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Intelligent Control and Modelling of a Micro Robot for In-pipe Application

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Abstract**—**In this paper, a worm-like micro robot designed for in-pipe application with intelligent active force control (AFC) capability is modelled and simulated. The motion of the micro robot is based on an impact drive mechanism (IDM) that is actuated using piezoelectric device. The trajectory tracking performance of the modelled micro robot is initially experimented via a conventional proportional-integral-derivative (PID) controller in which the dynamic response of the robot system subjected to different input excitations is investigated. Subsequently, a robust intelligent method known as active force control with fuzzy logic (AFCFL) is later incorporated into the PID scheme to enhance the system performance by compensating the unwanted disturbances due to the interaction of the robot with its environment. Results show that the proposed AFCFL scheme is far superior than the PID control counterpart in terms of the system's tracking capability in the wake of the disturbances.

Keywords**—**Active Force Control, Micro Robot, Fuzzy Logic, In-pipe Application.

I. Introduction

NOWADAYS micro robots are widely used in a number of engineering applications since robots of this type may be able to operate in unstructured environment thanks to their enhanced adaptability to effectively operate even under hostile conditions such as radioactivity, electromagnetic field and high temperature gradients. One such application of interest is the operation of micro robot in a pipe line that can perform a number of tasks such as in-pipe inspection, fault diagnostics, condition monitoring and obstacle removal. Some basic research on mobile mechanisms for use in pipes has been reported in which many are driven by piezoelectric actuators [1]-[3], giant magnetostrictive actuators [4], pneumatic actuators [5],[6], or electromagnetic actuators [7].

Research and development on the use of piezo actuators and micro mechanisms for micro robots has been actively carried out [8],[9]. Compared to other actuators, the piezoelectric type proves to be more promising and practical because of its high power and better response. A number of piezoelectric actuators have been proposed, such as those based on stacked, bimorph and uni morph configurations. Characteristics of the new piezoelectric linear step locomotive mechanism for an in-pipe micro inspection robot were studied [10]. It can move not only in a straight pipe but also through a curved or bent configuration.

In this research, a micro robot with intelligent active force control (AFC) capability is modelled and simulated for in-pipe application. A mathematical model that justifies the dynamic characteristics of the worm-like micro robot is first presented. Then, the dynamic response of the robot system subjected to different input excitations is investigated. A PID controller is applied to the micro robot system to follow the desired trajectory, while an AFC controller is utilized to reject the unwanted disturbances which may be created due to friction forces or fluid viscosity in the pipe. An intelligent method like Fuzzy Logic (FL) is used to find the AFC parameters, respectively. The performance of the control system under different types of disturbances is evaluated through a rigorous simulation study presented in this paper.

II. Robot Modelling

A. Motion Mechanism

Mechanism of motion for this micro robot is derived from a mechanism which named Impact Drive Mechanism (IDM). This is a method for moving an object under friction by impulsive force. It utilizes static friction and impulsive force caused by the rapid displacement of an actuator. The motion mechanism basically consists of three parts: the main body, actuator and the inertial weight. When the actuator makes rapid extension or contraction, a strong inertial force is generated and the main body is moved against static friction. When the actuator makes slow retraction, the inertial force could be smaller than static friction so that the main body keeps the position. Repeating those fast and slow actuator displacements carries out the motion.

The mechanism is able to control the minute motion of several nanometer and at the same time has virtually unlimited movable range. The mechanism can be extended to multiple degree-of-freedom systems with multiple actuators and counter weights. The IDM is considered to be a suitable mechanism for micro systems since its construction is quite simple.

Fig. 1 shows a basic motion principle of the Piezo IDM.

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The motion mechanism consists of three components: the main body, the actuator and the inertial weight. The main body is laid down on the guiding surface with only the friction acting between the surfaces. On the one end of the main body an actuator is attached. The weight does not touch the surface. Making slow extension and rapid contraction can carry out motion toward the other direction.

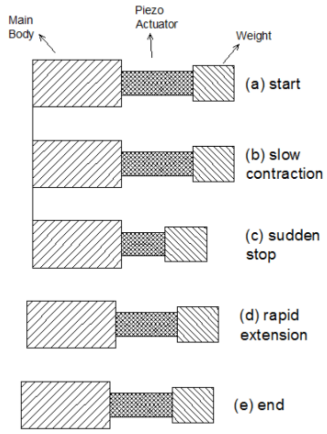


Fig. 1 Principle of operation (towards left)

B. Dynamic Modelling

In this research, a typical static friction model is selected to express the frictional coefficient induced in the interface between elastic feet of the robot and inner wall of the pipe. The frictional force F_f can be expressed as

$$F_f = \left[\mu_k + (\mu_s - \mu_k) exp\left(\frac{1}{\dot{x}} \ln\left(\frac{-\mu_k}{\mu_s - \mu_k}\right)\right)\right] F_n \quad (1)$$

where μ_s , μ_k represent the static and kinetic frictional coefficients, F_n represents the total normal force acting on the sliding surface, and includes the pre-pressure and the weight of entire body of the in-pipe robot. The governing equations are therefore derived from the free-body diagram as the following two coupled equations:

$$m_1 \ddot{x}_1 = -k_p(x_1 - x_2) - C_p(\dot{x}_1 - \dot{x}_2) - F_p + F_f \quad (2)$$

$$m_2 \ddot{x}_2 = k_p(x_1 - x_2) + C_p(\dot{x}_1 - \dot{x}_2) + F_p \quad (3)$$

Where m_1 and m_2 respectively represent the masses of the main body and the weight, and their corresponding displacements are expressed as x_1 and x_2. The stiffness and damping coefficients of the piezoelectric actuator are symbolized as k_p and C_p, respectively. F_p is the piezoelectric force and F_f is the frictional force. The IDM could be regarded as a mechanical vibration system with two degree-of-freedoms. Equations (4) and (5) are used for describing the dynamic behavior after applying *Laplace* method with initial conditions, t =0, F_f =F_p= 0 for both sides of (2) and (3).

$$m_2 s^2 X_2 = (k_p + C_p s)X_1 - (k_p + C_p s)X_2 + F_p(s) \quad (4)$$

and

$$m_1 s^2 X_1 = k_p(X_2 - X_1) + C_p s(X_2 - X_1) - F_p(s) + (\mu_s - \mu_k)(m_1 + m_2 + m_p) g \frac{\mu_s - \mu_k}{\ln\left(\frac{\mu_k}{\mu_k - \mu_s}\right)} \quad (5)$$

where m_p is the actuator mass.

By deriving X_2 from (4) and inserting in (5), we have:

$$m_1 s^2 X_1 = k_p\left(\frac{(k_p + sC_p)X_1 + F_p(s)}{m_2 s^2 + C_p s + k_p} - X_1\right) + C_p s\left(\frac{(k_p + sC_p)X_1 + F_p(s)}{m_2 s^2 + C_p s + k_p} - X_1\right) - F_p(s) + (\mu_s - \mu_k)(m_1 + m_2 + m_p) g \frac{\mu_s - \mu_k}{\ln\left(\frac{\mu_k}{\mu_k - \mu_s}\right)} \quad (6)$$

Finally, the transfer function for this system can be obtained as:

$$T.F = \frac{X_1}{F_p(s)} = \frac{m_2 s^2 + \left(2C_p + \frac{(\mu_s - \mu_k)(m_1 + m_2 + m_p)g}{\ln\left(\frac{\mu_k}{\mu_k - \mu_s}\right)}\right)s + 2k_p}{m_1 m_2 s^4 + m_2\left(C_p - \frac{(\mu_s - \mu_k)(m_1 + m_2 + m_p)g}{\ln\left(\frac{\mu_k}{\mu_k - \mu_s}\right)}\right)s^3 + C_p k_p s + [k_p(m_1 + m_2) + C_p m_1]} \quad (7)$$

This dynamic model will be incorporated into the proposed micro robot controller schemes, namely the PID and the AFC controller implemented with Fuzzy Logic.

III. CONTROL SCHEME

We applied three input sources in the form of step, square and sinusoidal input functions via feedback control techniques in order to determine the system responses. Two types of controllers, namely the PID and AFC controllers shall be applied and incorporated into the micro robot system.

A. PID Controller

Proportional-Integral-Derivative (PID) control is the most commonly used control algorithm in industry and has been universally accepted in industrial control. The popularity of PID controllers can be attributed partly to their robust performance in a wide range of operating conditions and partly to their functional simplicity, which allows engineers to operate them in a simple, straightforward manner. A schematic diagram of a system employing a PID controller is shown in Fig. 2.

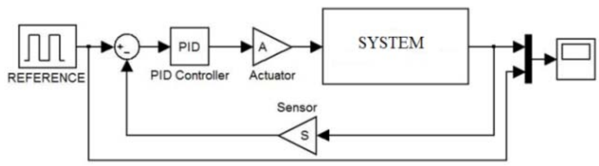


Fig. 2 Schematic diagram of a system with PID controller

The basic idea behind a PID controller is to read a sensor, then compute the desired actuator output by calculating the proportional, integral, and derivative responses and summing those three components to compute the output. The PID controller calculation (algorithm) involves three separate parameters; the proportional, integral and derivative terms. The PID control algorithm is given as follows:

$$G_{PID} = K_P + \frac{K_I}{s} + K_D s \quad (8)$$

Where K_P, K_I, and K_D are the proportional, integral, and derivative gains, respectively. In this study, the *Ziegler–Nichols* method is employed to tune the PID parameters. The final gains including K_P = 50, K_I = 10, and K_D = 8. For simulating, we assume the parameters of micro robot as shown in Table I. The resultant tracking control based on the gains can be seen in Fig. 3 and these gains shall be used throughout the simulation study.

TABLE I PARAMETERS OF THE MICRO ROBOT

parameter	value	parameter	value
m_1	425 g	C_P	4.5 kg/s
m_2	120 g	k_P	15 kN/m
m_P	60 g	g	9.8 m/s^2
μ_s	0.4	μ_k	0.2

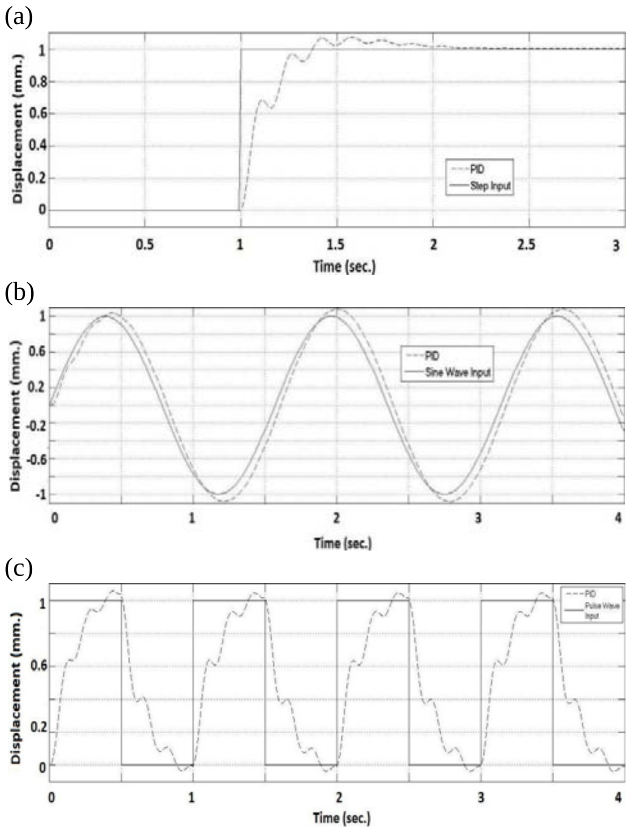


Fig. 3 Performance of PID controller for (a) step, (b) sine wave, and (c) square input functions

B. AFC Controller

Use The research on active force control (AFC) is initiated by Johnson (1971) and later Davison (1976) based on the principle of invariance and the classic Newton's second law of motion [11],[12]. It has been demonstrated that it is possible to design a feedback controller that will ensure the system set point remains unchanged even in the presence of the disturbances or adverse operating and loading conditions provided that the actual disturbances can be modelled effectively. Hewit and Burdess (1981) proposed a more complete package of the system such that the nature of disturbances is oblivious to the system and that it is readily applied to multi-degree of freedom dynamic systems [13]. Thus, an effective method has been established to facilitate robust motion control of dynamical systems in the presence of disturbances, parametric uncertainties and changes that are commonly prevalent in the real-world environment. Usefulness of the method was extended by introducing intelligent mechanisms to approximate the mass or inertia matrix of the dynamic system to trigger the compensation effect of the controller [14].

The AFC method is a technique that relies on the appropriate estimation of the inertial or mass parameters of the dynamic system and the measurements of the acceleration and force signals induced by the system if practical implementation is ever considered. For theoretical simulation, it is normal that perfect modelling of the sensors is assumed and that noises in the sensors are totally neglected. In AFC, it is shown that the system subjected to a number of disturbances remains stable and robust via the compensating action of the control strategy. A more detailed description on the mathematical treatment related to the derivation of important equations and stability criterion [12]. For brevity, the underlying concept of AFC applied to a dynamic rotational system is presented with reference to Fig. 4.

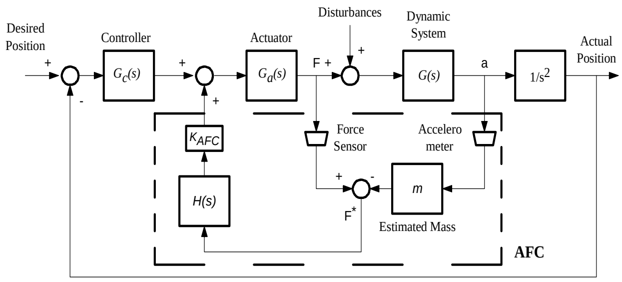


Fig. 4. a schematic diagram of an AFC scheme

The notations used in Fig. 4 are as follows:

$G(s)$	:	Dynamic system transfer function
$G_a(s)$	:	Actuator transfer function
$G_c(s)$	:	Outer loop controller
K_{AFC}	:	AFC constant
H(s)	:	Weighting function
F	:	Applied force
F^*	:	Estimated force
m	:	Estimated mass
a	:	Linear acceleration

The estimated disturbance is obtained by considering the following expression:

$$F^* = F - m\,a \tag{9}$$

F can be readily measured by means of a force sensor and a using an accelerometer. m may be obtained by assuming a perfect model, crude approximation or intelligent methods [15]. F^* is then passed through a weighting function $H(s)$ to give the ultimate AFC signal command to be embedded with an outer control loop. This creates a two degree-of-freedom controller that could provide excellent overall system performance provided that the measurement and estimated parameters were appropriately acquired. The outer control loop can be a proportional-integral-derivative (PID) controller, resolved motion acceleration controller (RMAC), intelligent controller or others deemed suitable. It is apparent that a suitable choice of $H(s)$ needs to be obtained that can cause the output to be made invariant with respect to the disturbances such that:

$$G_a(s)H(s) = 1 \qquad (10)$$

A set of outer control loop control is applied to the above open loop system, by first generating the world coordinate error vector, which would then be processed through a controller function, $G_c(s)$, typically a classic PID controller. The main computational burden in AFC is the multiplication of the estimated inertial parameter with the angular acceleration of the dynamic component before being fed into the AFC feed forward loop. The effectiveness of the AFC scheme applied to rigid robot arms have demonstrated [14],[16]. Robust intelligent AFC method that is capable of controlling a vehicle suspension system and effectively suppressing the introduced disturbances has shown in [17].

A useful point to note is that, the constant K_{AFC} can effectively serve as a mode switch between the PID only scheme (AFCFL – OFF) or PID plus intelligent AFC method (AFCFL – ON) by simply setting the K_{AFC} to 0 or 1 respectively. The in between value of K_{AFC} can also be experimented to show the effect of percentage K_{AFC} which however is not covered in this study.

C. Implementation of Fuzzy Logic

Use The concept of applied FL was pioneered by Lotfi Zadeh in the mid-60s. A fuzzy controller is an expert control system skilled of performing smooth interpolation between hard boundary crisp rules [18]. The basic FL concept is shown in Fig. 5.

Fig. 5 Fuzzy logic concepts

Fuzzification is the first step of the FL in which crisp input values are transformed into fuzzy input involving the construction of suitable membership functions representing the fuzzy sets. The next step is process of rules evaluation that normally in the form of linguistic statements (e.g., if then rules) to determine the dynamics of the controller as a response to the given fuzzy inputs. It is then passed through a defuzzification process using an averaging technique to produce crisp output values. The main goal of using the fuzzy logic in the study is to Fig. the estimated mass M of a trolley intelligently so that it can be used by the AFC method to affect its control strategy. The design procedure of the fuzzy controller used in the study is described as follows:

1. Membership functions representing the input (position) and output (estimated mass) of the FL component are determined as part of the fuzzification process. Approximate values within specific bound are achieved based on crude approximation. The functions utilized in the study can be seen in Fig. 6.

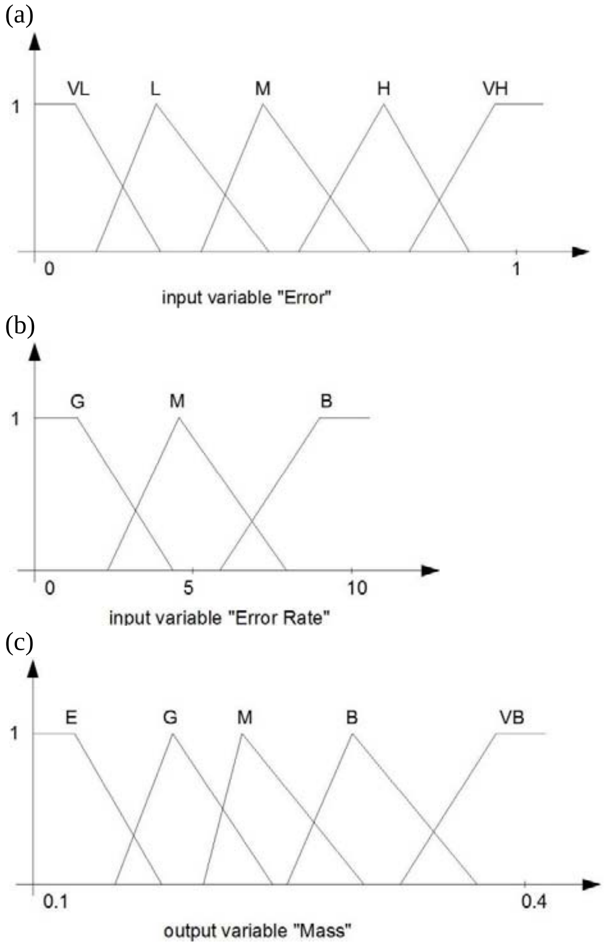


Fig. 6 Membership functions for (a) Error, (b) Error Rate and (c) Mass

2. A set of rules is designed in the form of *if-then* structure. In the study, we use Mamdani fuzzy inference system. An example is given as follows: IF Error L and Error Rate M THEN *M* is G

The above statement implies that if the difference between input and output as Error is low and Error Rate is medium, then the estimated mass (M) of system is good (G). For FL method, the output range of the estimated mass is set from 20 to 200 grams.

3. A crisp output is acquired through a defuzzification process using an averaging technique called *centroida**l*** or *centre of gravity* method and is described by the following equation:

$$\bar{x} = \frac{\int \mu_x(x) x dx}{\int \mu_x(x) dx} \qquad (11)$$

In this research, FL controller is developed using the Fuzzy Logic Toolbox (FLT) to be used with MATLAB and Simulink. Once the FL 'black box' is appropriately designed, it is embedded in the overall control strategy as depicted in Fig. 7.

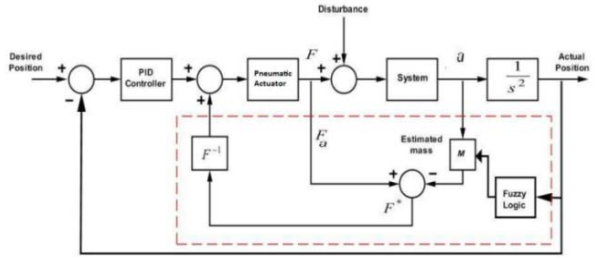


Fig. 7 Proposed AFCFL scheme

The linguistic labels used to describe the fuzzy sets were 'Very Low' (VL), 'Low' (L), 'Medium' (M), 'High' (H), 'Very High' (VH), 'Good' (G), 'Bad' (B), 'Excellent' (E). It is possible to assign the set of decision rules as shown in Table I. The fuzzy rules are extracted from fundamental knowledge and human experience about the process. These rules contain the input/the output relationships that define the control strategy.

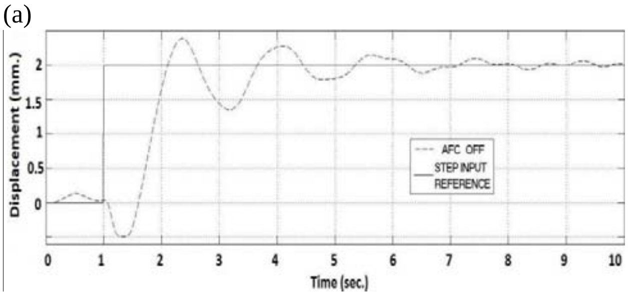
TABLE II DECISION TABLE

E / dE	VL	L	M	H	VH
G	E	E	G	M	B
M	E	G	M	B	VB
B	G	M	B	VB	VB

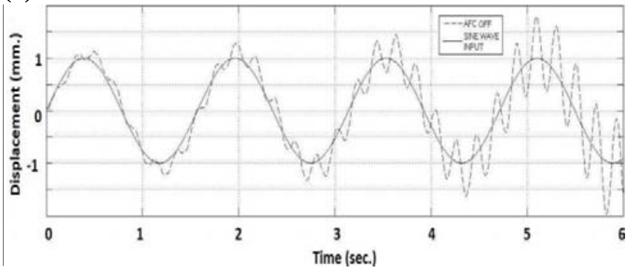
IV. SIMULATION AND DISCUSSION

Use either The applied disturbance considered in the study is a harmonic force that emulates a constant vibratory excitation with a magnitude of 20 N and frequency, 25 rad/s, i.e., according to the following function, 20 sin 25*t*. For simulating the proposed control schemes, i.e., PID and PID plus AFCFL, a number of input sources were considered that are related to step, sinusoidal and square wave forcing functions. The responses to these inputs are shown in Figs. 8 and 9.

(a)



(b)



(c)

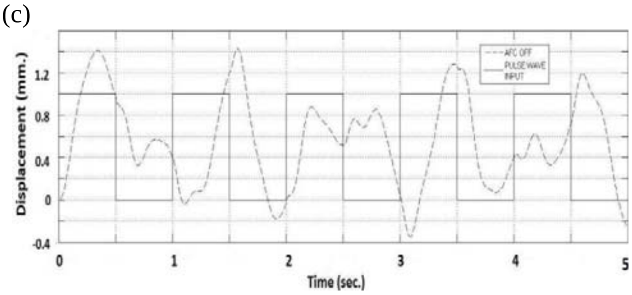
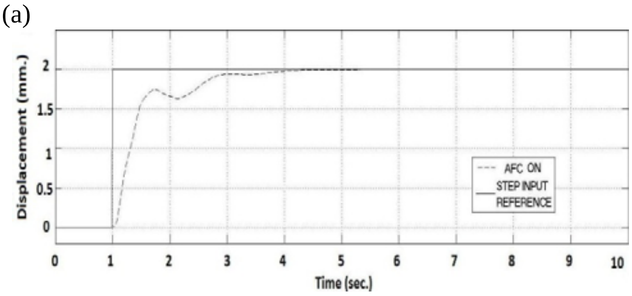
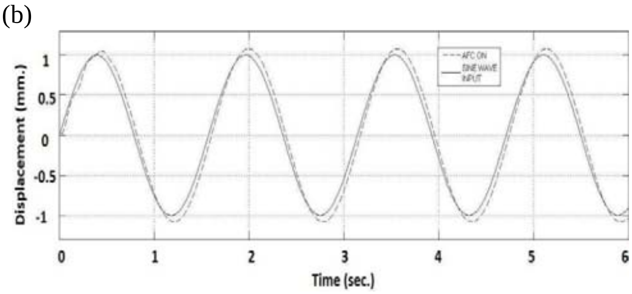


Fig. 8 Effect of harmonic disturbance on system response for PID controller only (AFCFL – OFF) for various input conditions

(a)



(b)



(c)

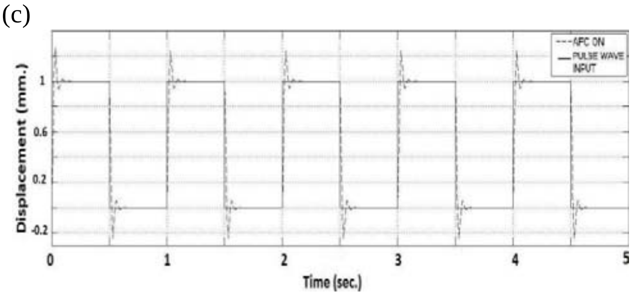


Fig. 9 Effect of harmonic disturbance on system response for PID controller only (AFCFL – ON) for various input conditions

From Fig. 8, it can be seen that the PID controller is able to perform the trajectory tracking task satisfactorily by bringing the responses to converge to the reference positions but at the expense of relatively large tracking errors with substantial ripples or oscillation, largely due to the nature of the applied disturbance (vibratory). This is in stark contrast to the results shown through the second set of graphs (Fig. 9) in which it is clearly demonstrated that the PID with intelligent AFC scheme (AFCFL – ON) manages to accurately and readily track the desired responses. This shows that the latter system is much more robust than its counterpart in compensating the harmonic disturbance at relatively high frequency. The proposed pneumatically actuated micro robot is able to operate effectively based on the closed-loop control configuration with the given loading and operating conditions.

V. CONCLUSION

In this study, a piezoelectric micro robot for in-pipe application was modelled and simulated using two feedback control techniques, i.e., PID and AFCFL schemes assigned to perform trajectory tracking task in the presence of the prescribed disturbances and interacting environments. The simulation results of the proposed schemes clearly demonstrate the effectiveness of the closed-loop control algorithms in executing the prescribed tasks with the AFC-based scheme significantly outperforms the PID counterpart. Future works may include a rigorous study on the effects of other loading and operating conditions on the system performance. The possibility of performing practical experimentation on the micro robot system should also be explored and investigated.

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