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Roll motion compensation by active marine gyrostabiliser

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Unmanned Surface Vehicle (USV) has been gaining more marine applications nowadays. However, the USV is vulnerable to excessive rolling motions induced by water waves, and this phenomenon may cause significant downtime to the operations of USV and engender detrimental effects to the on-board instrument and sensors. Active control system had been proposed to compensate the rolling stability issue but most of the proposed devices were expensive. This paper developed a gyrostabiliser on USV model to compensate the excessive rolling motion. Gyrostabiliser consists of rotor, gimbal and spinning axes, which commonly used for measuring or maintaining orientations and angular velocities. The gyrostabiliser was mounted vertically inside the USV model. Experiments were conducted to obtain the ideal gains of gyrostabiliser's controller, to investigate the differences between active- and passive-gyrostabiliser, and to identify the induced pitch effect of the vertical gyrostabiliser to the USV model. The roll angle of the USV was measured by gyro sensor, whereas the precession motor and flywheel motor were controlled by a non-encoder Direct-Current (DC) motor. A proportional controller of the gyrostabiliser was implemented through Arduino Integrated Development Environment (IDE) to ensure optimal performance of gyrostabiliser in precession speed and direction control. The results showed that both active- and passive-gyrostabiliser managed to mitigate the roll angle of USV from +/- 15° back to less than 1° and reached steady state within 2.32 seconds and 2.60 seconds, respectively. The active gyrostabiliser had advantage to return to zero precession angle while the passive gyrostabiliser accumulated 30° precession angle in the experiment. The induced pitch angle by the gyrostabiliser had been found in an insignificant magnitude for the case study. The outcomes of this paper lead to an alternative for improving the robustness of USV in rolling reduction.

[**Keywords**: Anti-rolling, Control, Gyrostabiliser, Unmanned surface vehicle]

Introduction

In-line with the rapid development of marine robotic and control technology[1,2], Unmanned Surface Vehicles (USV) have been popular for marine purposes such as military[3], surveillance[4], search and rescue[5], and maritime operations. Normally, USV will be equipped with equipment, instruments, and sensors for fulfilling their designed functions. The operation of most of the on-board devices are generally sensitive to the vessel motions[6]. For instance, excessive rolling motion of USV can reduce the quality of surveillance image, and in the worst-case scenario it causes capsizing of the vessel and damage the on-board equipment.

Gyrostabiliser generates torque through the reaction of spinning wheel, gravity, and excitation moment[7]. This phenomenon provides gyroscope with many useful functions in mechanical motion control which are reorientation of space craft[8], bicycles[9], air drone[10], land vehicles[11], and marine vessel[12]. Marine gyrostabiliser is a device to reduce rolling of marine vehicles exerted by waves and wind. Marine gyrostabiliser is installed inside the vehicle's hull. This device moves its weight, normally at high-speed spinning and tilting, to generate gyroscopic force to compensate the external environmental forces acting on the marine vehicles. Gyrostabiliser has identical structure which is made up of gimbals to hold the spinning wheel, and the spinning wheel will rotate about the spinning axis to generate controlling moment through gyroscopic effect from the rotating flywheel. Gyrostabiliser can be divided into passive- and active-gyrostabilizer. Passive gyrostabiliser does not require specific control while active gyrostabiliser requires precession and flywheel spin rate to control the stabilising effect[13]. The higher the speed of flywheel, the controlling will be more effective as the moment generated will be increasing[14]. Besides effective roll motion compensation, the using of gyrostabiliser on USV also bring other benefits as it does not create unnecessary hydrodynamic drag, relatively easier to maintain, and it changes the orientation effectively without emitting dirty[15].

Significant performance was reported as above-mentioned for the early designs of marine gyrostabiliser. However, several factors have limited their usage, such as intense structural loading, the displacement of vessel, and the insufficiency of control and maintenance of the sailing conditions. Nevertheless, with the rapid development of advanced materials, innovation of mechanical design, improvement on the digital control systems and the maturity of low-cost micro-controller board, the potential usage of gyrostabilisers has been revitalized, especially for small crafts. Furthermore, the use of digital control systems allows the adaption and monitor of the dynamic characteristic to fit the environmental and sailing conditions[16].

The objective of this paper is to conduct a series of experiments to investigate the feasibility of developing a gyrostabiliser in a simplified USV model. The system incorporated a PID control scheme into the compensation of USV's roll motion, and to evaluate the effectiveness of the gyrostabiliser. The differences of active control and passive control for the gyrostabiliser were investigated as well.

Theoretical modelling of gyrostabiliser

Marine gyrostabiliser is comprised of a flywheel mounted in a gimbal frame, as illustrated in Figure 1, which allows two out of three rotational degrees of freedom. The high-speed spinning flywheel generates angular momentum as stabilizing power of the gyrostabiliser[17]. As the rotational speed ω_s increases, the spinning flywheel accumulates larger angular momentum, K_g as follows[7]:

$$K_g = J_s \times \omega_s \qquad \text{... (1)}$$

Where, J_s is the rotational moment of inertial and ω_s is the angular velocity, respectively. The stabilizing power depends on the weight, radius, and rotational speed of the flywheel. The larger angular momentum, the more anti-rolling torque generated. The gimbal is mounted rigidly to the marine vessel hull for effectively transferring generated torque τ_g from the gyrostabiliser to the marine vessel based on the basic equation as follows[7]:

$$\tau_g = J_s \times \omega_s \times \omega_p \qquad \text{... (2)}$$

Where, ω_p is the precession rate of the spinning flywheel.

Angular momentum generated by gyroscope is the physical quantity which defines a rotating object whose rate of change gives the net torque causing the rotation. The magnitude of angular momentum is directly proportional to the mass of the object as well as the angular velocity, the increase in the gyroscope mass or velocity will increase the angular momentum and the torque[18]. Therefore, the flywheel is normally made of steel or heavier material and rotates in very high revolution speed, as this can ensure the sufficient stabilizing power.

Precession is the axis of rotation, rotating itself about the second axis, scientifically called change in the first Euler angle. Gyroscopic precession happens when there has an external torque to be applied on the spinning axis, and the direction of angular momentum changes with respect to the torque acting on the centre of mass[19].

Marine gyrostabiliser can be classified into two types: gyrostabiliser with natural precession motion and controller-driven precession motion. Controller driven precession motion gyrostabiliser is attained by

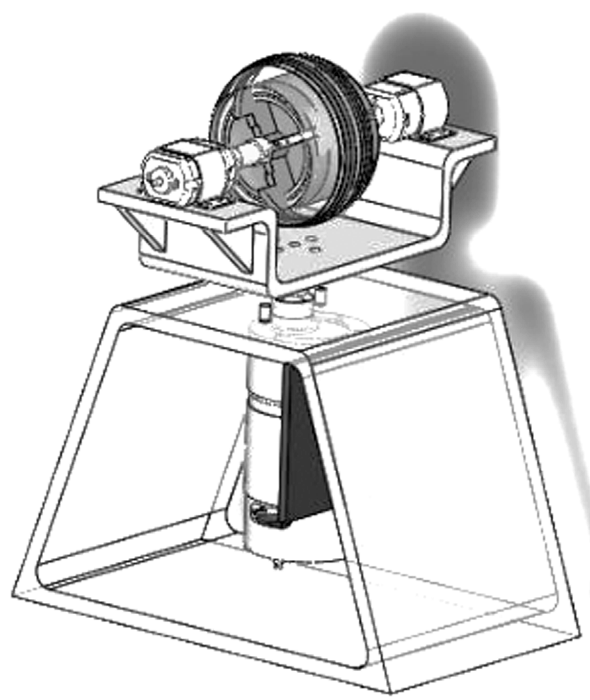

Fig. 1 — Structure of marine gyrostabilizer

adding a digitally controlled electric motor to a natural precession motion gyrostabiliser. Natural precession motion gyrostabiliser is usually in synchronous with the rolling motion of marine vessel in term of sea-wave frequency, but it is not applicable to slower waves due to friction in support bearings. A controller-driven precession motion gyrostabiliser can eliminate the threshold dead-band of wave moment, and thus giving more precise stabilization performance.

Materials and Methods

Overall set-up

The model of the gyroscope, gimbal, and the electrical components in a marine gyrostabiliser was illustrated in Figure 2. The USV model was fabricated using water resistance acrylic plates. The components were made up of one precession motor, two Direct Current (DC) motors, one Arduino UNO controller, one flywheel, flywheel holder and the housing. The gyroscope was placed at the middle of the USV model. The mass of the USV model incorporated with gyrostabiliser was 2970.97 g. When there has a rolling motion detected, the sensors sent the signals to control the precession motor and further to control precession rate and the direction. Figure 3(a) shows the experiment setup in which the USV model incorporated with gyrostabiliser was located in a round-shape water basin to simulate the vessel movement under the disturbance of water wave. The disturbance of wave was exerted by the interaction of the radiation wave and reflective wave from the wall effects during the motions of the floating USV model.

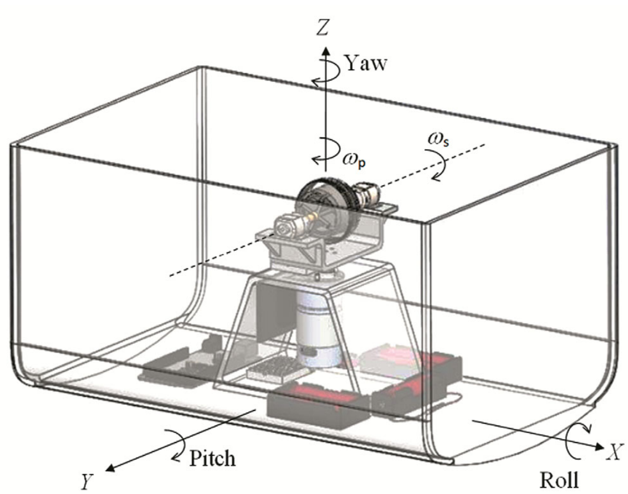

Fig. 2 — Overall set up of gyrostabiliser in USV hull model

Gyroscope flywheel

The gyroscope flywheel was modified from a gyro-ball to ensure smooth rotation and even mass distribution during the high-speed rotation. The weight was 270 g with radius of 3 cm; thus, the rotational moment of inertia was 0.0081 kgm^2. This flywheel was the most essential component in a gyroscope in which its high-speed rotation generated sufficient restoring moment to counter the rolling motion of USV model.

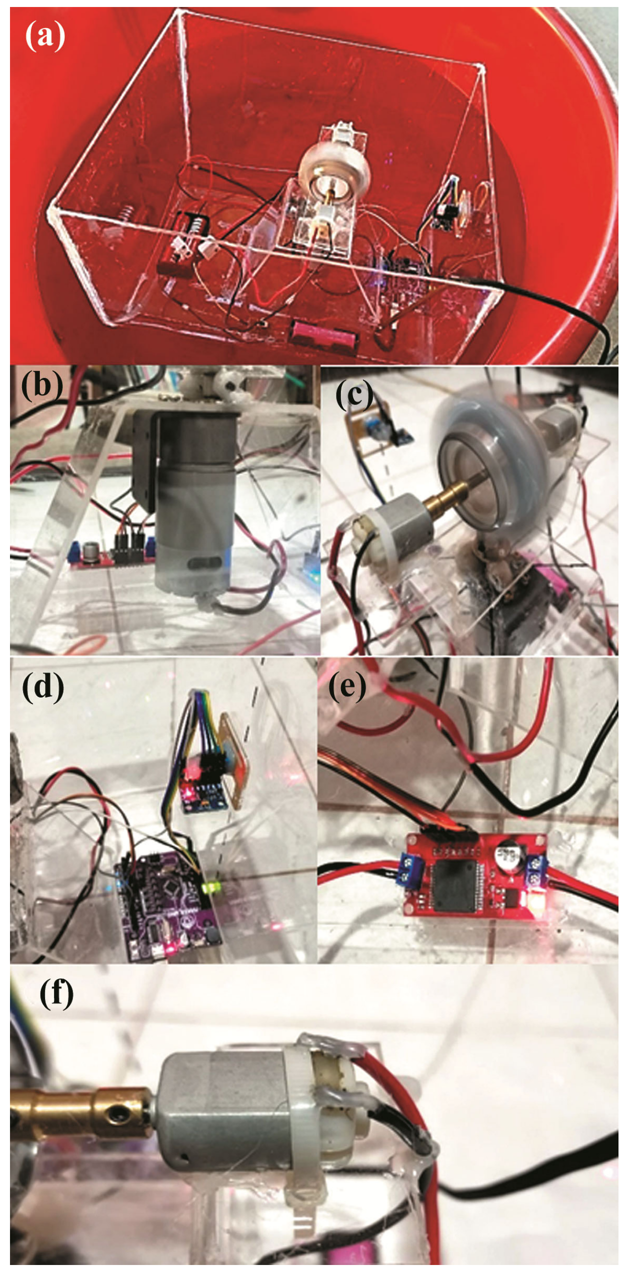

Fig. 3 — (a) Model set up in water basin, (b) precession motor, (c) gyrostabilizer, (d) MPU6050 and Arduino, (e) motor driver, and (f) flywheel motor and shaft coupler

The DC motor was utilised to rotate with approximately 10,000 rpm (revolution per minute) with stall torque of 0.53 Nm. Two DC motors were installed to ensure sufficient generated torque for flywheel rotation. Thus, the angular momentum of flywheel was 0.176 kgm^2s^{-1}.

Motor and gyroscope sensor

A MPU6050 gyroscope sensor can measure the orientations in *x*-, *y*- and *z*-axes, detect the rolling angle of USV, and send the output to the PID control scheme. The VNH2SP30 motor driver was used to drive the precession motor in responding to the rolling angle, hence the motor had to be rotating and accelerating in different directions quickly. High power and torque JGB37-550 DC motor acted as the precession motor in which the speed and rotational direction can be varied based on the signals received from the motor driver. The specifications for the motor, driver and gyroscope sensor are listed in Table 1.

PID controller

The PID controller and the algorithm to control the motor was coded and developed in Arduino Integrated Development Environment (IDE) through the use of an open-source Arduino PID Library. Arduino board processes inputs from various hardware and transfers the control output to the motor. In this paper, the microcontroller output was used to control the gimbal precession motion. Only PI controller was applied in this study to control the gyrostabilizer. Derivative controller was left out simply because the performance of this controller is highly dependent on the smoothness of gyroscope sensor readings. To smooth out sensor readings, it is necessary to incorporate series of digital temporal filters into the Arduino algorithm, which could severely delay the whole control procedures, and hence the performance of the controllers.

The block diagram of PI controller is as shown in Figure 4. The controller is comprised of two gains: proportional (K_P) and integrator (K_I) gains, respectively. The function of K_P was to calculate the difference of actual value and the error. It reduced the error by multiplying the proportional gain factor. The K_I considered the past values of error and integrated them over time to obtain the area of error under the curve in the time series. By multiplying the value by the gain factor K_I, the controller will seek to fully eliminate the steady-state error to 0 more effectively. However, the required time to achieve zero error was also much longer due to the use of K_I. With the increase of K_P gain factor, the tendency for damping increased, so tuning was needed to ensure smooth

Table 1 — Specifications for motor, driver, and gyroscope

VNH2SP30 motor driver	
Model channel	1
Operating voltage	5.5 V – 16 V
Continuous current output	14 A
Peak output current	30 A
Maximum PWM frequency	20 kHz
JGB37-550 motor	
Operating voltage	6 V – 15 V
Free-run speed (at 12 V)	550 RPM
Free-run current (at 12 V)	1.1 A
Stall current (at 12 V)	20 A
Rated torque (at 12 V)	9 kg.cm
Shaft diameter	6 mm D-shape
Weight	300 g
MPU6050 sensor	
Feature	3-axis gyroscope & 3-axis accelerometer
Operating temperature	-40 °C ~ 85 °C
Power supply	4.3 V – 9 V
Gyroscope range	+/-250, +/-500, +/-1000, +/-2000 °/s
Acceleration range	+/-2g, +/-4g, +/-8g, +/-16g
Weight	2.1 g

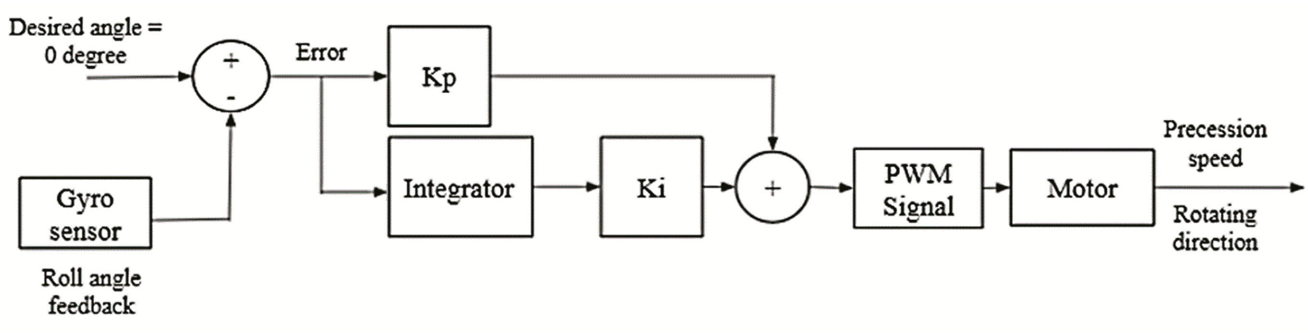

Fig. 4 — PI controller block diagram

reduction of error. After passing through the PI controller, the optimum correction value was sent to precession motor in Pulse-Width Modulation (PWM) signals so that the speed can be varied based on the changes of correction value. Eventually, the feedback of the USV angle was detected by gyroscope sensor, and the correction process was repeated until the USV achieving the desired set point of roll angle.

Microcontroller

The Arduino UNO is a microcontroller board with 13 digital input/output pins, consisting of six PWM pins (3, 5, 6, 9, 10, 11), and six analog inputs (0, 1, 2, 3, 4, 5). The Arduino UNO board had sufficient pins for the PID-controlled gyrostabiliser which required motor driver, gyro sensor, and encoder motor to operate. Arduino UNO was needed to control one DC precession motor and one MPU6050 sensor. The 5V pin was the output voltage supply; it was needed to supply voltages to MPU6050 gyro sensor, and VNH2SP30 motor driver. Pin 2 of the Arduino UNO board was used for sending output signals from Arduino to MPU6050, whereas pin 6 was an analog pin, which sent the PWM signals to JGB37-550 encoder motor so that the motor run in continuous behaviour. Pin 7 sent signals to input B at VNH2SP30 motor driver and pin 8 was for input A. The function of both inputs A and B was to control the motor rotational direction while PWM signals were to control the motor revolution speed. A0 was connected to enable (EN) pin at motor driver, which had the function of enable or disable the drivers. HIGH signal was sent to enable and LOW signal was for disabling. The other function of the EN pin was to indicate the thermal shutdown and disabled it when needed. A4 and A5 pin were connected to SDA (Serial Data Auxiliary) and SCL (Serial Clock Line) to transfer and synchronize all the data from MPU6050 with inter-integrated circuit (I2C) bus.

Experimental setup

The first experimental testing was conducted to determine the ideal proportional and integral gains for stabilising the roll motion of USV. The manipulating variables are PI gains, namely the K_P and K_I, as well as the flywheel rotational speed (RPM). During the testing, the USV hull model was disturbed initially by a roll motion of 15°, and then it was relieved to roll freely in response to different gyrostabilisation control settings as shown in Table 2.

The second experimental testing was to investigate the different responses between an actively- and a passively-controlled gyrostabiliser. In passive operation, the gimbal precession was naturally regulated by the reactive response of gyrostabiliser, in accordance to the USV hull model rolling motion. As for the actively controlled gyrostabiliser, the fine tuned PI controller (K_p = 10 and K_I = 0) in the experiment above was applied to estimate the corrective gimbal precession control signals.

Table 2 — Gyrostabiliser tuning

No.	K_P	K_I	PWM Duty Cycle (%)	Results (output)
1	20	0	±15.69	Oscillatory
2	10	0	±15.69	Oscillatory
3	5	0	±15.69	Oscillatory
4	20	0	±11.76	Oscillatory
5	10	0	±11.76	Stable
6	5	0	±11.76	Stable
7	20	0	±9.80	No response
8	10	0	±9.80	No response
9	10	0.3	±11.76	Oscillatory
10	10	0.1	±11.76	Oscillatory, Stable

The third experiment was to identify the effect of precession on the pitching moment for vertical gyrostabiliser. When the precession reached 45°, the gyrostabiliser usually induces significant amount of rotating moment at the other axis that causes unintentional pitching motion. In this experiment, the flywheel speed was kept constant, and PI controller gains were preset to K_p = 10 and K_I = 0. The USV hull model was disturbed by a roll motion of 15° and quickly relieved before it was allowed to roll freely in response to the gyrostabilisation control. Both of the roll and pitch responses were recorded for subsequent analysis.

Results and Discussion

Sensitivity of PI gains

The first experimental analysis identified the ideal K_p and K_I gains of this system. At the same time, the maximum precession rate was also determined by adjusting the PWM duty cycle supplied to the precession motor. Table 2 summarized the tuning outcomes of K_P and K_I as well as the saturation threshold of PWM duty cycle. The PI controlled gyrostabiliser remained oscillatory until the PWM duty cycle was kept below ±11.76 %. The best controller performance was achieved when the controller gains are set to K_P = 10 and K_I = 0. The use of proportional controller alone gives the best performance in roll motion compensation, with fastest settling time. Integration of integral control scheme to default proportional controller actually undermines the stability of the gyrostabiliser system, causing it to be more oscillatory and longer time to settle down. It is simply because the integral controller tends to make a control system to be more oscillatory.

Figure 5 illustrates a free decay test of USV hull model when the gyrostabiliser was switched off. The USV was disturbed initially by a roll displacement of 15° and quickly relieved to roll freely on a still water surface. The time taken to reach steady state was recorded to be 17.85 seconds. Please take note that the uncommon sharp spike as observed at t = 7 seconds was not caused by the movement of USV actually, but it was indeed caused by the FIFO (*First In, First Out*) overflow in Arduino board.

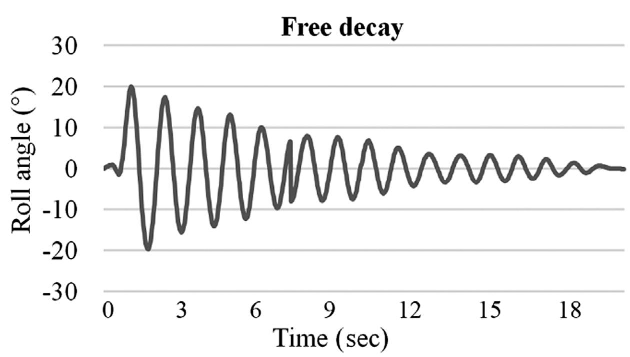

Fig. 5 — Free decay test response of USV hull model

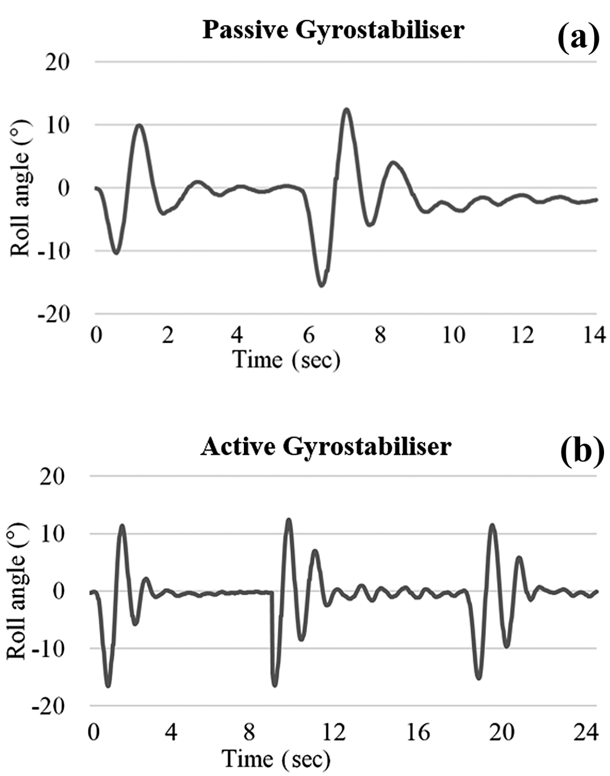

Fig. 6 — Roll motion compensation by (a) passive gyrostabiliser, and (b) active gyrostabiliser

Differences of active- and passive gyrostabiliser

The passive gyrostabiliser as shown in Figure 6(a) took average of 2.60 seconds to reach its settling time as compared to active gyrostabiliser (Fig. 6b), which only required 2.32 seconds. Observation in Figure 6(a) also shows that the flywheel of passive gyrostabiliser has failed to actively return to its initial configuration when it reaches the steady state, as shown in Figure 7(a). This causes the roll angle of USB hull model to be offset by around 3°, as a result of shifted USV centre of gravity. This outcome, however, was not reproduced in active gyrostabiliser (see Fig. 7b).

Active gyrostabiliser also showed slightly smaller roll motion fluctuations in USV hull model at steady state, as compared to the passively controlled gyrostabiliser. However, the roll angle by active gyrostabiliser is observed to be more "jerky". This

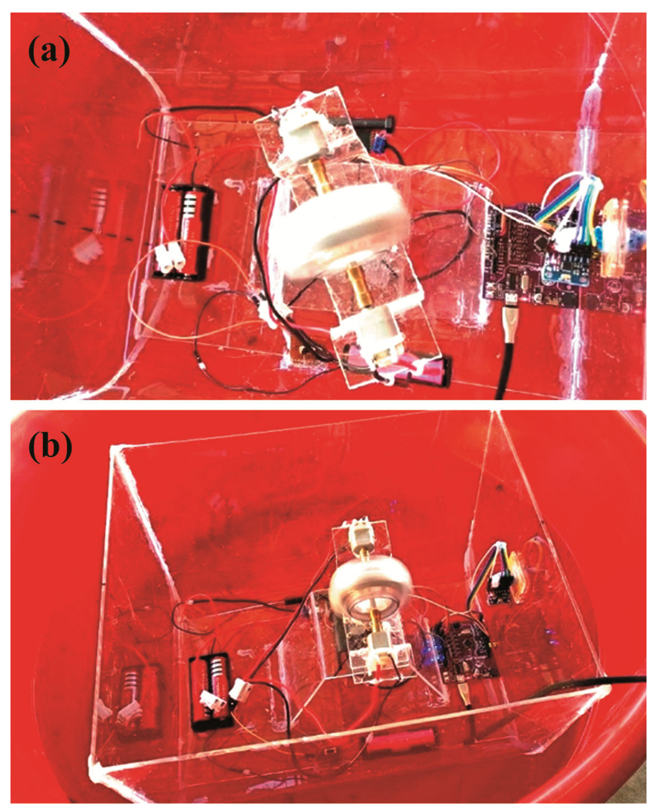

Fig. 7 — Comparison between the positions of precession motor for stabiliser in (a) passive mode, and (b) active mode, at steady state

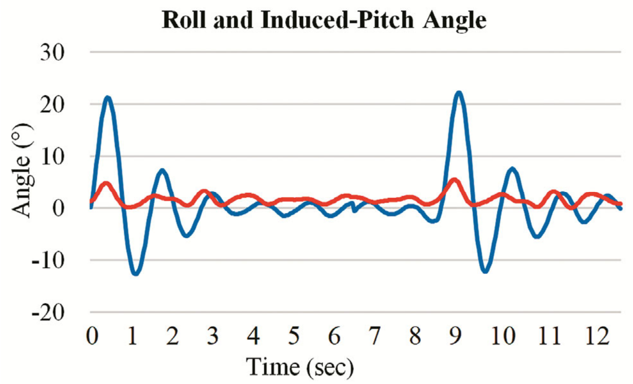

Fig. 8 — Roll (blue) and induced-pitch (red) motions of USV hull model

was simply due to the precession motor in this set up was fine tuned to be responsive.

Pitch motion induced by anti-rolling torque

The gyrostabiliser incurred additional pitching moment as the precession angle increased. In Figure 8, the pitch angle increased with small amplitudes at the same frequency of roll angle. Since the maximum and minimum of the precession angle in this experiment was observed to be less than ±45°, this indicates that no significant amount of rotating moment has been imposed on the *Y* axis. Therefore unintentional pitching motion as recorded in Figure 8 was highly possible caused by the wave disturbance reflected from the round-shaped water basin wall. Take note that at $t = 6$ seconds, the response showed uncommon spike. It is due to the FIFO-overflow problem in Arduino system.

Conclusions

A marine gyrostabiliser was developed and tested experimentally. The gains of PI controller need to be selected carefully. Gyrostabiliser in active control mode reached its steady state faster but small jerking was exerted if the friction of precession motor was large. In passive-control mode, it may cause offset in static roll and pitch angle as the precession motor was not actively back to its original position. Pitch motion was induced by the anti-rolling torque; however, the pitch angle was in small amplitude in the experiment. These findings imply that a gyrostabiliser can be realised for wide range usage on USV.

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Conflict of Interest

The authors declare that there is no conflict of interest.

Author Contributions

ZHY: Investigation, formal analysis, writing - original draft; CHHT: Conceptualization, supervision, writing - review & editing, funding acquisition; HSK, LKQ & TN: Resources, writing - review & editing.

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