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REAL-TIME IMPLEMENTATION OF FEED RATE ACTIVE FORCE CONTROL OF A SYRINGE FLUID DISPENSER

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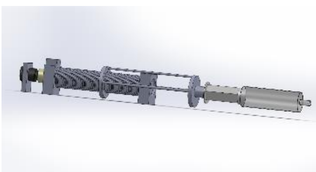
Graphical abstract



Abstract

For precise application, it is imperative to provide accurate and stable performance. The feed flow rate of a syringe fluid dispensing system is regulated through a Proportional-Integral-Derivative (PID) and Active Force Control (AFC) control scheme that was actuated using a DC servo motor considering a real-time implementation. The focus of this study is to control the speed of a DC motor by implementing an AFC strategy in rejecting the disturbance in the system. The AFC is implemented by cascading its control loop with the outer PID controller loop to form a two degree-of-freedom (DOF) controller. The performance of the proposed PID with AFC control scheme was investigated considering both the theoretical simulation and experimental works. The simulation was performed in MATLAB/Simulink computing platform while the real-time experimentation was done by utilising the *Arduino MEGA 2560* microcontroller with MATLAB/Simulink driver for the data acquisition, interface and control implementation. The results implies the robustness of the AFC-based system in controlling the feed flow rate of the fluid in the dispenser. The best performance is obtained for 100% AFC with the disturbance due to vibration almost completely compensated via the proposed scheme in comparison to the PID counterpart.

Keywords: Proportional-integral-derivative control, active force control, real-time implementation, DC motor, ball screw mechanism, syringe fluid dispenser

Abstrak

Bagi aplikasi yang memerlukan kejituan tinggi, adalah penting untuk memastikan prestasi adalah tepat dan stabil. Kadar alir suapan bagi satu sistem penyaluran bendalir picagari dikawal melalui penggunaan skema kawalan berkadaran-kamiran-terbitan (PID) dan kawalan daya aktif (AFC) yang digerakkan melalui satu motor servo DC dengan mengambil kira pelaksanaan dalam masa-sebenar. Fokus kajian ialah untuk mengawal kelajuan motor DC dengan melaksanakan strategi AFC bagi menghapuskan gangguan di dalam sistem. AFC terlaksana dengan menghubungkan gelungnya secara siri dengan pengawal gelung luar PID bagi membentuk satu sistem pengawal dua-darjah kebebasan (DOF). Prestasi pengawal PID bersama skema AFC yang dicadangkan telah dibuat kajiselidik dengan mengambil kira kedua-dua tugas simulasi dan juga eksperimen. Simulasi dijalankan menggunakan platform komputeran MATLAB/Simulink manakala pelaksanaan eksperimen dibuat menggunakan pengawal mikro *Arduino MEGA 2560* beserta perisian MATLAB/Simulink untuk tujuan perlaksanaan perolehan data, antaramuka dan kawalan. Hasil keputusan penyelidikan menunjukkan bahawa sistem berasaskan AFC memberikan prestasi terbaik dalam mengawal kadar alir bendalir di dalam penyalur. Prestasi terbaik adalah bagi keadaan 100% AFC dengan hampir keseluruhan gangguan akibat daripada kesan getaran dapat dipampas oleh kaedah saranan berbanding dengan PID.

Kata kunci: Kawalan berkadaran-kamiran-terbitan, kawalan daya aktif, pelaksanaan masa-sebenar; motor DC, mekanisme skru-bebola, penyalur bendalir picagari.

1.0 INTRODUCTION

Feed rate control is a powerful tool used in various fields which includes food industry, chemical industry, cosmetics, drug delivery and oil extraction. Syringe pump is popular to be used as a tool for providing the feed rate control. However, syringe pump is known to cause fluctuations in the flow rate [1]. This is due to the mechanical oscillations within the syringe pumps [2]. Therefore, this present study attempts to control the feed flow rate of a syringe fluid dispenser by utilizing a DC motor as the main actuator combined with control methods and appropriate feed drive employing a ball screw mechanism.

Robust and precise performance of a DC motor is crucial as it involves the capacity of rejecting disturbances in the system as it operates. A DC motor applying a PID control method is normally sufficient in providing excellent performance in the absence of disturbances [3]. However, once these conditions prevail, the performance of the PID controller significantly degrades. Hence, classical control method is not sufficient to provide robust performance.

A number of researches was done to improve the performance of the classical control method. These are done by using adaptive control [4-6] and intelligent features such as fuzzy logic based control [7-9], neural-network based control [10-12] and evolutionary control [13-15] techniques. These control methods improved the stability of the system, but they typically involved complex mathematical models, algorithms and assumptions which makes it largely limited to theoretical and simulation study only [4]. Furthermore, due to its complexity in numerical computation that in turn causes delay, these control methods could not be implemented in real-time.

Another hybrid control method is proposed in this paper to control the feed rate of a syringe fluid dispenser by controlling the speed of a DC motor through the PID plus AFC control strategy [16, 17]. This paper aims to show that the control method was successfully applied to reject disturbances applied to the system in a real- time implementation. This paper starts with a description of the AFC strategy followed by the mathematical model of the syringe fluid dispensing system. Simulation study was done to model the syringe fluid dispensing system as well as to compare the performance of the conventional control and AFC methods. Experimentation was done to determine the performance of the AFC strategy as well as to compare with the performance obtained through the simulation study. An analysis and discussions of the results were presented next and conclusion as well as suggestions for further study were given from the results.

2.0 METHODOLOGY

2.1 Modelling of the Syringe Fluid Dispenser

A ball screw consists of a nut, screw and balls which converts rotational motion into linear motion. The equation of motion for a ball screw is [18]:

$$T = \frac{FL}{2\pi e} \tag{1}$$

where T is the torque, F is the force, L is the pitch and e is the efficiency. The efficiency of a ball screw is typically 90% [16]. The force produced by a ball screw is then applied to push the plunger in the syringe that in turn displace the fluid which will result in a flow of liquid out of the nozzle of the syringe as illustrated in Figure 1.

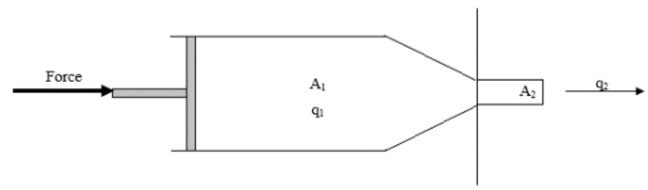


Figure 1 Syringe fluid dispenser

The *Newton's* second law of motion as well as conservation of mass was used to control the volumetric flow rate of the syringe nozzle, q_{out}. From the equilibrium of mass flow rate in and out of the system ($\dot{m}_{in}$ and $\dot{m}_{out}$) and principle of continuity, we have:

$$\dot{m}_{in} = \dot{m}_{out} \tag{2}$$

which can be equivalently expressed as:

$$q_{in} = q_{out} \tag{3}$$

where A is the cross sectional area and υ is the velocity in a pipeline. From the *Newton's* second law of motion:

$$F = \dot{m}v \tag{4}$$

or

$$F = A_1 v_1 \tag{5}$$

Integrating the above into the AFC scheme gives the model of the syringe fluid dispenser as illustrated in Figure 2.

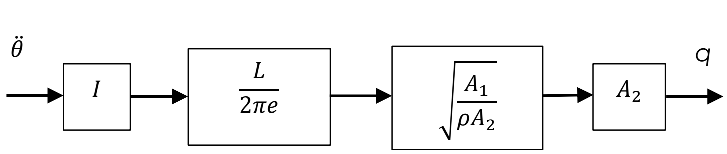


Figure 2 Block diagram of the syringe fluid dispenser model

2.2 Active Force Control

The underlying concept of disturbance rejection control was first conceived by *Johnson* (1971) followed by *Davidson* (1976) [16]. The main aim of its implementation is to secure the system's stability and robustness in the presence of known and unknown disturbances. Through the pioneering works of *Hewit* and *Burdess* (1981) and other researchers, active force control (AFC) has been proven to be simple, robust and effective compared to conventional methods in controlling dynamical systems, both in theory and practice [18-20]. Figure 3 illustrates a block diagram of an AFC scheme in which the AFC loop is serially combined with the PID counterpart. In other words, the AFC-based scheme is in fact constitutes the PID plus AFC control algorithms. The classic PID is based on the following equation:

$$\text{PID}(s) = K_p + \frac{K_i}{s} + K_d s \tag{6}$$

where K_p, K_i and K_d are the proportional, integral and derivative gains, respectively.

The principle of AFC is derived from *Newton's* second law of motion for a rotating mass, we have:

$$\sum \tau = I\ddot{\theta} \tag{7}$$

where τ is the sum of all torques acting on the body, I is the mass moment of inertia of the rigid body and $\ddot{\theta}$ is the angular acceleration of the body in the direction of the applied torque. The equation governing the applied AFC method is:

$$\tau + \tau_d = I\ddot{\theta} \tag{8}$$

The estimated disturbance torque could therefore be obtained through the estimation of the disturbance torque, $\tau_d{}^*$ and is expressed as:

$$\tau_d{}^* = I'\ddot{\theta} - \tau' \tag{9}$$

Through the manipulation of the selected parameter, AFC is able to reject the known and unknown disturbances applied to the system.

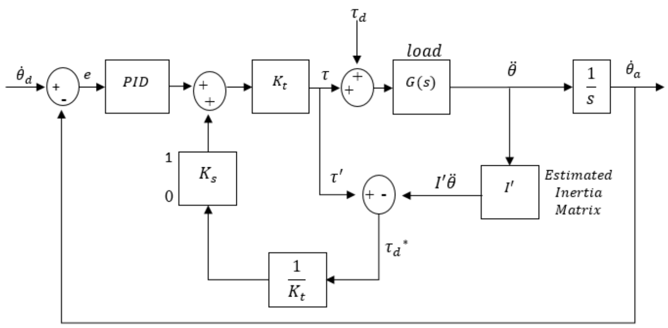


Figure 3 Block diagram of the AFC scheme

The notations used in Figure 3 are as follows:

- K_t : motor torque constant
- K_s : AFC switch
- $\dot{\theta}_d$: reference speed
- $\dot{\theta}_a$: actual speed
- I' : estimated inertia matrix
- $\tau_d{}^*$: estimated disturbance torque
- τ : applied control torque
- τ_d : disturbance torque

Note that K_s is the AFC switch; when K_s = 0, it implies only PID control and when K_s = 1, then it is PID plus AFC control in operation or just simply, an AFC control scheme.

2.3 Simulation and Experimentation

A simulation study of the system was performed based on MATLAB/Simulink computing platform. Figure 4 shows a Simulink block diagram of the scheme. Note that for AFC scheme, the changes in the inertia matrix and introduced disturbance and AFC percentage were particularly experimented both in simulation and experiment to demonstrate the effectiveness and robustness of the proposed method.

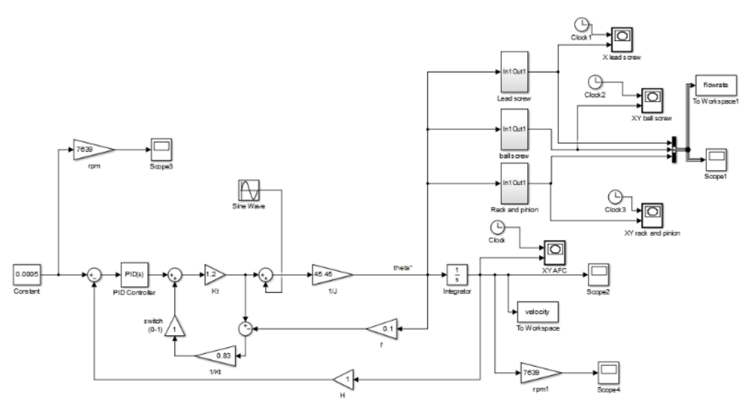


Figure 4 Simulink block diagram of the proposed control scheme

An experimental setup was designed and developed, the complete rig of which is shown in Figure 5. Note that one end of the syringe is attached to the ball screw and the ball screw is in turn fixed to a DC servo motor through a computer control interface that embeds the PID and AFC control algorithms. The computation of the controller parameters for both simulation and experimental works are assumed to be heuristically and appropriately tuned via a one-value-at-a-time (OVAT) method.

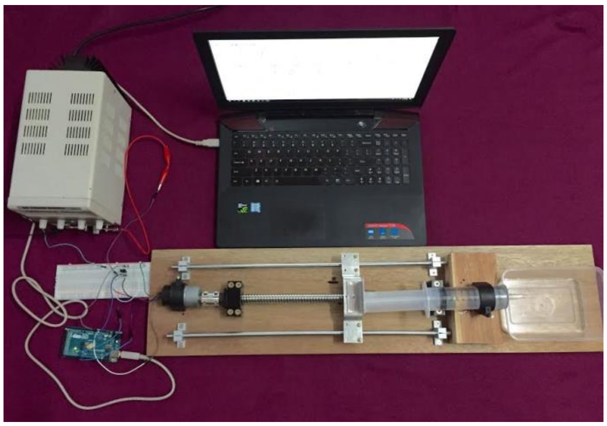


Figure 5 A view of the experimental rig

The schematic of the practical system in MATLAB/Simulink configuration is shown in Figure 6. The experimental model is designed and developed to complement the simulation counterpart by replacing the virtual sensors/actuators in the simulation with the real input/output hardware corresponding to the sensors/actuators and physical connections through the use of a microcontroller (*Arduino MEGA 2560*) for the experimental section.

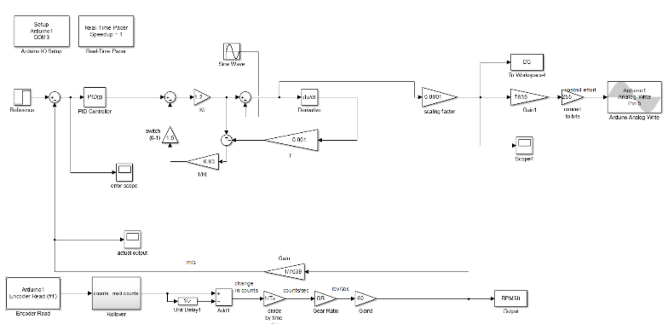


Figure 6 A schematic of the practical control scheme

3.0 RESULTS AND DISCUSSION

The syringe fluid dispenser system is validated by comparing the simulated and experimented flow rates of the dispenser with the study done by Mohammad and co-workers [21]. The flow rate of the bore fluid in the spinneret for the production of Hollow Fibre Membrane (HFM) is computed to be in the range between 0.7 to 1.6 cm^3min^{-1}. Both the simulation and experimental works are executed by controlling the speed of the DC motor by using the PID and AFC controllers. The performance of both controllers with and without disturbances were compared and analysed. Figure 7 shows the simulation results of the PID and AFC control without the presence of any known disturbances.

Both simulation results show great performance obtained by the PID and AFC controllers. The estimated inertia was varied in the AFC scheme to show the effect of varying the estimated inertia. The best performance is obviously occurring at 0.01 kgm^2 with the largest value producing the worst performance.

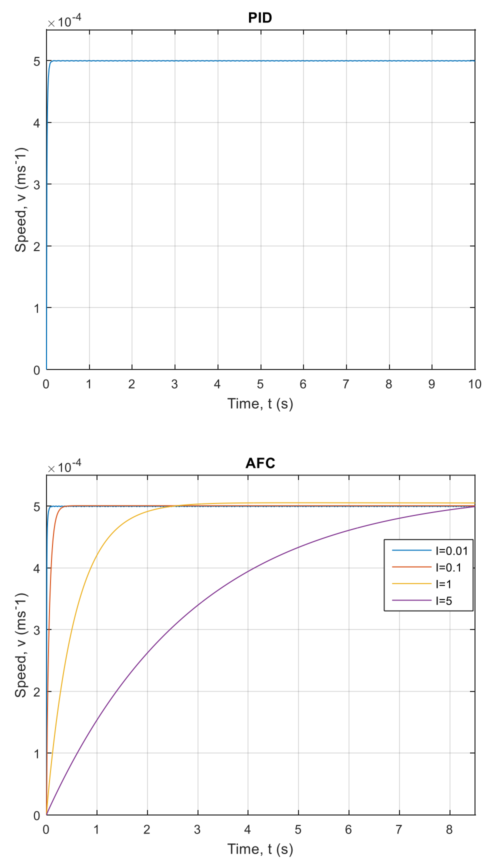


Figure 7 Simulation results of PID and AFC without disturbance

To test the robustness of both controllers, a vibration disturbance (harmonic force) at 100 Hz frequency with an amplitude of 0.0005 ms^{-1} was applied to the system. The amplitude looks seemingly small due to the fact that the system itself is relatively small and quite sensitive to disturbances. Figure 8 shows the simulation results with the presence of the known disturbance. It is evident that the PID control could not suppress the vibration with the high frequency vibration still persists between the range of about 3.7 to 6.3 x 10^{-4} ms^{-1} mark. This therefore shows that the PID control is not suitable for controlling the system with the presence of such disturbance. AFC on the other hand successfully rejects the disturbances applied to the system for all inertias. This therefore demonstrates that AFC-based scheme is a reliable and effective method compared to PID in rejecting disturbances.

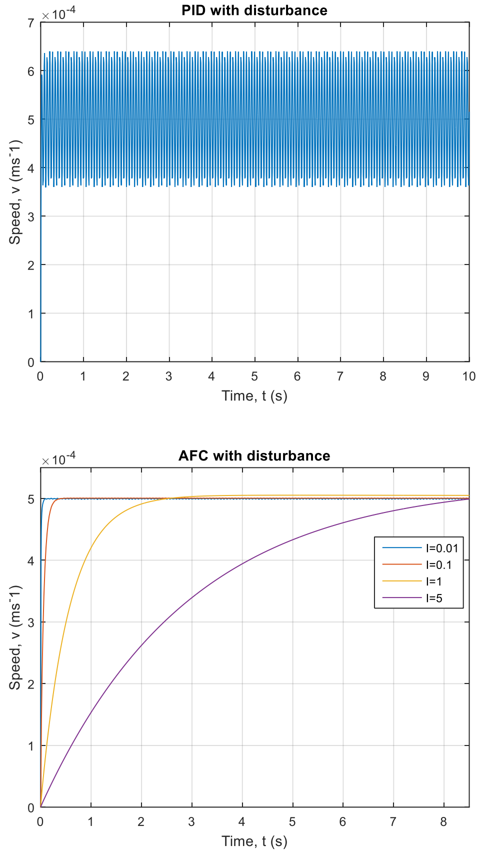


Figure 8 Simulation results of AFC and PID with harmonic disturbance

Figure 9 shows the effect of varying the AFC percentage applied to the system. The process of varying the percentage AFC is performed by varying the gain of the switch block, K_s in Figure 3. A gain of 1 implies that 100% AFC is applied to the system; a gain of 0.5 shows 50% AFC while a gain of 1.5 indicates 150% AFC. Based on Figure 9, both the 50% and150% AFC percentage conditions cause a series of undesirable high frequency ripples to the system performance while 100% AFC is deemed the most optimum condition (minimal fluctuation with hardly any ripples). The last condition (100% AFC or K_s set to 1) is later applied to the AFC-based scheme for various other operating and loading conditions.

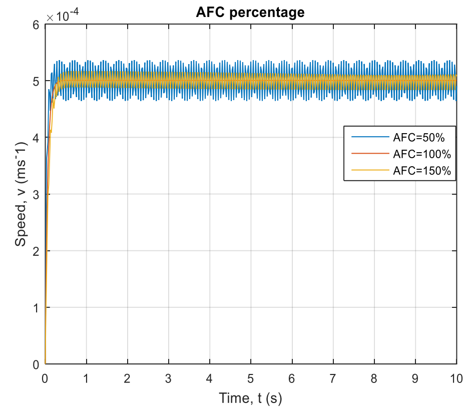


Figure 9 Effect of varying the AFC percentage

The feed flow rate of the syringe fluid dispenser determined with AFC of inertia value 0.1 kgm^2 is shown in Figure 10. It can be seen that the produced flow rate through the ball screw drive is in the range of about 0.65 to 1.4 cm^{3}min^{-1} which is within the range of the previous study of 0.7 to 1.6 cm^{3}min^{-1}.

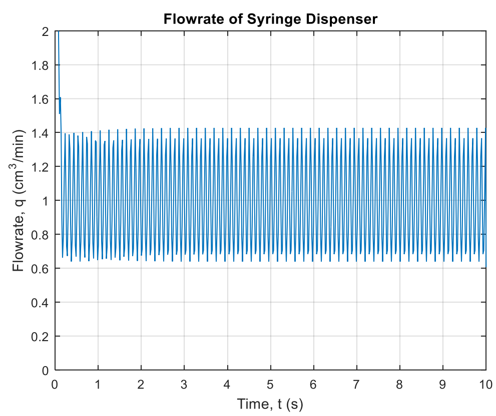


Figure 10 Flow rate of syringe fluid dispenser

Figure 11 shows the experimental results of the PID and AFC controllers without the presence of any known disturbances with particular reference to the velocities at the nozzle. Note that for the PID control, there are sharp notable spikes in the trend at 5, 6 and 8 s which may be due to the presence of the introduced disturbance or other uncertainties in the system. All the AFC schemes manage to eliminate this occurrence even at different inertia matrix setting, implying the robustness in performance. The performance improves with the decrease of the estimated inertia with a value of 0.0001 kgm^2 gives the best performance.

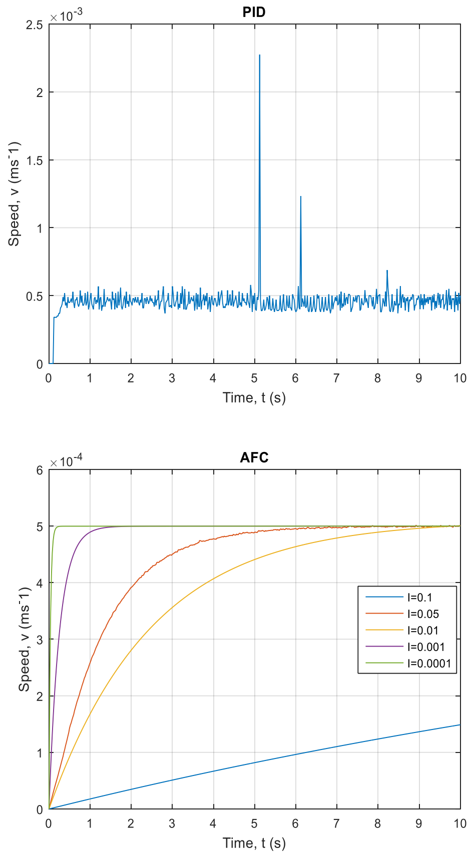


Figure 11 Experimental results of PID and AFC without disturbance

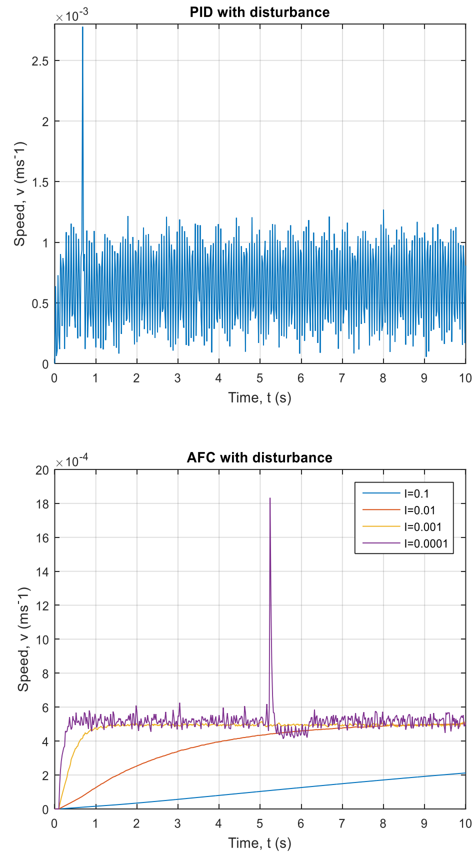


Figure 12 Experimental results of PID and AFC with disturbance

Figure 12 illustrates the experimental results of the PID and AFC controllers with the presence of known disturbance. Experimental results of the PID controller shows the presence of large high frequency fluctuations in the system. This may be directly and largely attributed to the introduced harmonic disturbance and/or some other unknown factors. Experimental results of the AFC scheme shows the ability of the AFC to significantly reject the presence of the disturbance. The best performance is observed at an inertia value of 0.01 kgm^2. Beyond this value the performance produces a series of irregular trend with undesirable spike at 5.2 s. Thus, it implies that the appropriate tuning of this inertia value is imperative to give more optimum result. Note that similar to the simulation study, the same disturbance was applied to the practical system to test the system performance in terms of robustness of the controllers. It also suggests that the trends in the experimental results conform to the simulation counterpart at the expense of larger track errors. However, this is deemed acceptable knowing the fact that the practical system is typically subjected to uncertainties and noise signals that are inherent in the physical sensors and actuators.

Experimental result of the PID control shows that the amplitude of noise is larger compared to the amplitude of noise of PID control in the simulation study. This therefore shows the ineffectiveness of PID control in the presence of disturbance as it is unable to reject disturbances applied to the system. Experimental result of the AFC control shows that the rejection capability of the AFC decreases with the value of the estimated inertia. Based on both simulation and experimental study, it shows that the decrease in estimated inertia greatly reduce the time taken for the system to reach steady state. The effect of varying the AFC percentage experimentally as shown in Figure 13. It is in good agreement with the simulation study that clearly shows that 100% AFC provides the best performance.

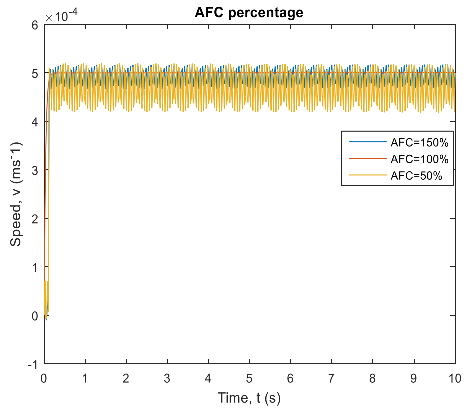


Figure 13 Effect of varying the AFC percentage

4.0 CONCLUSION

The application of AFC method to control the feed flow rate of a syringe fluid dispenser was successfully carried out, both in simulation and in real-time experimentation. It is demonstrated that AFC is efficient and has better performance in rejecting the introduced disturbance by totally suppressing the vibration compared to PID. It can also be deduced that decreasing the value of the estimated inertia to a large extent, increases the capability of the AFC scheme to reject disturbances excellently. Both results also show that a 100% AFC applied to the system gives the best performance. The simplicity of the both the PID and AFC control algorithms enable the possibility of readily implementing the control in real-time. Further research could be done to study the techniques used to adaptively tune the estimated inertia in the AFC to give the best performance for this type of application.

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