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Modelling and Control of a Worm-Like Micro Robot with Active Force Control Capability

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***Abstract*— In this paper, a pneumatic worm-like micro robot with active force control (AFC) capability is modelled and simulated in a constrained environment (pipe). A mathematical model that represents 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 proportional-integral-derivative (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 frictional forces or fluid viscosity in the pipe. The control system is tuned so that an accurate trajectory tracking is possible. The performance of the control system under different types of disturbances is evaluated through a rigorous simulation study. The obtained results clearly demonstrate an effective trajectory tracking capability of the worm-like micro robot in spite of the negative effects of the external disturbances.**

***Index Terms*—Active Force Control, Micro Robot, PID Controller, Robust Tracking, In-pipe.**

I. Introduction

Micro robotics is a field that has generated much interest amongst researchers and robot engineers alike due to its potentials operating in adverse working conditions and constrained environments. Examples can be seen in micro robots performing various tasks such as exploration and inspection in industrial pipes that can be associated with petroleum piping installations, chemical plants, heat exchangers, and gas or water supply systems; a much smaller scale robotic system may be applicable to carry out endoscopic procedure in vessels of the human body. An in-pipe inspection micro robot is useful to inspect the state and conditions of the pipe to detect leaks, cracks or modification of cross section in pipe lines. The robot is able to move effectively in the pipe and transport exteroceptive sensors that give different results such as finding or detecting the position/location and type of problem and measurements about the environment.

Some basic research on mobile micro robotic mechanisms for use in pipes have been reported, such as those that are driven by piezoelectric actuators [1, 2, 3], by giant magnetostrictive actuators [4] by pneumatic actuators [5, 6], or by electromagnetic actuators [7].

However, most of these robots are still in the developmental stage and certain problems still have to be addressed and solved before they become practical. Such micro robots for small pipes have low pulling force and have difficulty negotiating curved pipes or vertical pipes. Besides, commercial charge-coupled device (CCD) cameras are too big to mount on these robots.

Lim *et al.* invented an inchworm like micro robot by using only one pneumatic line [8]. It is based on drilling different-sized micro holes in two plates among three chambers. The rear clamp, the elongation module, and the front clamp work sequentially as the air flows to each chamber. It enables the robot not only to generate inchworm like locomotion, but also to allow significant reduction of the stiffness of pneumatic lines and the drag force due to one pneumatic line. In order to operate the robot efficiently, the stroke according to the supplied pneumatic pressure is investigated.

In another design, a pneumatic flexible robot prototype for in-pipe inspection was designed and experimented as described in [9]. A dynamic model which takes into account the flexibility, damping and friction was developed. A number of experiments were carried out in order to characterize the robot and provide the input for the numerical model. The model was validated by comparing the experimental and numerical robot gait in time domain. The robot motion for different pipes network geometry is also presented in the research. The works described above mostly focus on the principle of actuation and assume an open loop control configuration that does not include sensory feedback information and control algorithm for critical task applications.

In the proposed research, we incorporate a robust feedback control mechanism into a pneumatically actuated micro robot taking into account the robust tracking performance in a constrained environment in pipe. The strategy used is based on active force control (AFC) technique that has been successfully applied to many dynamical systems [10-13]. Pioneering AFC work applied to robotic manipulator was presented by Hewit and Burdess (1981), in which an efficient disturbance rejection technique was established to facilitate the robust motion control of the dynamical system in the presence of disturbances, parametric uncertainties and changes that are commonly prevalent in the real-world environment [10]. Mailah *et al.* investigated the usefulness of the AFC method by introducing intelligent mechanisms to approximate the mass or inertia matrix of the dynamic system to trigger the compensation effect of the controller. It was

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recognized that the AFC was robust and effective both in theory as well as in practice [12, 13]. In this research, the AFC method is extended to correct the accuracy, stroke and reach point of the micro robot, all pertaining to robust tracking performance. The micro robot shall be modelled and later simulated with the active force control mode incorporated.

II. Modeling and Simulation of Micro Robot System

A. Mechanism of Robot Movement

The proposed study considers that the robot is specifically intended for in-pipe application and that it produces a worm-like locomotion. The gait cycle consists of five phases illustrated by schematic drawings in Fig. 1 [8].

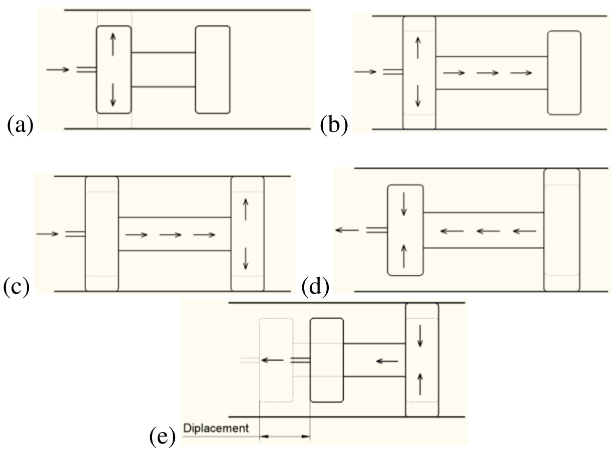


Figure 1: Mechanism of micro robot movement, (a) First part: The rear bladder expands and pushes onto the inner pipe wall, holding the robot fixed (b) Second part: The robot body stretches (c) Third part: The front bladder expands (d) Fourth part: The rear bladder deflates (e) Fifth part: The robot body deflates executing the net gait

B. Mathematical Formulation

For the given dynamic system comprising a series of air chambers and bladders in a cylindrical space (inside pipe) with control volumes (CV_1 and CV_2) as shown in Fig. 2, the pneumatic resistance is given as:

$$P_1 - P_2 = R\dot{m} \rightarrow \dot{m} = \frac{P_1 - P_2}{R} \quad (1)$$

Where, R is defined in terms of the mass rate of flow, P_1 is the input pressure, P_2 is the output pressure, and $\dot{m}$ is the mass flow rate of the fluid. The differential mass flow rate in terms of the pneumatic capacitances (C_1 and C_2) can be expressed as:

$$\dot{m}_1 - \dot{m}_2 = (C_1 + C_2)\frac{\mathrm{d}p_2}{\mathrm{dt}} \quad (2)$$

Where,

$$C_1 = \frac{\rho A^2}{K_3}, C_2 = \frac{\mathrm{Ax}}{\mathrm{RT}} \quad (3)$$

and

$$\dot{m} = \dot{m}_1$$

By inserting Eq. (1) into Eq. (2), we have:

$$\frac{P_1 - P_2}{R_1} - \dot{m}_2 = (C_1 + C_2)\frac{\mathrm{d}p_2}{\mathrm{dt}} \quad (4)$$

Using Eq. (1), the following expression can be written as:

$$\dot{m}_2 = \frac{P_2 - P_3}{R_2} \quad (5)$$

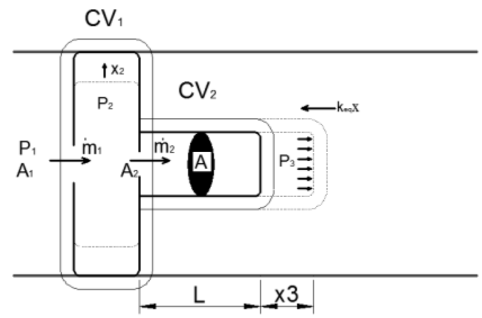


Figure 2: Free body diagram related to CV_1 and CV_2

Eq. (3) can also be expressed as:

$$\frac{P_1 - P_2}{R_1} - \frac{P_2 - P_3}{R_2} = (C_1 + C_2)\frac{\mathrm{d}p_2}{\mathrm{dt}} \quad (6)$$

Similar to CV_1 and referring to Fig. 3, the expressions for CV_2 and CV_3 are given as follows:

$$\frac{P_2 - P_3}{R_2} - \frac{P_3 - P_4}{R_3} = (C_1' + C_2')\frac{\mathrm{d}p_3}{\mathrm{dt}} \quad (7)$$

$$\frac{P_3 - P_4}{R_3} = (C_1'' + C_2'')\frac{\mathrm{d}\rho_4}{\mathrm{dt}} \quad (8)$$

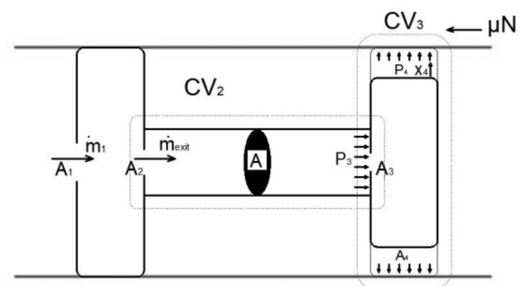


Figure 3: Free body diagram related to CV_2 and CV_3

By using Eq. (5), P_2 can be written as:

$$P_2 = \frac{1}{R_1 - R_2}\left[R_1 R_2 (C_1 + C_2)\frac{\mathrm{d}\rho_2}{\mathrm{dt}} - R_2 P_1 + R_1 P_3\right] \quad (9)$$

From Eq. (8), P_4 can be determined as:

$$P_4 = P_3 - R_3(C_1'' + C_2'')\frac{\mathrm{d}\rho_4}{\mathrm{dt}} \quad (10)$$

For the displacement of section, it is given as:

$$P_i A_i = K_i x_i \rightarrow \frac{\mathrm{d}p_i}{\mathrm{dt}} = \frac{K_i}{A_i}\frac{\mathrm{d}x_i}{\mathrm{dt}} \quad , \mathrm{i} = 2,3,4 \quad (11)$$

Substituting Eqs. (8) and (9) into Eq. (6), we have:

$$\frac{R_3}{R_1 - R_2}\left[R_1 R_2 (C_1 + C_2)\frac{K_2}{A_2}\frac{\mathrm{d}x_2}{\mathrm{dt}} - R_2 P_1 + R_1 P_3\right] + R_2\left[P_3 - R_3(C_1'' + C_2'')\frac{K_4}{A_4}\frac{\mathrm{d}x_4}{\mathrm{dt}}\right] - (R_2 + R_3)P_3 + R_2 R_3 (C_1' + C_2')\frac{K_3}{A_3}\frac{\mathrm{d}x_3}{\mathrm{dt}} = \mathrm{m}\frac{\mathrm{d}^2 x_3}{\mathrm{d}^2 t} \quad (12)$$

For the above condition, since the movement of the front and rear bladders is assumed to sufficiently quick while the displacement is relatively small enough (neglecting the friction) and that the lengths of the front and rear bladders do not change, Eq. (12) could be simplified as:

$$\frac{R_3}{R_1-R_2}\left[R_2P_1+R_1P_3\right]-R_3P_3+R_2R_3\left(\frac{\rho A^2}{K_3}+\frac{A}{RT}\right)\frac{K_3}{A_3}\frac{dx_3}{dt}= m\frac{d^2x_3}{d^2t} \qquad (13)$$

Using Laplace transformation, the transfer function based on displacement can be found as:

$$T.F.=\frac{\left(\frac{-R_2R_3}{R_1-R_2}\right)}{\left[ms^2-R_2R_3\left(\frac{\rho A^2}{K_3}+\frac{A}{RT}\right)\frac{K_3}{A_3}s-\frac{K_3}{A_3}\left(\frac{R_3R_1}{R_1-R_2}-R_3\right)\right]} \qquad (14)$$

III. Control Schemes

For testing the system effectiveness in producing and tracking the desired locomotion accurately, 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 control*

Proportional-Integral-Derivative (PID) control is the most commonly used control algorithm in industry and has been universally accepted in industrial control [14]. 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 system employing a PID controller is shown in Fig. 4.

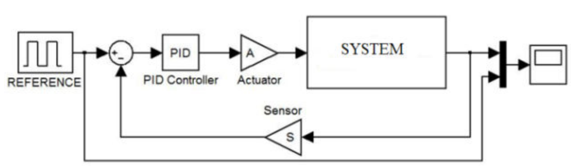
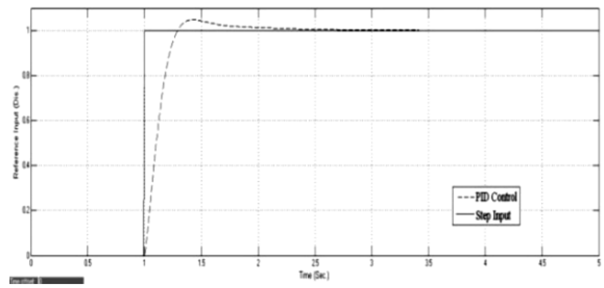


Figure 4: Schematic diagram of system

The basic idea behind a PID controller is to read a sensor, then compute the desired actuator output by calculating 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:

$$G_{PID}=K_P+\frac{K_I}{s}+K_DS \qquad (15)$$

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 were determined as $K_P=90$, $K_I=120$, $K_D=14$. The resultant tracking control based on the gains can be seen in Fig. 5 and these gains shall be used throughout the simulation study.



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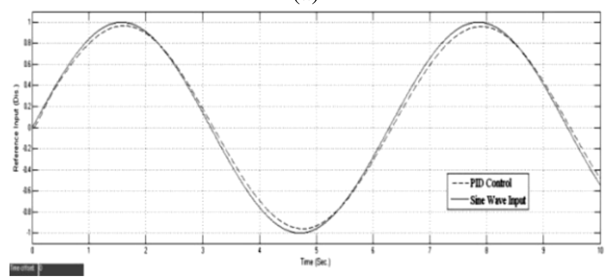

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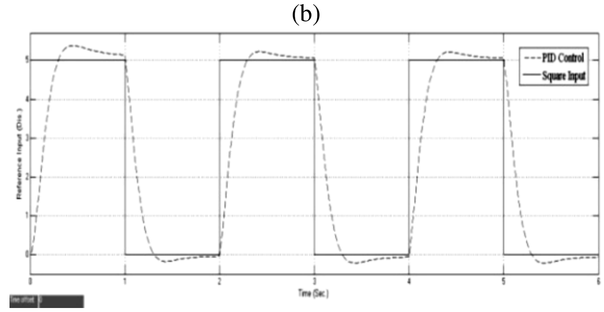

(c)

Figure 5: Performance of PID controller for (a) step, (b) sine wave and (c) square input functions

B. *Active Force Control*

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 [15, 16]. It has been demonstrated that it is possible to design a feedback controller that will ensure the system setpoint 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 [10]. 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. Mailah *et al.* extended the usefulness of the method by introducing intelligent mechanisms to approximate the mass or inertia matrix of the dynamic system to trigger the compensation effect of the controller [11, 12, 17]. 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

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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, can be found in [10]. For brevity, the underlying concept of AFC applied to a dynamic rotational system is presented with reference to Fig. 6.

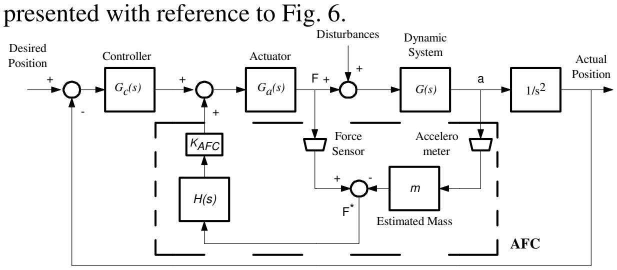


Figure 6: A schematic diagram of an AFC scheme

The notations used in Fig. 6 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:

$$F^* = F - \text{m a} \tag{16}$$

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 [11]. 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:

$$G_a(s)H(s) = 1 \tag{2}$$

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 that maybe represented by Eq (15). 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 feedforward loop. Mailah *et al.* [18], Mailah [11] and Pitowarno *et al.* [19] have demonstrated the effectiveness of the AFC scheme applied to rigid robot arms. Gigih *et al.* [20] have equally shown a robust intelligent AFC method that is capable of controlling a vehicle suspension system and effectively suppressing the introduced disturbances.

A useful point to note is that, the constant K_{AFC} in Fig. 6 can effectively serve as a mode switch between the PID only scheme (AFC – OFF) or PID plus AFC method (AFC – 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.

IV. Simulation Results and Discussion

For the proposed simulation study of the system, MATLAB and Simulink was used. The parameters of micro robot are shown in Table I.

Table I: Parameters of micro robot

Parameter	Value	Parameter	Value
R_1	0.9	ρ	$1000\ \frac{\text{kg}}{\text{m}^3}$
R_2	0.45	A	$0.0675 \times 10^{-2}\ \text{m}^2$
R_3	0.2	T	300° K
K_3	$0.1\ ^{\text{N}}/_{\text{mm}}$	R	$8\ \frac{\text{pa m}^3}{°\text{K}}$
A_3	$0.04 \times 10^{-2}\ \text{m}^2$	m	0.15 kg

The applied disturbance considered in the study is a harmonic force that emulates a constant vibratory excitation with a magnitude of 40 N and frequency, 10 rad/s, i.e., according to the following function, 40 sin 10t as shown in Fig. 7. The disturbance shall act as a test for the robustness of the system performance via observation of the response obtained.

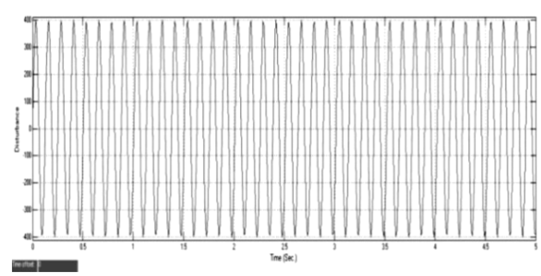
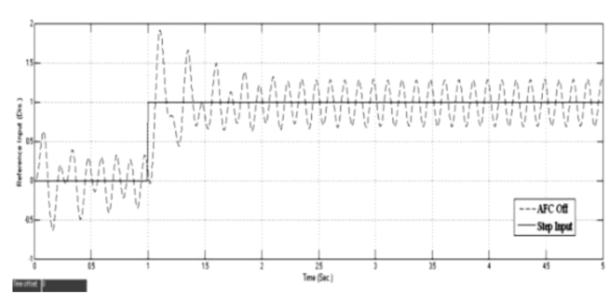


Figure 7: The applied harmonic disturbance considered in the study

For simulating the proposed control schemes, i.e., PID and PID plus AFC, 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.



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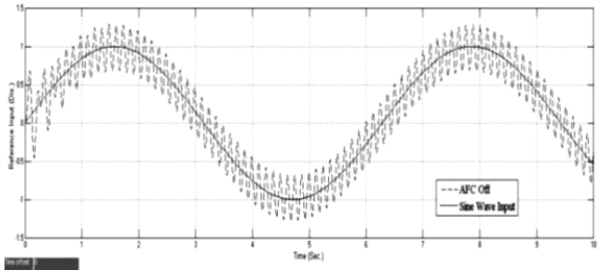

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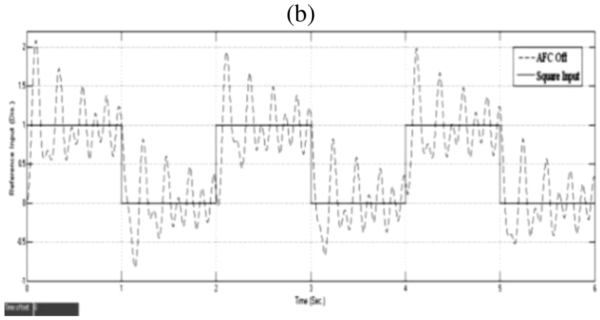
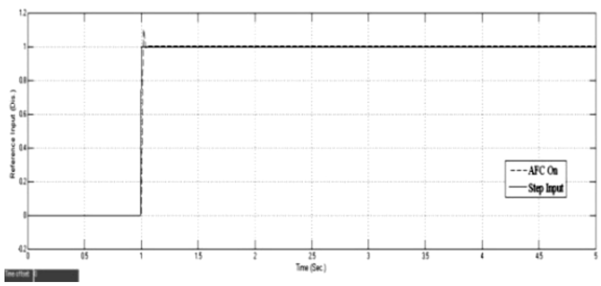


(c)

Figure 8: Effect of harmonic disturbance on system response for PID controller only (AFC – OFF) for various input conditions



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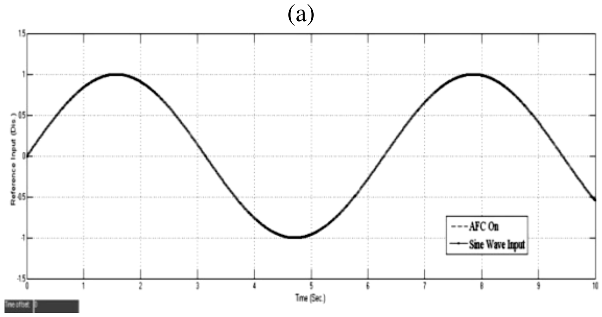

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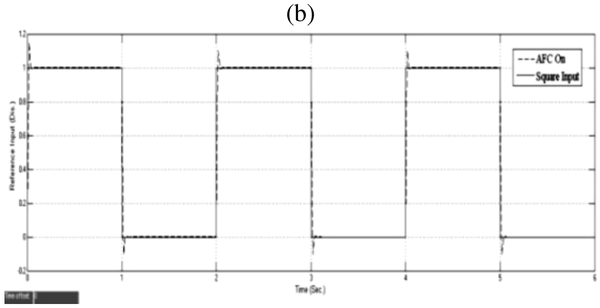

(c)

Figure 9: Effect of harmonic force on the performance of PID plus AFC scheme (AFC – 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 AFC scheme (AFC – 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 pneumatic worm-like micro robot was modelled and simulated. A hybrid control strategy including the PID incorporated with the AFC was employed to ensure an accurate and robust trajectory tracking of the robot system under the presence of the prescribed disturbances and operating environment. The PID controller was initially tuned using the typical *Ziegler-Nichols* method so as to achieve satisfactory performance. The simulation results of the proposed schemes clearly demonstrated the effectiveness of the closed-loop control algorithms, particularly the PID with AFC method (AFC – ON). Future works may include the rigorous study on sensitivity analysis related to the effects of other loading and operating conditions. The possibility of performing practical experimentation on the micro robot system should also be explored and investigated.

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