity [m/s] with respect to opening valve angles of 5°, 15°, 25°, 35°, and 45°.

The fluid velocities in the bypass area of the MC-PIG are used to calculate the k valves along with the pressure difference between the front and rear (Δp) via Eq. 5 as:

$$k = \frac{2\,\Delta\,p}{\rho V_{bp}^{2}}, \tag{5}$$

where ρ is the fluid density in kg/m^3. V_{bp} is the velocity of the fluid. Fig. 6 shows the calculated and approximated k valves of different opening angles and pipe sizes. It can be seen that the pressure loss coefficient varies according to the morphological structure of the MC-PIG (i.e., the bypass-valve area) defined by the opening angle. The results indicate a similar characteristic in three pipeline sizes (16″, 18″, and 22″ in diameter).

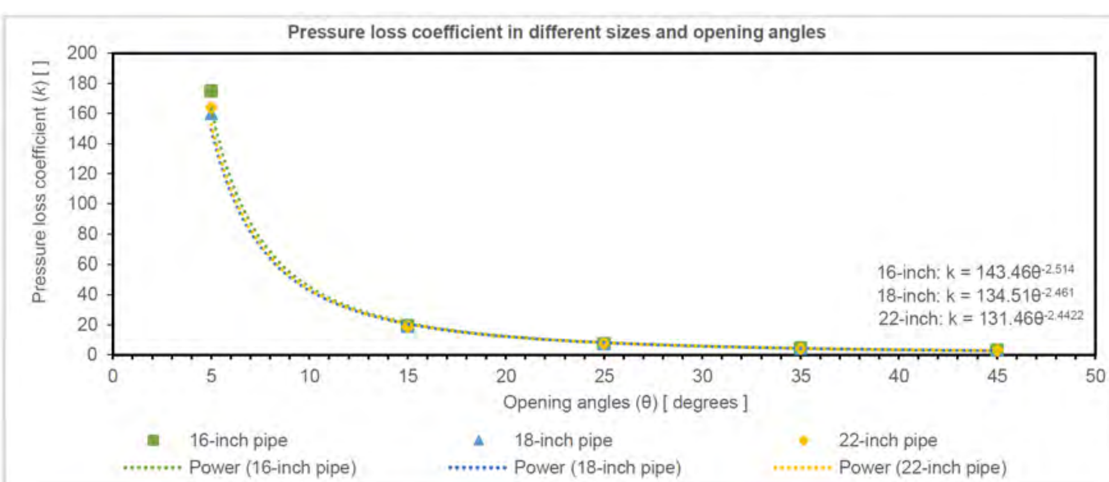

Fig. 6—Pressure loss coefficient at different opening valve angles (5°, 15°, 25°, 35°, and 45°) and different pipe sizes (16″, 18″, and 22″ in diameter).

Numerical simulation

To investigate the characteristics of the MC-PIG, we simulate it under different operating conditions. Simulation is also used to demonstrate the terminal velocity and transient behavior of the MC-PIG. The equation of motion (Eq. 1) governed by the dynamic model is used here for numerical simulation. The numerical method, Runge-Kutta, is applied to solve the differential equations to obtain the position and velocity profiles of the PIG. The numerical simulation is also subsequently used for prediction and comparison with our real prototype testing results. To evaluate the PIG behavior, we set up the simulation using the actual data measuring 16″, 18″, and 22″ in diameter. The dry friction between the MC-PIG and the pipeline is assumed to be constant [10] in this experiment. The medium properties are calculated from the operating conditions. The pressure loss coefficient (k) is derived from CFD. The key parameters used in the simulation are presented in Table 1 and 3.

Table 3—Parameters for the numerical simulation.

Parameters	16″ Pipe	18″ Pipe	22″ Pipe
Mass of PIG [kg]	427	718	1,026
Friction [N]	400	400	400
Pressure loss coefficient	$2288.3\ \theta^{-1.8}$	$2015\ \theta^{-1.758}$	$1954\ \theta^{-1.762}$

In the first simulation, we investigate the terminal velocity for each bypass (opening) valve angle. We can find the terminal velocity by simulating until the MC-PIG reaches a steady state. The MC-PIG follows the same trend in each pipeline size, as shown in Fig. 7. As a result, the MC-PIG can achieve high terminal velocity while operating with small bypass angles. We can determine the controllability range of the desired speed based on this result. Furthermore, we can adjust the trend by changing the dry friction, resulting in other ranges and trends of controlled speed, as presented in Fig. 8

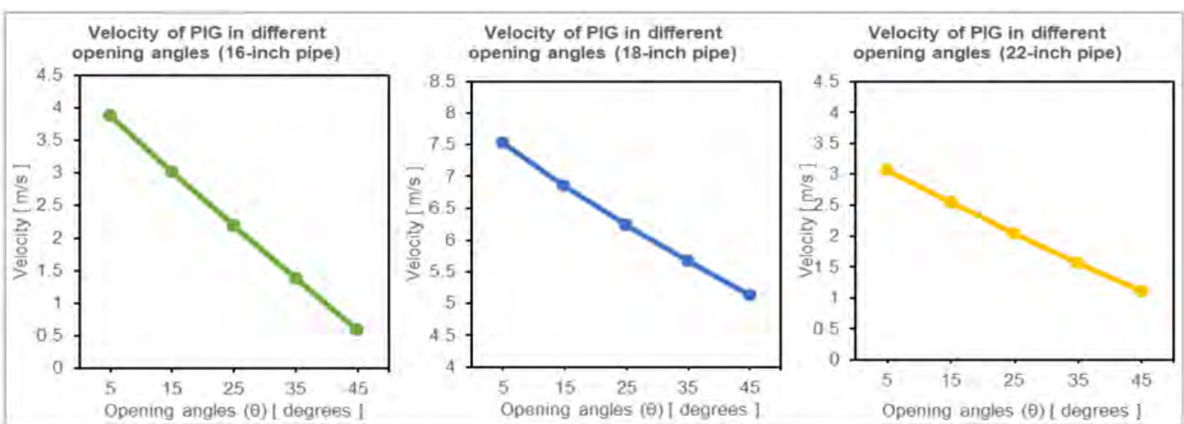

Fig. 7—The characteristics of the MC-PIG in 16″, 18″, and 22″ under different valve angles.

In the second simulation, we investigate the response of the MC-PIG with respect to different bypass (opening) valve angles. The small bypass valve of the MC-PIG results in high terminal velocity as well as a fast response (Fig. 9). As shown in Fig. 10, the velocity of the MC-PIG can spontaneously adapt to changes in the valve angle.

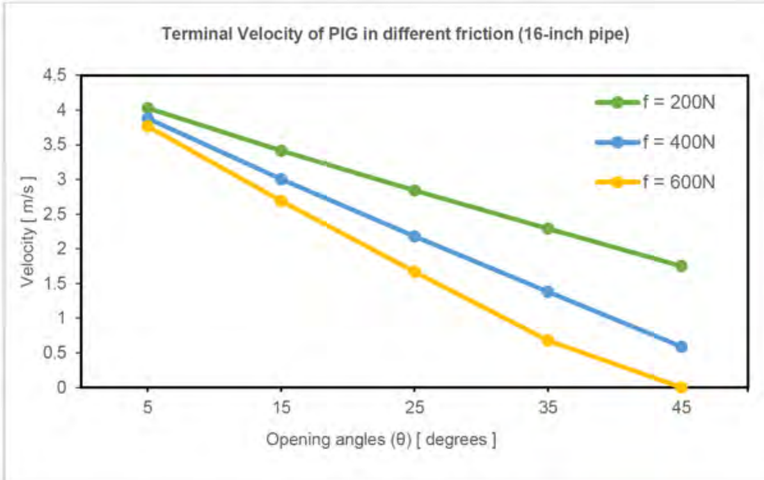

Fig. 8—The characteristics of the 16-inch MC-PIG under different dry frictions.

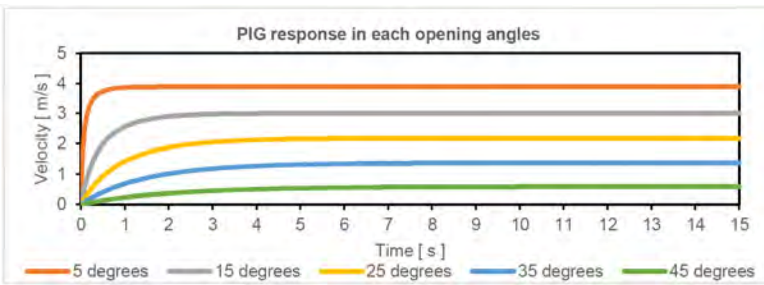

Fig. 9—Transient characteristics of the 16-inch MC-PIG.

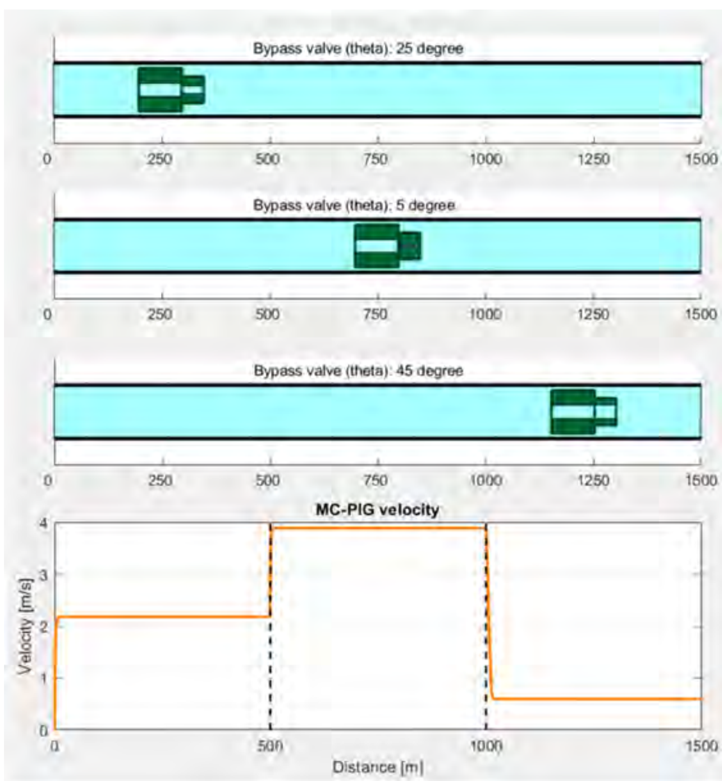

Fig. 10—Numerical simulation (see Supplementary Video 1, https://www.manoonpong.com/MCPIG/SupplementaryVideo1.mp4).

In the third simulation, we apply classical PI control [11] to automatically adjust the opening valve angle of the MC-PIG to maintain its desired velocity under different operating conditions. Three conditions (abruptly changing, sinusoidal, and unsteady pressure conditions) are used for the demonstration. Our results show that the MC-PIG can effectively perform real-time adaptation (i.e., adjusting its valve angle) to maintain its desired velocity (Fig. 11).

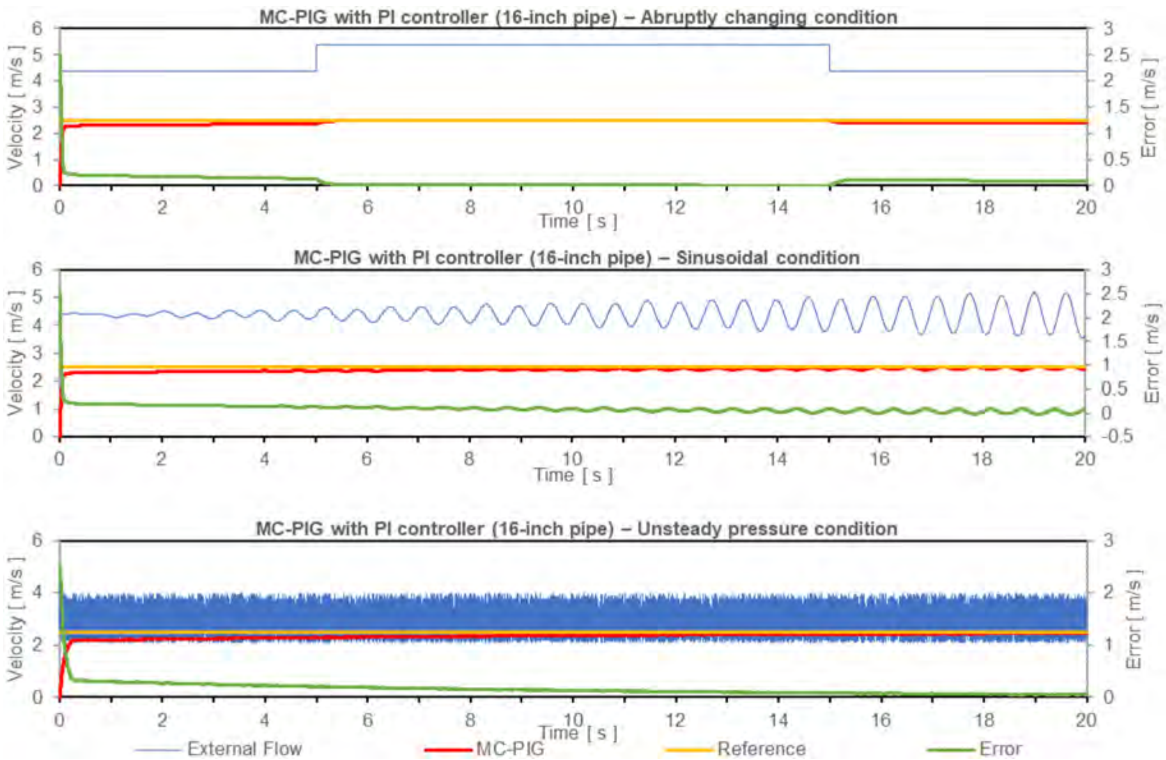

Fig. 11—Numerical simulation of the 16-inch MC-PIG with PI control under different operating conditions.

Prototype

Prototype testing is carried out to confirm the concept of morphological adaptation (i.e., changing the opening valve of the module) to enable the MC-PIG to adapt its velocity in a real environmental setup (physical setup with fluid, TRL4). In addition, the testing results are used to confirm that our simulation approach can be used to simulate and predict MC-PIG behavior. We build a 3D-printed MC-PIG prototype with interchangeable valves (Fig. 12). The angles of the valves are 5, 15, 25, 35, and 45 degrees. The rubber seal gasket is integrated with the 3D-printed valve and PIG body to seal the gap between the PIG and pipe.

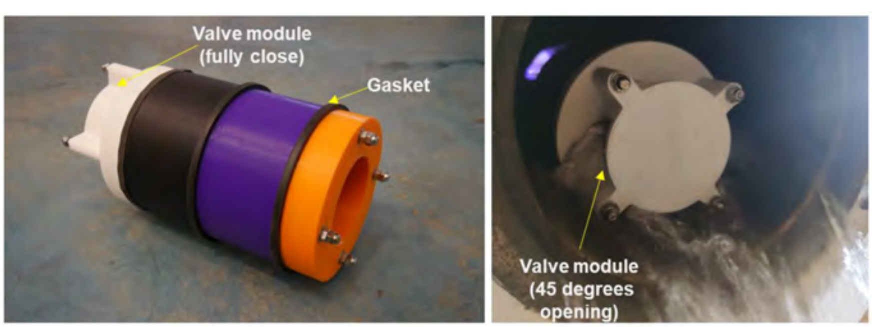

Fig. 12—The MC-PIG prototype for testing with a 6″ pipe.

The pipe testing loop (Fig. 13) includes input and output reservoirs, a water pump (CDL8550, 37 kW), control system, pressure sensor (SFC-116T), 6-inch UPVC transparent pipe, ball valve, and PIG launcher and receiver. The PIG's velocity is calculated using 1) light curtain sensors installed at four locations along the pipe at a distance of 1.25 meters, and 2) visual analysis based on images extracted from recorded videos. The total length of the pipe section is around 5 meters. The loop is left open at the end of testing to allow the water to drain. Using water as a medium, the flow rate inside the pipe is around 0.293 m/s.

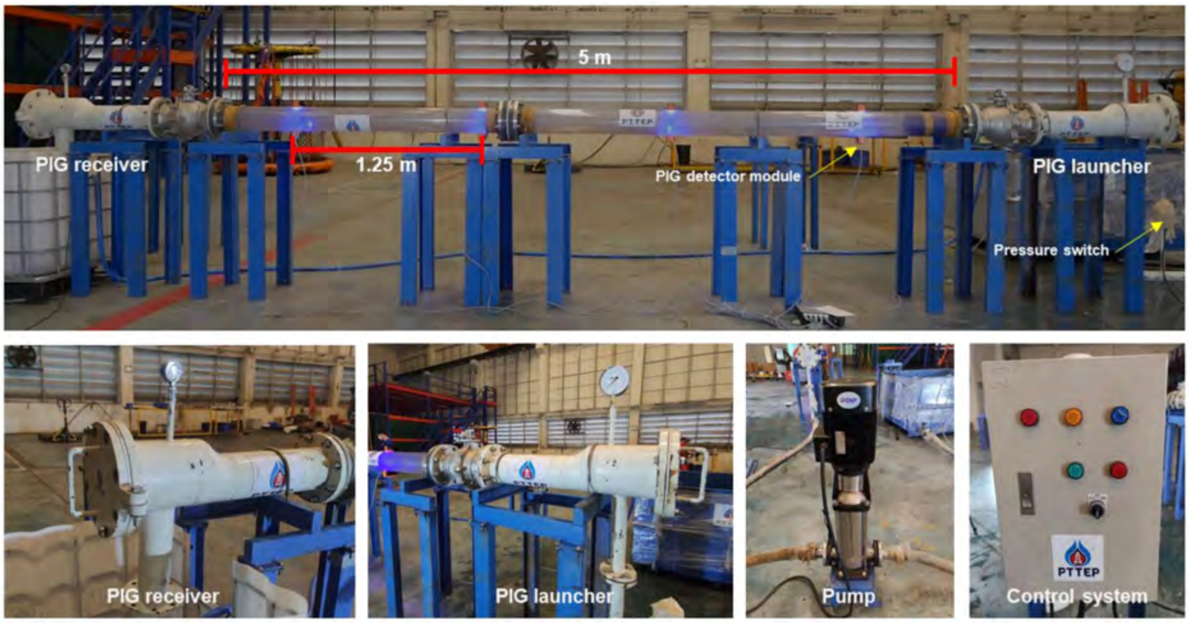

Fig. 13—The experimental setup and testing system of the 3D-printed MC-PIG prototype.

To obtain the average velocity of the MC-PIG, we repeat the tests three times for each opening valve angle. Fig. 14 presents the testing results and a comparison of the real testing and numerical simulation results in a 6-inch pipe under different angles. The numerical simulation results are obtained based on the same conditions and CFD k values (Fig. 6). Table 4 lists the configuration parameters. The environmental settings are identical to those used in 16″, 18″, and 22″ diameter pipes, with the exception that the fluid in this real setup is water. An example of the MC-PIG motion is shown in Fig. 15.

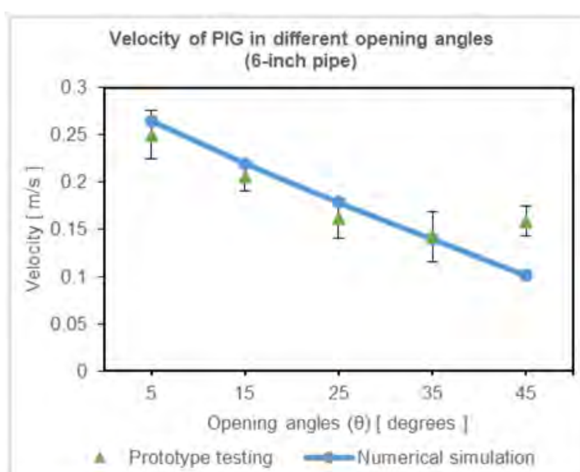

Fig. 14—Comparison results between the prototype and numerical simulation (see Supplementary Video 2, https://www.manoonpong.com/MCPIG/SupplementaryVideo2.mp4).

Table 4—Parameters for the numerical simulation.

Parameter	6″ Pipe
Pipe diameter [cm]	15.3
Inlet velocity of fluid [m/s]	0.293
Outlet pressure at the end of the pipe [bar]	0
Operating temperature [°C]	29
PIG's weight [kg]	2.21
Friction force [N]	10

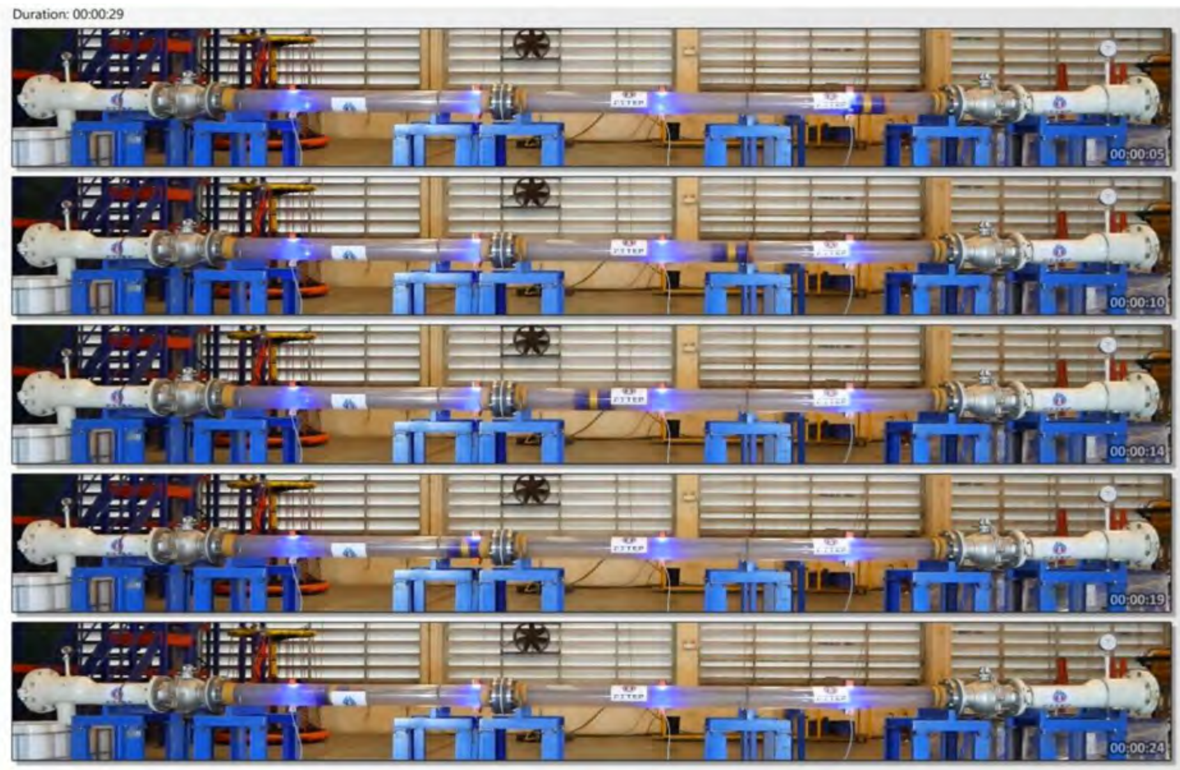

Fig. 15—Example of the PIG motion at the 25-deg opening valve angle in the testing loop from top to bottom (see Supplementary Video 3, https://www.manoonpong.com/MCPIG/SupplementaryVideo3.mp4).

At each opening angle, the results show a small deviation or variance. The MC-PIG with a 45-degree opening angle shows no significant speed difference when compared to smaller angles (25 and 35 degrees). This is due to a variety of factors, including gasket wear, which can reduce friction, and dirt and rust in the pipe, which can be removed during the tests. Furthermore, the gaskets of the prototype have an outer diameter of around 150 mm, while the pipe's internal diameter (ID) is 153 mm (6 inches). The large diameter of the rigid parts prevents the gaskets from complying with the inner pipe wall in this design. Since the testing loop includes a PIG launcher and ball valve with smaller diameters than the pipe, the size of the gaskets is reduced. As a result, the PIG encounters only minor friction. The outer diameter of rigid parts must be reduced in the following design to allow the gasket bending to comply with the surface of the inner pipe.

Discussion and conclusion

This study presents a morphological adaptation method for controlling the cruising speed of a conventional PIG. The method alters the bypass or opening valve of an add-on module, affecting the pressure loss coefficient and resulting in speed regulation. The results of CFD, numerical simulation, and prototype testing show that morphological adaptation can control the speed based on the size or angle of the bypass or opening valve. Furthermore, since the passive concept focuses on pressure regulation from the flow acting on the PIG, the passive control system requires a higher fluid flow speed than that desired by the PIG to control the speed. The pressure loss coefficient and friction are the two main design parameters for specifying the controlled speed range of PIG, as shown in Eq. 4. While the range of the pressure loss coefficient is determined by the geometry of the PIG, which in this study is varied by changing the angle of the bypass valve, the friction is determined by the material of the sealing part, and this can be chosen and studied further. Friction is also affected by the state of the pipe and medium. The numerical simulation slightly differs from the real testing result. The friction, assumed to be constant in the numerical simulation, and the properties of the external fluid are two factors that cause this deviation.

The presented MC-PIG module is in an early stage of development and will require further design and control system integration. As a result, our future research will focus on the detailed design of the MC-PIG system (Fig. 15), which will be deployed in various pipe sizes (e.g., 12″-16″ diameter pipes). These pipe sizes will allow for implementing electronic and actuator components inside the MC-PIG for speed adaptation and the size of the MC-PIG can be adjusted to the pipes by changing the sealing parts. The module can be also connected to a traditional PIG by a flange, while a universal joint will also be used to connect the MC-PIG to the main PIG body. This will lead to a flexible or bendable PIG system for in-pipe navigation. At the same time, the gasket or sealing parts (colored red) of the traditional PIG will require fluid bypass holes to allow external flow to bypass through the MC-PIG valve only for speed regulation. Overall, this attachment concept aims to provide a connection to commercially available PIGs with minimal modification. Furthermore, we will also focus on localization and state estimation to improve the odometric accuracy and allow us to better control the speed of PIG for effective and precise inspection. Therefore, the MC-PIG will benefit not only the oil and gas industry but also other industries that require routine in-pipe inspections, such as chemical plants, power plants, and plumbing systems.

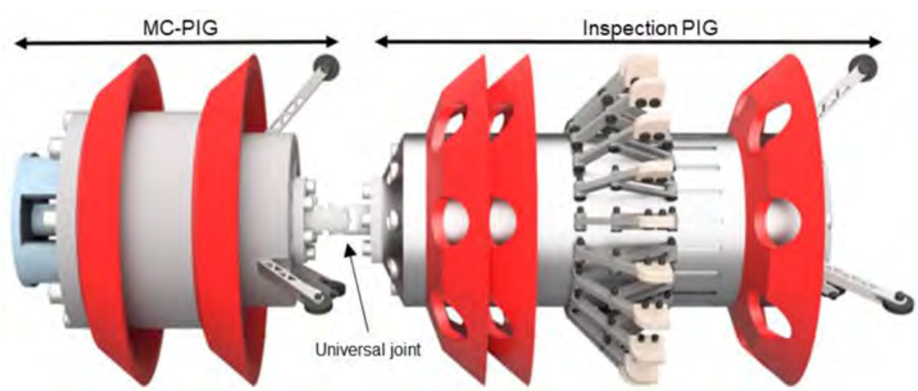

Fig. 16—The conceptual design of the MC-PIG attached to a conventional inspection PIG.

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REFERENCES

1. Solghar A. A. and M. Davoudian, "Analysis of transient PIG motion in natural gas pipeline," *Mech. Ind.*, vol. **13**, no. 5, Art. no. 5, 2012, doi: doi: 10.1051/meca/2012039.
2. S. Hosseinalipour, A. Khalili, and A. Salimi, "Numerical Simulation of Pig Motion through Gas Pipelines," Jan. 2007, pp. 971–975.
3. Tolasquim S. T. and A. O. Nieckele, "Design and control of pig operations through pipelines," *Pet J. Sci. Eng.*, vol. **62**, no. 3–4, pp. 102–110, Sep. 2008, doi: 10.1016/j.petrol.2008.07.002.
4. A. O. Nieckele, A. M. B. Braga, and L. F. A. Azevedo, "Transient Pig Motion Through Non-Isothermal Gas and Liquid Pipelines," *Oct*. 2016, pp. 611–618. doi: 10.1115/IPC2000-175.
5. T. T. Nguyen, H. R. Yoo, Y. W. Rho, and S. B. Kim, "Speed control of PIG using bypass flow in natural gas pipeline," in ISIE 2001. 2001 IEEE International Symposium on Industrial Electronics Proceedings (Cat. No.01TH8570), Jun. 2001, vol. **2**, pp. 863–868 vol.**2**. doi: 10.1109/ISIE.2001.931581.
6. T. T. Nguyen, S. B. Kim, H. R. Yoo, and Y. W. Rho, "Modeling and simulation for PIG flow control in natural gas Pipeline," *KSME Int. J.*, vol. **15**, no. 8, pp. 1165–1173, Aug. 2001, doi: 10.1007/BF03185096.
7. T. T. Nguyen, S. B. Kim, H. R. Yoo, and Y. W. Rho, "Modeling and simulation for PIG with bypass flow control in natural gas pipeline," *KSME Int. J.*, vol. **15**, no. 9, pp. 1302–1310, Sep. 2001, doi: 10.1007/BF03185671.
8. T. Guibin, Z. Shimin, Z. Xiaoxiao, S. Liyun, and Z. Qingbao, "Research on Bypass-valve and its Resistance Characteristic of Speed Regulating PIG in Gas Pipeline," in 2011 Third International Conference on Measuring Technology and Mechatronics Automation, Jan. 2011, vol. **2**, pp. 1114–1117. doi: 10.1109/ICMTMA.2011.561.
9. X. Zhu, S. Zhang, G. Tan, D. Wang, and W. Wang, "Experimental study on dynamics of rotatable bypass-valve in speed control pig in gas pipeline," *Measurement*, vol. **47**, pp. 686–692, Jan. 2014, doi: 10.1016/j.measurement.2013.08.060.
10. H. Zhang, S. Zhang, S. Liu, Y. Wang, and L. Lin, "Measurement and analysis of friction and dynamic characteristics of PIG's sealing disc passing through girth weld in oil and gas pipeline," *Measurement*, vol. **64**, pp. 112–122, Mar. 2015, doi: 10.1016/j.measurement.2014.12.046.
11. A. O'Dwyer, Handbook of PI and PID Controller Tuning Rules, 3rd Edition. World Scientific, 2009. doi: https://doi.org/10.1142/p575