Attitude Control of Gliding Bomb using Classical PID and Modified PI-D Controllers

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***Abstract*— The importance of guided bombs in a battlefield motivates researchers to apply different control design techniques towards improving its performance and get precise target impact. Thus, this paper is devoted to compare between two configurations of PID controller for attitude control design of gliding bomb. Towards the control system design a linearized model is derived from the nonlinear equations describing the physics and performance of the intended bomb glider and then the PID controllers are synthesized with that model to justify its performance. The design parameters of the controllers are tuned using a genetic algorithm. Comparative study and analysis of results are presented for system response, disturbance rejection and noise attenuation.**

Keywords—PID controller; Modified PI-D; Genetic Algorithm; Gliding bomb; Attitude control

I. INTRODUCTION

With high speed advance of technology, smart bombs play an important role on the battlefield in performing important and critical missions[1]. Since the range of such bombs is limited, it is necessary that the launching aircraft come very close to the target. This presents high exposure of such aircraft to surface-to-air missiles and guns. To reduce this risk, it is therefore highly desirable to increase the stand-off range of the bomb ,so that such bombs can be launched a greater distance from the target.

Several attempts have been made to overcome this problem. Other systems have been developed to extend the range of certain types of bomb and to provide guidance and control. These devices are wing adaptor kits, which include folded wings and four movable fins forms cruciform or plus tail unit.

Many patents have been developed in designing this wing adaptor kit to extend range of bomb, some kits attached to the bomb are separated when bomb reaches the target[3], other not[4,5]. After combining this kit with standard, general purpose bomb such as MK 82 general purpose bomb, it transforms the ballistic chunk of iron bomb into targetable stand-off glide bomb, so creating sophisticated precision guided munition gliding bomb[2].

Six degree of freedom 6-DOF mathematical model is an approach to model gliding bombs. It is important for analyzing, measuring properties of gliding bomb control system, simulate its motion, and study the effect of disturbance and noise on the system. Linearized model is derived for simple analysis and control[6].

Nowadays control systems play important role in unmanned aerial vehicles, missiles and guided bomb gliders autopilot design. Traditional approaches like PID controllers are widely used due to its general applicability. Genetic algorithm as a tuning method is inspired in natural evolution and genetic recombination mechanisms. This technique is basically a procedure of parallel and adaptive search for complex problem solution and can be used in conjunction with intelligent techniques[8,12].

Conventional PID controller has good static performance, simple designing technique, reliability and robustness, but it has weak dynamic performance, bad function on nonlinear, time-varying and uncertain systems. Several methods are available in tuning gains of PID controller such as Ziegler-Nichols, Tyres-Luyben,… and optimization tuning techniques[7]. Generally, different methods of tuning PID controller are proposed. These tuning methods are classified into three main categories,

1) Closed loop methods*:* in which the plant operates in closed loop and PID controller parameters are tuned in automatic state, examples for this method such as Ziegler-Nichols method, Modified Ziegler-Nichols method, Tyreus-Luyben method, and damped oscillation method.

2) Open loop methods*:* in which the plant operates in open loop and PID controller parameters are tuned manually, examples for this method are Cohen-Coon method, Internal Model Control method, Fertik method and minimum error criteria methd.

3) Soft computing methods*:* in which controller parameters are tuned based on uncertainity, robustness and minimum solution cost, examples for this method are Fuzzy Logic, Genetic Algorithm, …etc.

In the following section, gliding bomb body axes is defined , nonlinear mathematical model is presented, for simplified analysis a linearized model is declared using small signal perturbation theory, transfer functions of roll angle, pitch angle and yaw angle are presented. In section III, both conventional PID and modified PI-D controller configurations are presented and gains of both controllers are tuned using genetic algorithm. In section IV, step response analysis for both controllers are presented, simulation of both systems for disturbance rejection and noise attenuation is done and actuator behavior in the presence of noise is simulated. Finally, comparative and analytical study of data are clarified in section V followed be reference section .

II. MODELING OF GLIDING BOMB

Modeling the flight dynamics consists of mission constrains, reference frame selection and derivation of governing equation of motion.

A. Coordinate system definition

Before illustrating equation of motion, body and reference frame is clarified as shown in Fig.1.

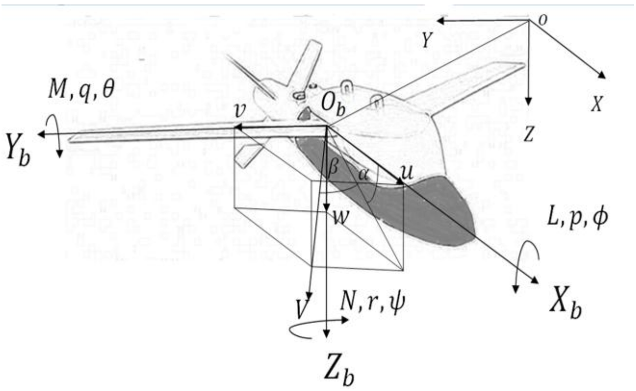

Fig. 1. Gliding bomb body coordinate system

B. Gliding bomb Equation of Motion

Towards the equations of motion, Gliding bomb is assumed to be rigid body, mass m and mass moment of inertia I_x, I_y, I_z are considered to be constant during any particular dynamic analysis and constant position of center of gravity[3], due to cruciform tail; coupling between yaw and roll can be neglected also coupling mass moment of inertia I_{xz}, I_{zx} are very small values if compared with I_z which is accepted assumption for UAVs [11].Translational and rotational motion of gliding bomb are described by the following nonlinear differential equations[1,10]:

$$\dot{u} = \frac{F_x}{m} + rv - qw \tag{1}$$

$$\dot{v} = \frac{F_y}{m} - ru + pw \tag{2}$$

$$\dot{w} = \frac{F_z}{m} + qu - pv \tag{3}$$

$$\dot{p} = \frac{1}{I_x}\left(L + \left(I_y - I_z\right)qr\right) \tag{4}$$

$$\dot{q} = \frac{1}{I_y}\left(M + (I_z - I_x)rp\right) \tag{5}$$

$$\dot{r} = \frac{1}{I_z}\left(N + \left(I_x - I_y\right)pq\right) \tag{6}$$

Where $[u \quad v \quad w]^{\mathrm{T}}$ are velocity components in body frame. $[p \quad q \quad r]^{\mathrm{T}}$ are angular velocity components in body frame. F_x, F_y, F_z are total forces acting along body axes. L, M, N are moments acting about body axes.

The kinematic equations are[6]:

$$\dot{\phi} = p + q sin\phi tan\theta + r cos\phi tan\theta \tag{7}$$

$$\dot{\theta} = q cos\phi - r sin\phi \tag{8}$$

$$\dot{\psi} = q\frac{sin\phi}{cos\theta} + r\frac{cos\phi}{cos\theta} \tag{9}$$

Where $[\phi \quad \theta \quad \psi]^{\mathrm{T}}$ are Euler angles.

Surface deflections $\delta_1, \delta_2, \delta_3, \delta_4$ as shown in Fig.2 are related to roll deflection δ_r, pitch deflection δ_p and yaw deflection δ_y deflections by the following relation[9]:

$$\begin{bmatrix}\delta_r\\ \delta_p\\ \delta_y\end{bmatrix} = \begin{bmatrix}0.25 & 0.25 & 0.25 & 0.25\\ 0.25 & -0.25 & -0.25 & 0.25\\ 0.25 & 0.25 & -0.25 & -0.25\end{bmatrix}\begin{bmatrix}\delta_1\\ \delta_2\\ \delta_3\\ \delta_4\end{bmatrix} \tag{10}$$

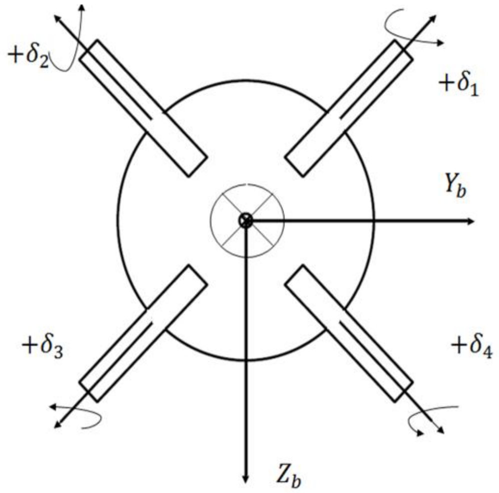

Fig. 2. Positive deflection of control fins viewed from rear

C. Gliding bomb Linearized Model

The previous differential equations are nonlinear and it’s difficult to solve these equations directly. Even if solution is available, powerful computational and mathematical tools are needed to completely solve these differential equations. To simplify this system, linearized model is obtained about an operating point using small perturbation theory[10]. In this approach, all variables are replaced by reference value plus a perturbation:

$$u = u_0 + \Delta u \qquad v = v_0 + \Delta v \qquad w = w_0 + \Delta w$$

$$p = p_0 + \Delta p \qquad q = q_0 + \Delta q \qquad r = r_0 + \Delta r$$

$$F_x = F_{x_0} + \Delta F_x \qquad F_y = F_{y_0} + \Delta F_y \qquad F_z = F_{z_0} + \Delta F_z$$

$$L = L_0 + \Delta L \qquad M = M_0 + \Delta M \qquad N = N_0 + \Delta N$$

and $v_0 = w_0 = p_0 = q_0 = r_0 = \phi_0 = \psi_0 = 0$[10].

So, the linearized equation of motion are:

$$\Delta\dot{u} = \frac{-R_x^u}{m}\Delta u - \frac{R_x^w}{m}\Delta w - g\,cos\,\theta_0\,\Delta\theta \qquad (11)$$

$$\Delta\dot{v} = \frac{R_y^v}{m}\Delta v + \left(\frac{R_y^r}{m} - u_0\right)\Delta r + g\,cos\,\theta_0\,\Delta\varphi + \frac{R_y^{\delta_y}}{m}\Delta\delta_y \quad (12)$$

$$\Delta\dot{w} = \frac{-R_z^u}{m}\Delta u - \frac{R_z^w}{m}\Delta w + \left(u_0 - \frac{R_z^q}{m}\right)\Delta q - g\,sin\,\theta_0\,\Delta\theta - \frac{R_z^{\delta_p}}{m}\Delta\delta_p \quad (13)$$

$$\Delta\dot{p} = \frac{L^p}{I_x}\Delta p + \frac{L^{\delta_r}}{I_x}\Delta\delta_r \qquad (14)$$

$$\Delta\dot{q} = \frac{M^u}{I_y}\Delta u + \frac{M^w}{I_y}\Delta w + \frac{M^q}{I_y}\Delta q + \frac{M^{\delta_p}}{I_y}\Delta\delta_p \qquad (15)$$

$$\Delta\dot{r} = \frac{N^v}{I_z}\Delta v + \frac{N^r}{I_z}\Delta r + \frac{N^{\delta_y}}{I_z}\Delta\delta_y \qquad (16)$$

$$\Delta\dot{\phi} = \Delta p \qquad (17)$$

$$\Delta\dot{\theta} = \Delta q \qquad (18)$$

$$\Delta\dot{\psi} = \Delta r \qquad (19)$$

Longitudinal and lateral stability derivatives are obtained from Missile Datcom program and tabulated in table I.

TABLE I. GLIDING BOMB STABILITY DERIVATIVES

Longitudinal derivatives	
$R_x^u = 34Kg.s^{-1}$	$R_z^u = 29.6Kg.s^{-1}$
$R_x^w = 5.87Kg.s^{-1}$	$R_z^w = -457Kg.s^{-1}$
$R_z^q = -154.6Kg.rad^{-1}$	$M^q = -67.63Kg.rad^{-1}$
$M^u = 20.2Kg.s^{-1}$	$M^w = -29.87Kg.s^{-1}$
$R_z^{\delta_p} = 13240Kg.rad^{-1}$	$M^{\delta_p} = -16412Kg.rad^{-1}$
Lateral derivatives	
$R_y^v = -28.5Kg.s^{-1}$	$N^v = 14.8Kg.s^{-1}$
$R_y^r = -163.9Kg.rad^{-1}$	$N^r = -49.8Kg.rad^{-1}$
$L^p = -168.1Kg.rad^{-1}$	$L^{\delta_r} = -1050Kg.rad^{-1}$
$R_y^{\delta_y} = 12420Kg.rad^{-1}$	$N^{\delta_y} = 1441.2Kg.rad^{-1}$

D. *Gliding bomb attitude transfer functions*

Based on linearized model, set of equations (11-19) can be decoupled into longitudinal and lateral equations of motion, and transfer functions of attitude angles are obtained in fourth order which can be simplified into short period transfer functions[10].

$$\frac{\phi(s)}{\delta_r(s)} = \frac{-256.1}{s(s+41.01)} \qquad (20)$$

$$\frac{\theta(s)}{\delta_p(s)} = \frac{-312.33\,(s+1.729)}{s(s^2+3.034s+129.3)} \qquad (21)$$

$$\frac{\psi(s)}{\delta_y(s)} = \frac{267.6(s+0.063)}{s(s^2+1.034s+61.32)} \qquad (22)$$

Servo transfer function can be displayed as follow:

$$\frac{\delta_{out}(s)}{\delta_{in}(s)} = \frac{60}{s+60} \qquad (23)$$

Where δ_{in} is command deflection from controller, δ_{out} is actuator output deflection to control fin. Servo time constant is 0.0167 seconds.

III. CONTROL DESIGN

It is interesting to note that more than half of the industrial controllers in use today are PID controllers or modified PID controllers. The usefulness of PID controls lies in their general applicability to most control systems[7]. In basic PID controller Fig.3., if the reference signal is step function, output of controller will involve impulse function due to derivative term in controller. This phenomena is called set-point kick.

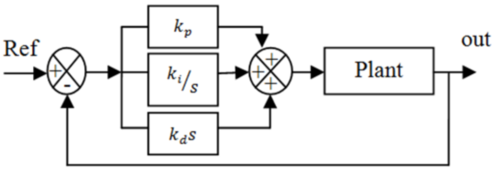

Fig. 3. Basic PID controller

Unlike basic PID, modified PI-D controller Fig.4. avoids this phenomena by applying derivative action only in feedback path[7].

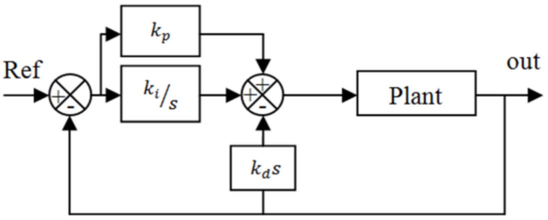

Fig. 4. Modified PI-D controller

In both previous discussed configurations, controller gains are tuned using genetic algorithm[8] which provide an adaptive searching mechanism inspired on Darwin's principle of reproduction and survival of the fittest. Basic operations of genetic algorithm are selection, reproduction, crossover and mutation. Advantages of using genetic algorithms are: it is a global search technique, can be applied to the optimization of ill-structured problems and do not require a precise mathematical formulation for the problem. In addition, genetic algorithms are robust, applicable to a number of problems and efficient, in the sense that either a suboptimal or optimal solution may be found within reasonable time[8]. In this process, the chromosome is formed by three values that correspond to three gains to be tuned to achieve desiered behaviour of :

- Overshoot < 5%
- Rise time <1 second
- Settling time <1.5 second
- Steady state error of 0

And has the property of disturbance rejection of about 90%within 1 second. The genetic algorithm has been confogured as follow:

- Population of 80
- Generations of 100
- Crossover 0.8
- Mutation 0.05

Controllers' gains are tabulated in tables II-IV.

TABLE II. PITCH CONTROLLER GAINS

Gains	PID	Modified PI-D
k_p	4.3	1.0231
k_i	0.0656	3.5740
k_d	0.4190	0.1271

TABLE III. YAW CONTROLLER GAINS

Gains	PID	Modified PI-D
k_p	8.8147	2.1709
k_i	0.0377	-0.0012
k_d	1.7424	0.0292

TABLE IV. ROLL CONTROLLER GAINS

Gains	PID	Modified PI-D
k_p	3.8090	1.0231
k_i	2.8252	3.5740
k_d	0.2947	0.1271

IV. SIMULATION RESULTS AND DATA ANALYSIS

In this section simulation results are presented. Step response of controlled attitude angles are shown in the following figures Fig.5-7.

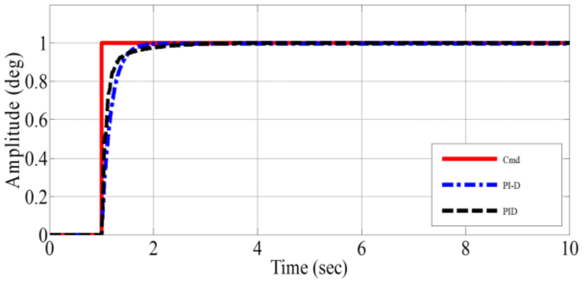

Fig. 5. Pitch angle step response

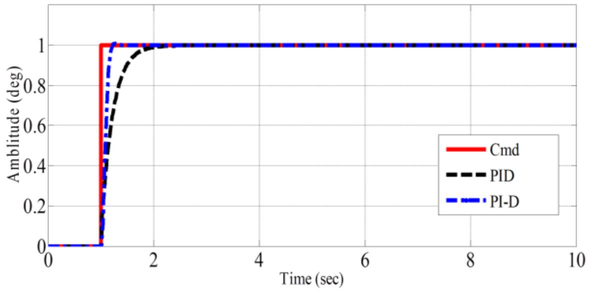

Fig. 6. yaw angle step response

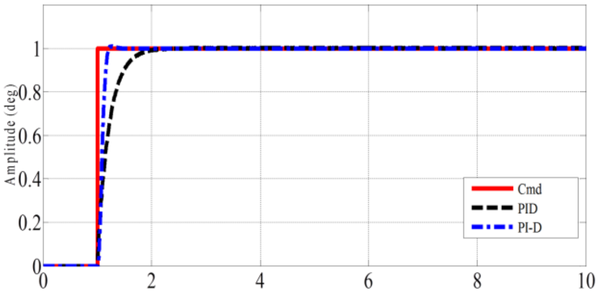

Fig. 7. Roll angle step response

Table V. illustrates time response specifications for both controllers.

TABLE V. TIME RESPONSE ANALYSIS

Table Head	Pitch		Yaw		Roll	
	PI-D	*PID*	*PI-D*	*PID*	*PI-D*	*PID*
Overshoot (%)	0	0	4.3	0	3	0
Rise time (sec)	0.18	0.0149	0.1413	0.0197	0.1127	0.4659
Settling time (sec)	0.9899	1.8222	0.9023	1.3596	0.1743	0.8259
Steady state error	0	0	0	0	0	0

From previous table it is found that both controllers give required response for system but system uses modified PI-D controller gives better response in roll and yaw loops with overshoot of 4.3% in yaw loop. But in pitch loop PID controller gives faster response but slower settling time.

To find effect of disturbance(Fig.9-11.), a pulse disturbance signal(Fig.8.) with duty cycle of 0.1 sec is applied to system output at time t=13 sec.

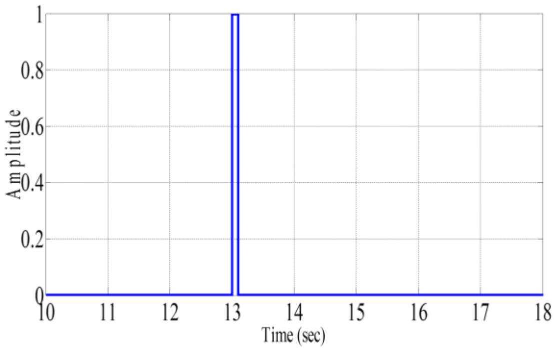

Fig. 8. Disturbance signal

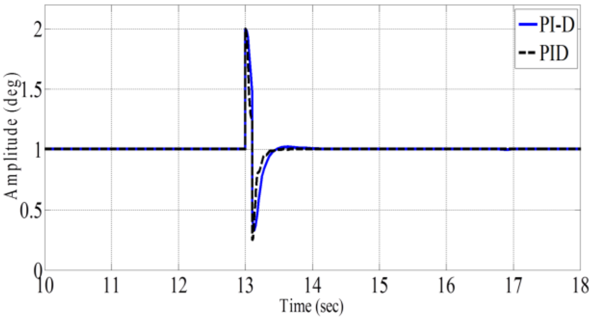

Fig. 9. Effect of disturbance on pitch

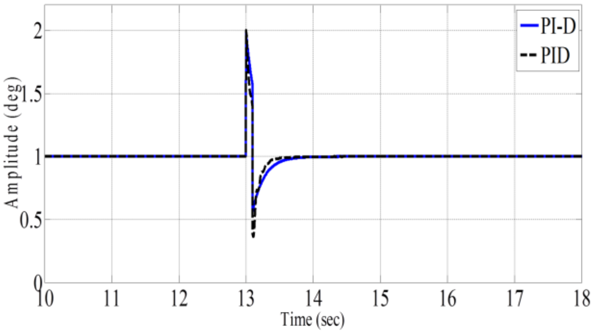

Fig. 10. Effect of disturbance on yaw

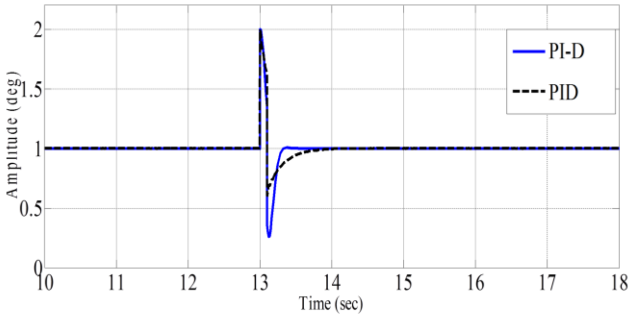

Fig. 11. Effect of disturbance on roll

From previous figures (Fig.9-11.) it is declared that system uses modified PI-D controller gives better disturbance rejection than basic one.

Also, to find the effect of noise (Fig.13-15.), a Gauss-Markov noise (Fig.12.) with specifications presented in table VI is applied to the system.

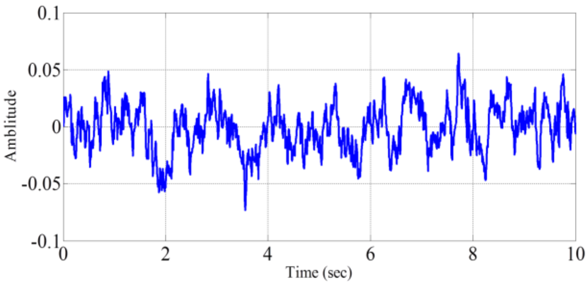

Fig. 12. Gauss-Markov noise signal

TABLE VI. GAUSS-MARKOV NOISE CHARACTERISTICS

Time constant	White-noise seed	Variance	Sample rate
0.1	[23341]	1	0.01

Actuator response due to reference signal and in presence of noise is presented in Fig.16-18.

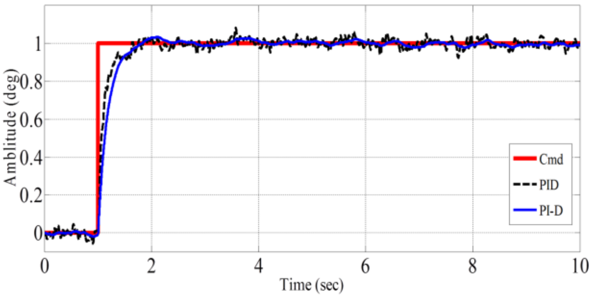

Fig. 13. Noise effect on pitch angle

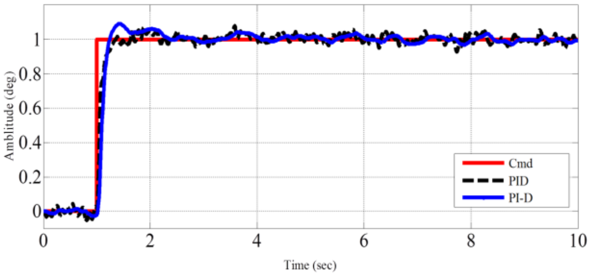

Fig. 14. Noise effect on yaw angle

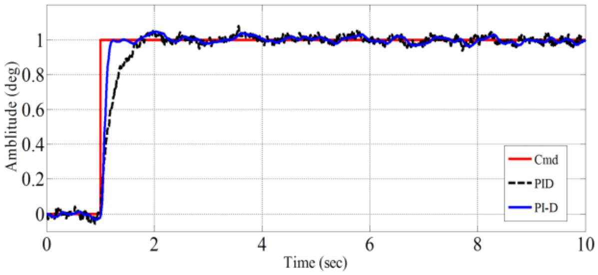

Fig. 15. Noise effect on roll angle

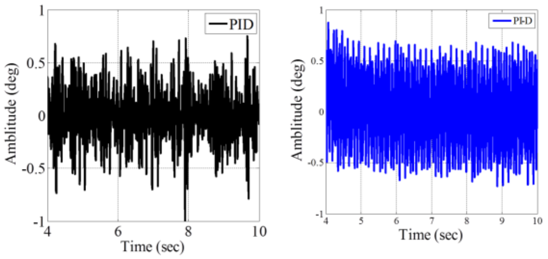

Fig. 16. Pitch actuator response in presence of noise

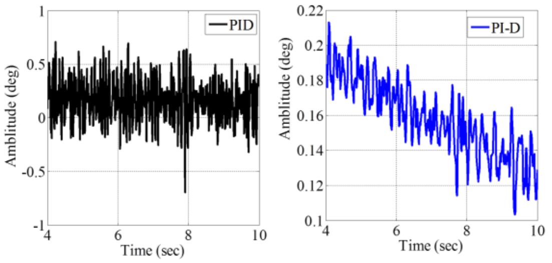

Fig. 17. Yaw actuator response in presence of noise

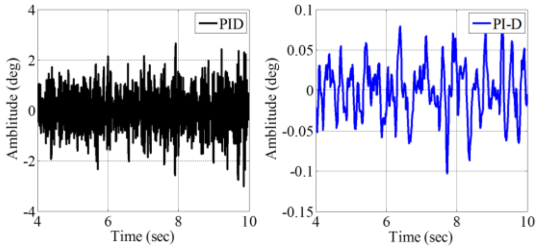

Fig. 18. Roll actuator response in presence of noise

V. CONCLUSION

This paper considered a glide bomb as a plant to be controlled using two configurations of PID controllers with genetic algorithm used to tune the controllers' gains. Software tools are used to define system parameters such as Missile Datcom for determining aerodynamic derivatives of intended bomb glider, while MATLAB and SIMULINK are used to build up nonlinear model in addition to trim and linearized models. These models are used to tune controllers gains based on genetic algorithm and analyze its performance. The comparative study between two configurations of PID controllers showed that the modified PI-D controller is better than basic one due to no kick off phenomena, better step response characteristics, better disturbance rejection and noise attenuation. In addition, actuators gave better system response when utilizing the PI-D controller in presence of noise.

The future work concerns the application of advanced/robust control techniques and its application in guidance and control of smart bombs.

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