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Proportional Integral Differential (PID) Controller

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Abstract- Piezoelectric ceramics are used in many areas of applications. One of such areas of applications is in controlling electronic devices for accuracy and improved precision. Piezoelectric ceramics however have the problem of inherent high resonance frequency resulting in the piezoelectric ceramic suffering from hysteresis and delay in response to input parameters. PID controllers have been used in providing improved control and response to the piezoelectric ceramic so as to overcome the problem of hysteresis as well as the inherent high resonance frequency and slow response of the piezoelectric ceramic. However, PID controllers have the problem of overshoot as a result of sub-optimal selection of PID tuning parameters. PID controllers also take a long time in adjusting to changes due to error. This paper presents a firefly algorithm based PID controller (F-PID) for minimizing the effect of hysteresis in piezoelectric ceramics and also improving the response of the PID controller.
Key Words: Piezoelectric Ceramic, PID Controller, Firefly Algorithm, Hysteresis, F-PID

Introduction

A piezoelectric ceramic is a material that has the ability to convert mechanical energy into electrical energy and vice versa(Xu, 2015). Piezoelectricity was discovered by Jacques and Pierre Currie in 1880. The piezoelectric material generates electric charge when subjected to stress. The application of an external voltage to the piezoelectric material causes a change in shape (Swallow et al., 2008).Piezoelectric materials play an important role in numerous applications in our everyday life. Some of these applications are found in optical devices, piezo buzzers in alarm clocks, in the medical field, in precision machines and many more(Ghiasi et al, 2016). Other areas of application include (Islam & Seethaler, 2014): semiconductor technology, sensors, actuators, reduction of vibration and noise, power transducers for high-power ultrasonic applications, piezoelectric motors, and photovoltaic.

Piezoelectric ceramics the inherent problem of slow response to changes in the input parameter, be it an applied voltage or a mechanical stress. It is therefore necessary to ensure that the response of the piezoelectric ceramic is optimal or at least near optimal in order to achieve increased accuracy and precision.

PID controllers are widely used in industrial control systems and few studies have been carried out on the use of these controllers for smart control (Zheng & Jiang, 2016). PID controllers are used in controlling piezoelectric ceramics with the aim of reducing hysteresis. Hysteresis is a phenomenon where a property of an electronic component or device lags behind changes in the variable causing it (Khadraoui et al., 2012). In other words, hysteresis can be seen as a dynamic lag between an input and an output that disappears if the input is varied very slowly (Etedali et al., 2013). PID controllers however, have some limitations. Some of these limitations include (Cai et al., 2010): large delay response and overshoots.

Several works have been proposed with the aim of overcoming the limitations of the PID controller. This paper presents a firefly algorithm based PID controller for controlling piezoelectric ceramics with the aim of minimizing hysteresis in the piezoelectric ceramic device.

Similar Works

These reviews present similar works that show the extent of research work with respect to minimizing hysteresis in PID controllers so as to effectively control piezoelectric ceramics.

Khadraoui et al., (2012) proposed a H∞ (H-infinity) and μ-synthesis (micro-synthesis) approach to control micro-systems so as to ensure robust performance of the micro-systems. The controller synthesis was formulated as a set-inclusion problem. However, the H∞ produced fragile controllers, in that small perturbations of the coefficients of the designed controller caused hysteresis which led to an unstable control system. Etedali et al., (2013) carried out the development of optimal PD/PID controllers for semi-active control of isolated structures equipped with piezoelectric friction dampers. The controllers performed better than friction damper in terms of simultaneous reduction of floor acceleration as well as maximum base displacement. Xu, (2014) presented a digital sliding-mode control of piezoelectric micro-positioning system based on input-output model. The controller was established based on a linear digital input–output nominal model. Simulation results showed that the scheme was superior to the conventional PID control for motion-tracking tasks. However, the sliding mode control had the problem of high frequency vibration displacement which resulted in unstable systems. Islam & Seethaler, (2014) developed a sensorless position control technique for piezoelectric actuators using a hybrid position observer, which required neither an accurate inverse mapping nor a sophisticated charge amplifier in order to compensate for hysteresis. The use of sensorless positioning technique didn't take into account the external force that would have effect on the variables of the piezoelectric device hence it caused hysteresis in the result. Xu, (2015) designed a second-order discrete-time terminal sliding-mode control (2-DTSMC) strategy and its application to motion tracking control of a piezoelectric nano-positioning system. The issue associated with the technique was that the system state converged to equilibrium point asymptotically with an infinite settling time which resulted in instability in the system. Etedali et al., (2016) designed a decoupled PID control approach for seismic control of smart structures. The use of modal analysis didn't give real quantities for PID controllers as modal analysis included representing an n-order differential equation into 2n-first order state space form. This approach was therefore more theoretical and did not give accurate performance of a system in real time. Zheng & Jiang, (2016) presented a mutation particle swarm optimization (MPSO) PID controller. The controller was used to optimize the weighted coefficient of the Back Propagation network. The developed controller improved system dynamic performance and precision. However, the controller was unable to solve the hysteresis effect which exists in piezoelectric ceramics. Zheng et al., (2017) presented a systematic modeling and control approach for nano-manipulations of a two-dimensional piezoelectric transducer (PZT) actuated servo stage. The major control challenges associated with piezoelectric nano-manipulators typically include the nonlinear dynamics of hysteresis, model uncertainties, and various disturbances. Sun et al., (2018) proposed a piezoelectric micro-motion stage based on lever amplification mechanism. The external dimension was 57mm×57mm× 5mm. The stiffness coefficient of displacement amplification mechanism of the piezoelectric micro-motion stage was derived by using energy method. An experimental test system based on PID closed-loop control was established where an open loop hysteresis curve was obtained. Safa et al., (2019) studied an output feedback position tracking control problem relevant for a linear piezoelectric ceramic motor (LPCM). The main goals of the control design included achieving extremely high resolution, accuracy, stability, and improved transient performance when system uncertainties, unknown dynamics, and external disturbances acted on the system. Wang et al., (2019) presented a new precise positioning method for piezoelectric scanner of atomic force microscopy.

From these reviews, it is evident that extensive work has been done in addressing the problems associated with controlling piezoelectric ceramics and PID controllers as a means of addressing the response problems of piezoelectric ceramics. This paper therefore presents a firefly algorithm based PID controller for minimizing hysteresis in piezoelectric ceramics and improving the response of the PID controller. Performance evaluation will be carried out in terms of error jitter and by considering two input signals; unit step impulse and an exponential decay signal.

Firefly Algorithm

In this work, the firefly algorithm was used as an optimization tool to optimally select the best PID tuning parameters for the best control of the piezoelectric ceramic.

The Firefly Optimization Algorithm (FOA) is a meta-heuristic, nature-inspired, optimization algorithm which is based on the social (flashing) behaviour of fireflies. This flashing light can be associated with the objective function to be optimized. The firefly algorithm is based on three idealized rules which include (Yang, 2013):

1. Fireflies are attracted to each other regardless of gender.
2. The attractiveness of the fireflies is correlative with the brightness of the fireflies, thus the less attractive firefly will move forward to the more attractive firefly.
3. The brightness of fireflies is dependent on the objective function.

A summary of the firefly algorithm is presented below:

Objective function f(x), x = (x1,…, x2d)T

Generate initial population of fireflies xi (i = 1, 2, …, n)

Light intensity Ii at xi is determined by f(x)

Define light absorption coefficient,

while (t <MaxGeneration)

fori = 1 : n all n fireflies

for j = 1 : n all n fireflies (inner loop)

if (Ii <Ij), Move firefly i towards j; end if

Vary attractiveness with distance r via exp[- r]

Evaluate new solutions and update light intensity

end for j

end for i

Rank the fireflies and find the current global best g*

end while

Postprocess results and visualization

F-PID Controller

The developed F-PID controller presented in this paper is represented by the flowchart in Figure 1. The firefly algorithm was used in selecting the optimal PID tuning parameters that will result in reduced hysteresis in the piezoelectric ceramic as well as improving the response of the PID controller.

Using FOA, a population of fireflies (representing the PID tuning parameters) was initialized. The FOA was used to iteratively search among the population of fireflies for the firefly with the brightest light intensity. The firefly with the brightest light intensity represents the set of PID tuning parameters that sufficiently minimize hysteresis effect in piezoelectric ceramic devices. FOA does this search by moving from one bright firefly to a brighter firefly. This search process was repeated until the brightest firefly among the population of fireflies was achieved.

As earlier stated, performance evaluation was carried out in terms of error jitter reduction. Two input signals were used in testing the performance of the developed F-PID controller. A unit step impulse reference signal represented by Figure 2 and an exponential decay signal were used in this research work.

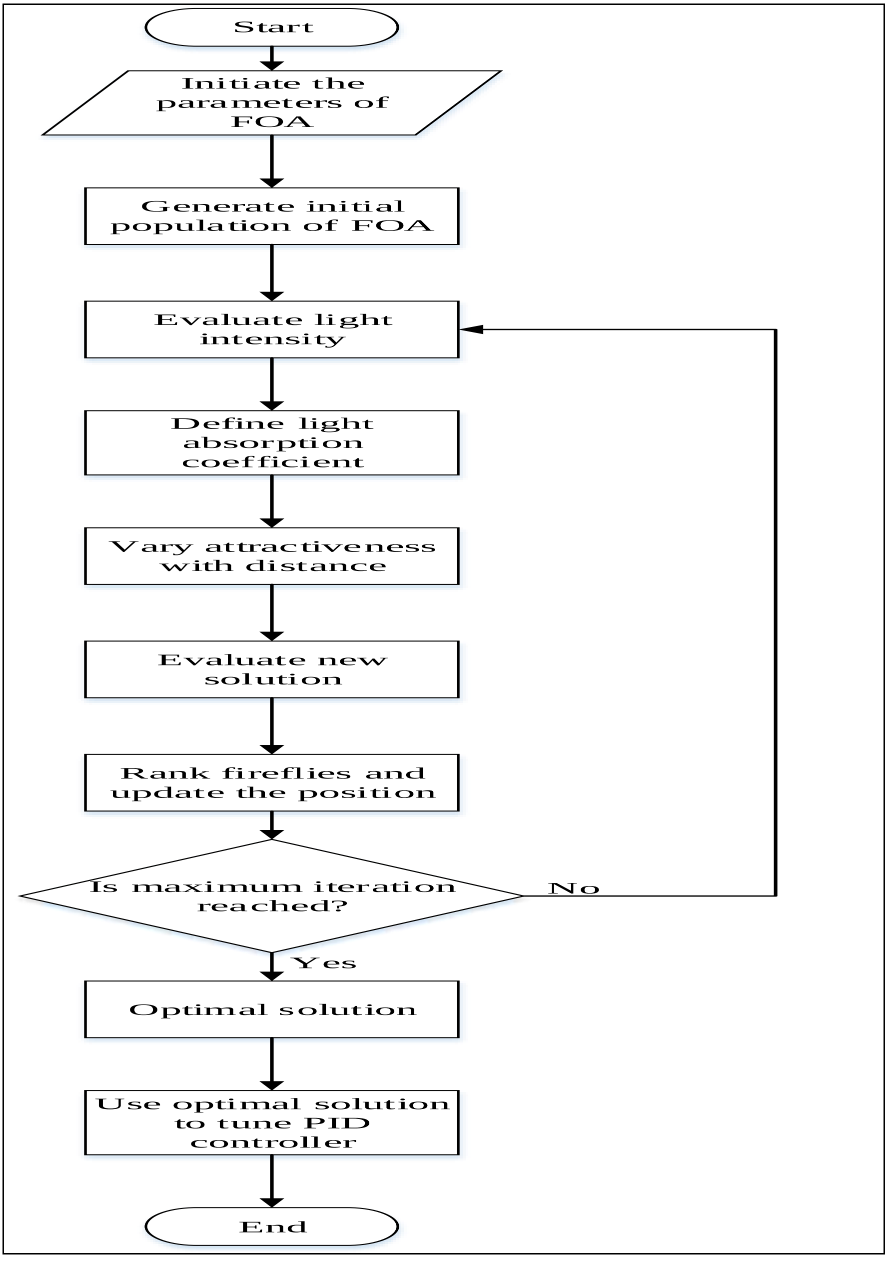

Figure 1: Flowchart of F-PID Controller

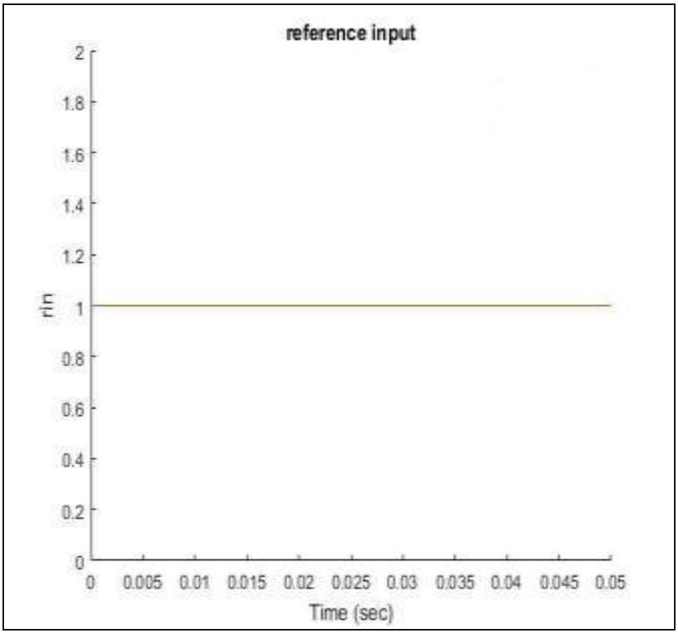

Figure 2: Unit Step Impulse reference Signal

The exponential decay signal is represented by equation (1).

$$r_{in}(k) = e^{-1.5 \times k \times ts} \times \sin(2\pi \times k \times ts) \qquad (1)$$

Results and Analysis

The results obtained for this work are in terms of error jitter and it covers the two input signals used.

Result for Unit Step Impulse

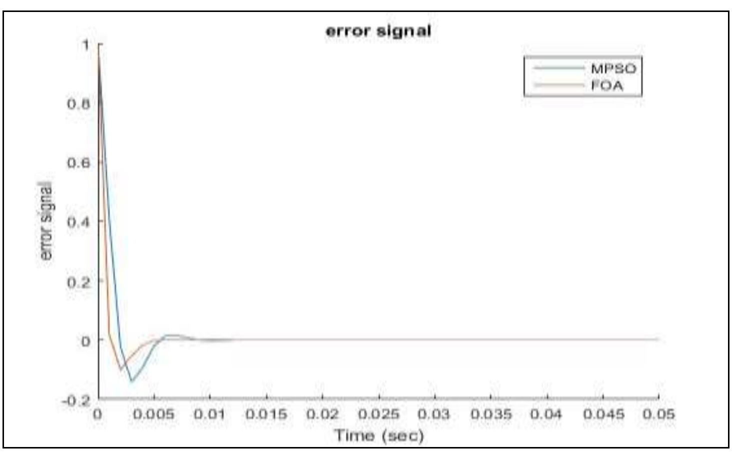

Figure 3: Error Signal Plot for Unit Step Impulse

Figure 3 shows the error plot of the system when the unit step impulse signal (from Figure 2) was applied to the piezoelectric ceramic controlled system. The desire for every system is to have an error that is equal to zero (error = 0). From Figure 3, the F-PID represented by FOA adjusted to the interference in the system faster than another PID controller that was based on MPSO. This improvement was as a result of the superior PID tuning parameters that the firefly algorithm obtained for the F-PID controller. This improvement translates to 37.5% in terms of reduction of error jitter.

Result for Exponential Decay Signal

The result for the exponential decay signal represented by equation (1) is presented in Figure 4. At time, t = 3.5s, interference was introduced into the input signal. The results obtained show how F-PID controller was able to adjust to this interference thereby keeping its error signal minimized.

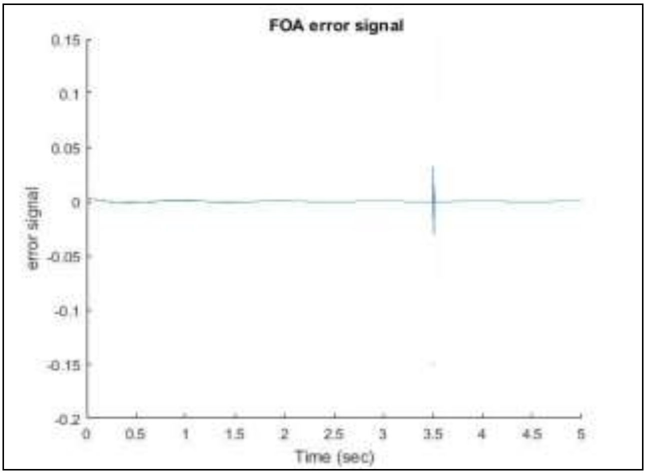

Figure 4: Error Signal Plot for Exponential Decay Signal (with F-PID Controller)

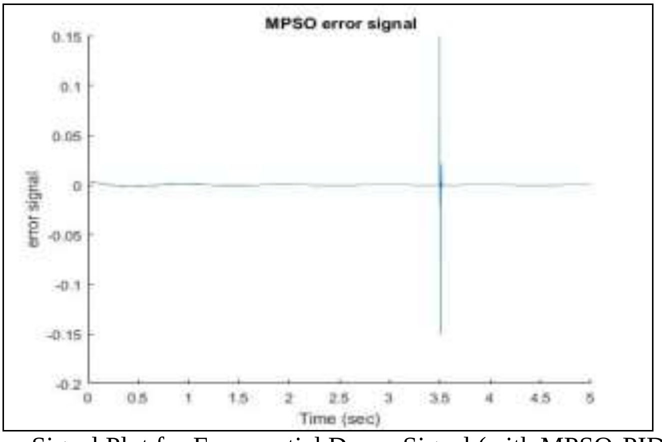

Figure 5: Error Signal Plot for Exponential Decay Signal (with MPSO-PID Controller)

From Figure 4 and Figure 5, both PID controllers have similar error plots. The error plots show that the two PID controllers were able to track and control the input reference signal (from equation (1)) by keeping the error in the system at zero (0). However, at t = 3.5s, interference was introduced into the input signal, hence the spike observed in the error signals. F-PID adjusted to the interference better than MPSO-PID. This is seen from the Figure 4 which has smaller amplitude (0.03) and Figure 5 which has a larger amplitude (0.15). This improvement translates to an improvement of 80% in terms of reduction of error jitter.

The results show how the developed F-PID controller was able to adjust to an error in the system as a result of an interference at time, t = 3.5s (for the exponential decay signal).

Conclusion

This paper presented a firefly algorithm based PID controller (F-PID) for piezoelectric ceramic control. Owing to the inherent high resonance frequency of the piezoelectric ceramic, as well as its slow response to changes in input parameters, a PID controller was used to minimize these challenges so as to mitigate hysteresis in the piezoelectric ceramic system. Firefly algorithm was employed in the PID controller to ensure optimal selection of PID tuning parameters so as to obtain efficient control of the piezoelectric ceramic system.

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