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Optimal Control for Torpedo Motion by Using MEMS Gyroscope and PID Controller

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ABSTRACT

The torpedo is the popular weapon of submerged fighting, but a successful attack is not achieved easily. In this study, the proposed algorithm is used to optimize the mathematical model and motion control for a torpedo. The present study gives an illustration of using MATLAB, Simulink, ... to calculate the equations of motion and math functions for controlling propellers with wings, rudders as well as find the best way to achieve the desired values. To optimize the system, a Micro-Electro-Mechanical System (MEMS) Gyroscope and Proportional Integral Derivative (PID) controller are used for adjusting and simulating to verify whether the simulated result matches with the practical responses or not. The numerical results show the response of the control system and the controller performance are stable and accurate. For evaluating the response of PID controller and system more exactly, step block and sine wave block are added as input signals. A comparison of the system performance between torpedo with PID controller and torpedo without PID controller is also investigated. The numerical results show a good agreement with previous experimental observations.

KEYWORDS

Motion control, torpedo, autonomous underwater vehicle, ability judgment.

INTRODUCTION

In recent years, researches on autonomous underwater vehicles (AUVs) have been paid a lot of attention because of their potential applications such as oceanographic, industry, military purposes, etc. [1, 2]. Among the types of AUVs, the torpedo is a nonlinear motion and complicated in practical applications [3]. This characteristic would pose serious challenges to control in the first decades of the twentieth century. The torpedo actuator system executes control commands to ensure that the object sponges the reference trajectory. Vuilmet [4] introduced a solution that combines a backstepping algorithm with accelerometer feedback technology to control a torpedo, sponge a preset trajectory by the navigation system. This solution shows promising results on realistic simulations, including highly time-varying ocean currents. Although important researches have been studied on the torpedo, the motion control of torpedo is still a challenging field for scientists and engineers. The development of this torpedo can overcome the weakness of the conventional torpedo, which used compressed air or compressed oxygen as an energy source, fixed rudders, and tail wings. Additionally, these torpedoes have limitations in terms of speed and maneuverability due to the lack of a propeller and limited external control surfaces such as controllable tail wings and rudders [5]. Thus, a PID controller, controllable rudders, and tail wings have been applied to this research to increase the efficiency of the conventional torpedo such as speed, accuracy, and maneuverability.

The torpedo can operate in six degrees of freedom and the dynamics of torpedoes are subjected to a variety of disturbances such as the velocity of the outside stream, the density, and the degree of pollution of water. A kinematic and dynamic model of the torpedoes is derived for the six degrees of freedom operating range and some disturbances are neglected [6]. Various control methods have been proposed to control underwater vehicles, whether through simulation or actual experiments [7, 8]. Tanakitkorn et al. [9] investigated the depth control for an AUV that allows a smooth transition from hover-style to flight-style operation. Their experimental results showed the approach was able to enforce over a range of vehicle ballasting configurations. To verify the experimental results, the numerical solutions become a promising idea to control the torpedo's motion. It is very fascinating to analyze the motion control of the torpedo by using the PID controller, Micro-electro-mechanical systems gyroscope, and to evaluate the ability judgment. It might be a great help for the future development of AUV technology. In this study, the motion control equations are developed on as firm a theoretical basis as present knowledge permit and an explanation of the methods of analysis may be found. A PID controller is used for optimizing the system. Besides, MEMS gyroscope is used to calculate and measure translational and rotational acceleration. This paper also presents several simulations of the MEMS gyroscope and control system with a PID controller in comparison with another method to evaluate the accuracy of the designed gyroscope and the stability of the system.

METHODOLOGY

The reaction of a torpedo to external forces is expressed by the fundamental law of dynamics. In the development of the motion equations, it is necessary to make assumptions about the nature of the torpedo. In the present study, the torpedo structure, mathematical model, math functions, and equations of motion of the torpedo as well as the hydrodynamic forces and moments are described. Contra-rotating propellers used in Torpedo are to counteract the torque that tends to cause rolling (Fig. 1). Transformation, rotational angle, linear velocity, and angular velocity are controlled by using this structure combining with two rudders and two tail wings.

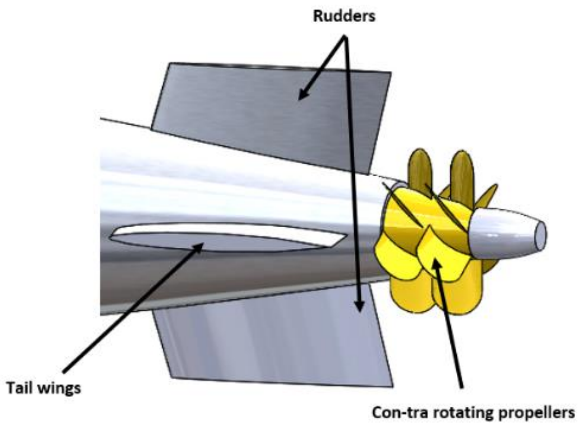


Figure 1. Propulsions, tail wings and rudder's structure.

To analyze the motion, the torpedo is described by 6-degree of freedom (DOF) which are surge, sway, heave, roll, pitch, yaw respectively. There are 3 DOF for translation and 3 DOF for rotation. To describe the motion of torpedo, two coordinates system are used: inertial coordinates (also known as earth-fix coordinates) and body-fixed coordinates. The position and orientation of the torpedo are illustrated on earth-fixed coordinates, the positive directions of these coordinates are as follows: the x-axis points toward the North, the y-axis points toward the East, and the z-axis points toward the center of the Earth. Along with the bow, starboard, and downward, respectively, are the positive directions of x, y, z-axis on these coordinates. And along the direction x-y-z, symbols X, Y, Z are three elements of the hydrodynamic force respectively and symbols K, M, N are three elements of the hydrodynamic moments (Figure 2).

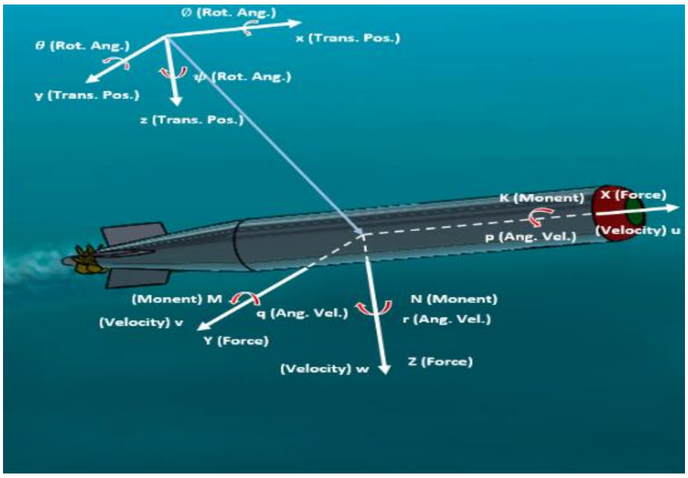


Figure 2. Torpedo structure and schematic of the Cartesian coordinate system.

12 state variables represent linear transformation, rotational angle, translational velocity, and rotational velocity. Along x, y, z axes respectively, they are as follows:

- Translational position: x, y, z
- Rotational angle: ϕ, θ, ψ
- Linear velocity: u, v, w
- Angular velocity: p, q, r

The angular velocity of the torpedo has the components p, q, r in body coordinates. It is required that the angular velocity be expressed in inertial coordinates (ϕ, θ, ψ). It is noted that $\dot{\psi}$ is the angular velocity about the z-axis, $\dot{\theta}$ is the angular velocity about the y-axis, and $\dot{\phi}$ is the angular velocity about the x-axis.

$$\omega = ip + jq + kr = i\dot{\phi} + j\dot{\theta} + k\dot{\psi} \tag{1}$$

The positions x, y, z and ϕ, θ, ψ orientation angles of torpedo are expressed by:

$$\eta = \left[\eta_1^T, \eta_2^T\right]^T \tag{2}$$

where $\eta_1=[x, y, z]^T$ and $\eta_2=[\phi, \theta, \psi]^T$. For analyzing and designing the torpedo control system, it is common to study the motion of torpedo in three separate channels, i.e. horizontal, vertical, and roll damping channel. The external force has an effect on torpedo are defined by:

$$\tau_{RB} = M_A \dot{v} + C_A(v)v + D(v)v + L(v)v + g(\eta) + \tau \tag{3}$$

where M_A, $C_A(v)$ is the inertia matrix and the centrifugal Coriolis matrix; D(v) is the matrix of hydrodynamic damping terms, g(η) is the vector of gravity and buoyant forces; L(v) is a forced matrix and rudder torque parameter; $\tau = \tau_r + \tau_f$ is the control-input vector describing the efforts acting on the torpedo include the rudder, the fins, and the propeller. The torpedo motion is given by:

$$M_{RB} \dot{v} + C_{RB}(v)v = \tau_{RB} \tag{4}$$

where M_{RB} is the matrix of inertia; C_{RB} is the matrix of centrifugal Coriolis; τ_{RB} is an external force vector that acts on the torpedo body. In the six-degree coordinate system, the torpedo motion equations are represented as follows:

$$\begin{cases} \dot{x} = u_0 \cos\psi \cos\theta + v(\cos\psi \sin\theta \sin\phi - \sin\psi \cos\phi) + w(\cos\psi \sin\theta \cos\phi + \sin\psi \sin\phi) \\ \dot{y} = u_0 \sin\psi \cos\theta + v(\sin\psi \sin\theta \sin\phi + \cos\psi \cos\phi) + w(\sin\psi \sin\theta \cos\phi - \cos\psi \sin\phi) \\ \dot{z} = -u_0 \sin\theta + v\cos\theta \sin\phi + w\cos\theta \cos\phi \\ \dot{\phi} = P + q\tan\theta \sin\phi + r\tan\theta \cos\phi \\ \dot{\theta} = q\cos\phi - r\sin\phi \\ \dot{\psi} = q\sec\theta \sin\phi + r\sec\theta \cos\phi \end{cases} \tag{5}$$

To control the torpedo object, it is important to transform the torpedo dynamics to form the MIMO nonlinear system with quadratic equation written as [10]:

$$\begin{gathered} y_1 = f_1(x) + \sum_{j=1}^{1} g_{1j}(x)u_j + d_1; y_2 = f_2(x) + \sum_{j=2}^{2} g_{2j}(x)u_j + d_2 \\ y_3 = f_3(x) + \sum_{j=3}^{3} g_{3j}(x)u_j + d_3 \end{gathered} \tag{6}$$

where u = $[u_1, u_2, u_3]^T$ are the control inputs which include the rudder angle, diving plane angle, and fin shake reduction. y = $[y_1, y_2, y_3]^T$ are the system outputs, including yaw horizontal, the depth vertical, and roll damping. d = $[d_1, d_2, d_3]$ are external disturbances, $f_k(x)$ and $g_{kj}(x)$ are smooth nonlinear functions with k = 1-3. To calculate linear transformation, rotational angle, linear velocity, and angular velocity, a MEMS gyroscope is applied to measure the translational acceleration and rotational acceleration. The MEMS gyroscope gives the rate of change of the angular position over time (angular velocity) [deg/s]. This means that we get the derivative of the angular positive over time. Then, the position and velocity need to be transformed from the measured acceleration. A is the translational acceleration and angular acceleration, V is the translational and rotational velocity matrix and η is the transformation and rotational angle matrix, the terms of velocity and position are:

$$\begin{cases} \eta = [x, y, z, \phi, \theta, \psi] \\ V = [u, v, \mathrm{w}, p, q, r] \\ V = \int A \\ \eta = \iint A \end{cases} \tag{7}$$

The power of propulsions and the angle of tail wings, as well as rudders, will be adjusted to reach the desired target in the time after V and η are determined. The variables in acceleration matrix A are defined through the output of the MEMS gyroscope. The process of motion control of torpedo is summarized in Figure 3.

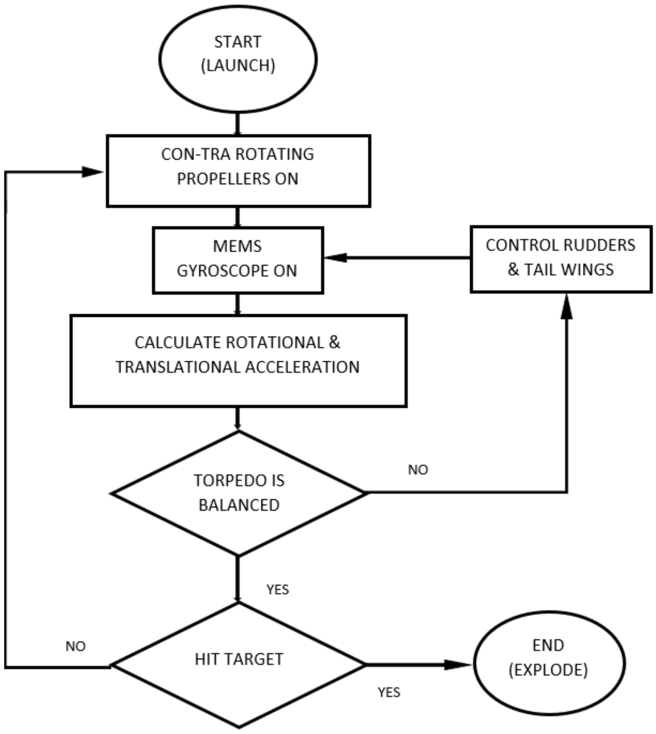


Figure 3. Process of motion control of torpedo.

The Simulink model of zero rate level gyroscope is proposed to simulate the MEMS gyroscope on MATLAB (Figure 4). The static bias, scale factor, and noise power are based on the datasheet of the L3GD20 gyroscope. To evaluate the accuracy of this model, its output with the real output gyroscope at a zero-rate level is compared.

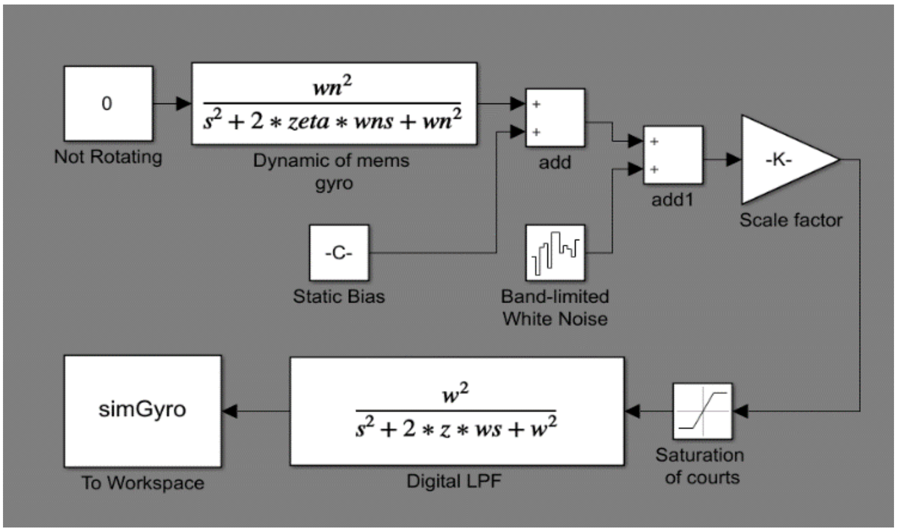


Figure 4. Gyroscope Simulink model of zero rate level.

Considering the case that torpedo has linear transformation along the x-axis, some forces apply on the torpedo head and body. In this part, the friction drag force and pressure drag force are analyzed. The friction drag force depends on the boundary layer surface shear stress, while the pressure drag force depends on the pressure difference in the flow direction. The drag force applying to the torpedo body is often written in terms of a dimensionless drag coefficient. The total drag coefficient C_d is calculated by:

$$C_d = C_{df} + C_{dp} = \frac{F_{df}}{\frac{1}{2}\rho U^2.A_f} + \frac{F_{dp}}{\frac{1}{2}\rho U^2.A_f} \tag{8}$$

where:

- C_{df} : the friction drag coefficient
- C_{dp} : the pressure drag coeffiecient
- F_{df} : the friction drag force (N)
- F_{dp} : the pressure drag force (N)
- U : the relative velocity (m/s)
- ρ : specific weight (kg/cm^3)
- A_f : frontal area (m^2)

Fig. 5 shows the profile of torpedo developed by Myring's equations is used to calculate the total drag force and transfer function [11]. Based on the design of Mark 46, Mod 5 torpedo, the geometric parameters of the torpedo are noted in Table 1.

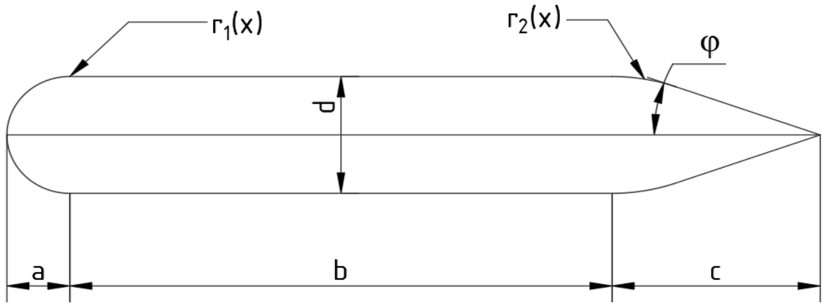


Figure 5. Torpedo shape design.

Table 1. The geometry of torpedo.

Parameters	Value
a	350 mm
b	2000 mm
c	600 mm
d	324 mm
n	2
φ	15^0

From Table 1, parameters are chosen and calculated as follow: ρ = 1031 kg/cm^3; C_D = 0.117; A_f = 2.548 m^2; m = 230 kg. As a result, the motion equation of the torpedo in this case is:

$$f(t) = 230 * \left(\frac{d^2 x}{dt^2} \right) + 154 * \left(\frac{dx}{dt} \right)^2 \tag{9}$$

The main purpose is to evaluate the response of the system and PID controller. Therefore, the equation of motion of torpedo is simplified and took the Laplace transform:

$$TF = \frac{X(s)}{F(s)} = \frac{1}{230s^2 + 154s} \tag{10}$$

The behavior of a torpedo in the water is a function not only of its hydrodynamic characteristics but also of its internal control system. The complete system must be considered before it can be decided whether a torpedo is capable of the performance that is required. The study of the complete, comprised of hydrodynamic characteristics and control system, is usually termed stability analysis. The stability and the working ability for torpedo are evaluated by using this control system with a PID controller. Because of the heavy workload of establishing continuous function correspondence, a piecewise PID algorithm is adopted to ensure accuracy. MATLAB tuning is utilized to tune the coefficient of this PID controller. The control system of the torpedo is shown in Fig. 6.

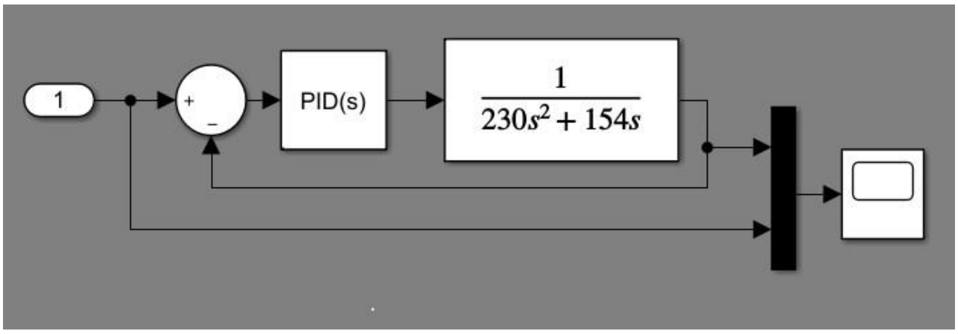


Figure 6. Closed-loop control system of torpedo.

RESULTS AND DISCUSSION

The proposed gyroscope model responding to real angular rate and simulated angular rate are shown in Figs. 7 and 8, respectively. From the two figures above, it is clear that the response of the simulated gyroscope is suitable for the response of the real gyroscope. This means the simulated gyroscope could satisfy real conditions.

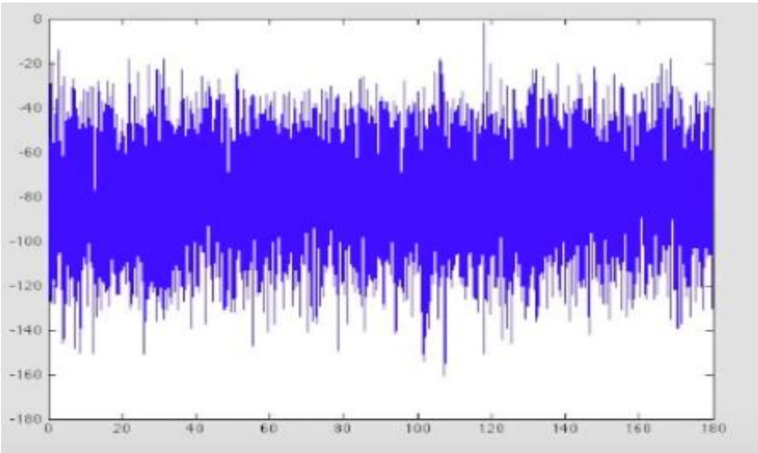


Figure 7. Real Gyroscope Data.

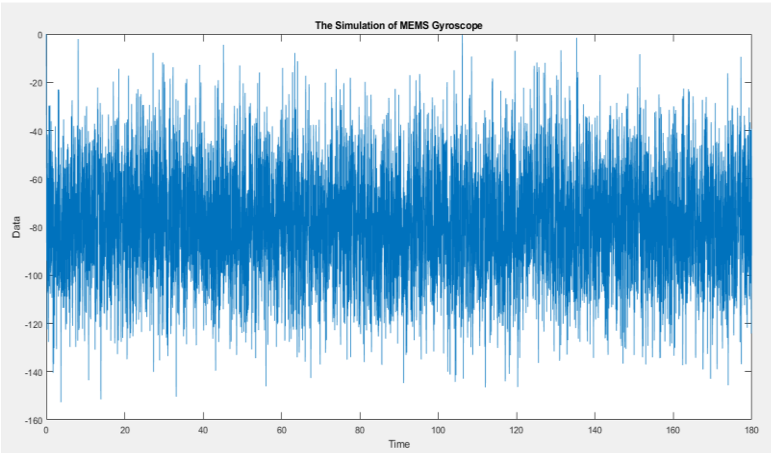


Figure 8. Simulated Gyroscope Data.

In reality, the most important requirements for torpedo are high maneuverability and accuracy. Therefore, the control system of the torpedo has to be stable and quick to reach the highest performance and accurate response. For evaluating the response of the PID controller and system, step block and sine wave block are added as input signals. The simulation results show a comparison of the control system without PID controller and with PID controller (Figs. 9-11). With the optimal response of the torpedo control system, the parameters of the PID controller were chosen based on the technological requirement which is the torpedo achieves stability as soon as possible. It can be seen that the torpedo achieves the steady-state in the first ten seconds by applying the PID algorithm. Hence, the numerical results of the response of control system in the present study show a good agreement with the previous experimental observation [8, 9]. There are oscillations in the response caused by the integrator "winding up" when there is a continual error between the desired and actual response. Reduce the limits of the integral value can reduce the oscillation but at the expense of disturbance rejection. As expected, the results show that the proposed method outperforms technical on its effectiveness and efficiency. The results of the proposed controller have strong adaptability and achieve a better control performance compared to all cases.

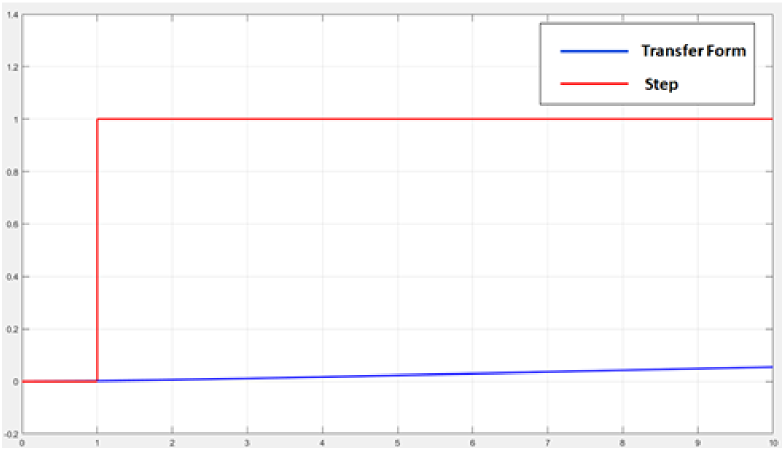


Figure 9. The response of system without PID controller for step input.

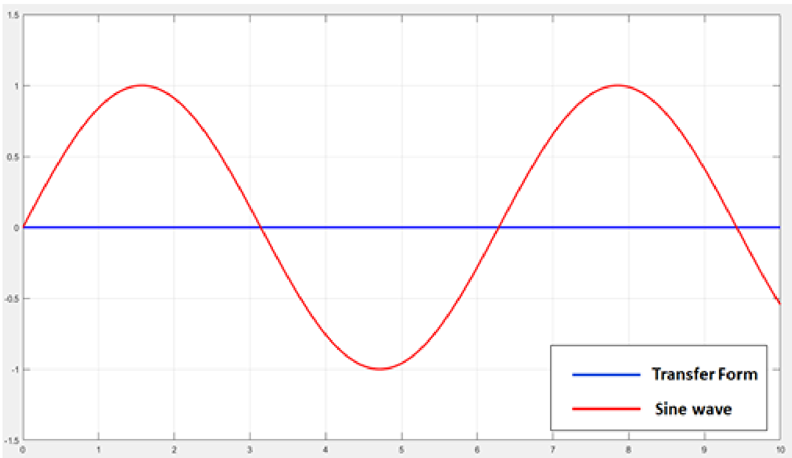
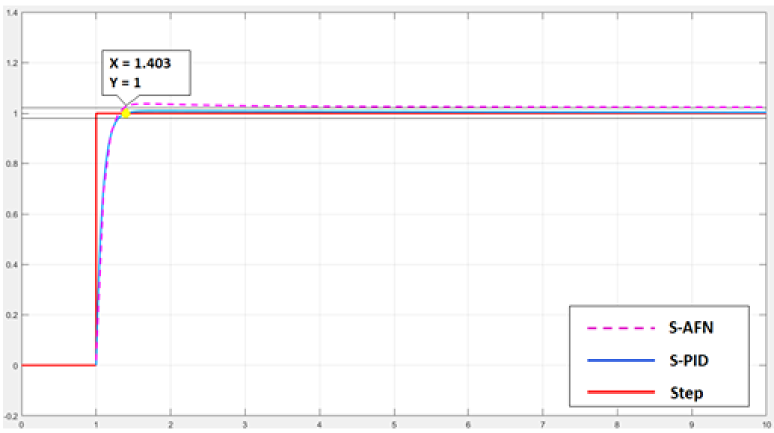


Figure 10. The response of system with PID controller for sine wave input.



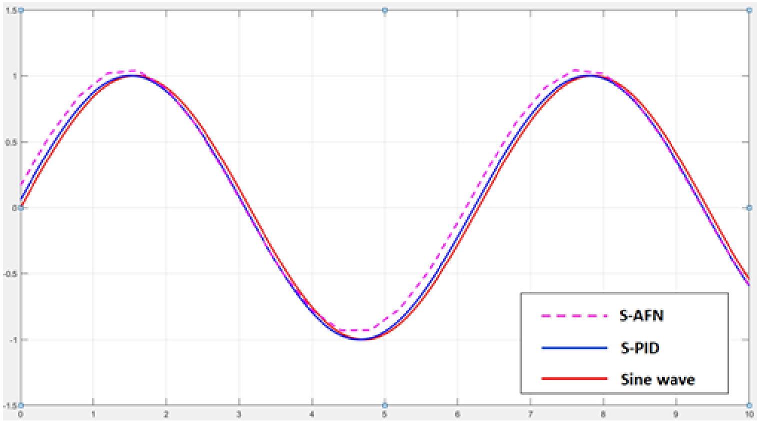


Figure 11. A comparison of the simulation responses of the torpedo control system without and with AFN Controller (purple), proposed PID Controller (blue), and sine wave (red).

CONCLUSION

The proposed algorithm is utilized to optimize the control system and the mathematical model for the torpedo in this study. The simulation results of the MEMS gyroscope and control system with PID controller have evaluated the degree of accuracy of the designed gyroscope and the stability of the system. The step block and sine wave block are added as input signals to evaluate the response of the PID controller and system more exactly. The numerical results programmed by using MATLAB and Simulink show the response of the control system and the controller performance are stable and accurate. The effectiveness of the proposed control scheme is confirmed by a comparison of the torpedo control systems without and with the PID controller. There is a verification between the numerical results and previous experimental observations.

CONFLICT OF INTEREST

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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