Liquid Slosh Suppression Hardware-in-the-Loop System by Implementing PID Model-Free Controller

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Abstract – *Traditionally, the model-based controllers are hard to implement for the container system which contains liquid due to the disordered behavior of the liquid slosh. The purpose of this article is to develop a liquid slosh suppression hardware-in-the-loop (HIL) system by implementing model-free PID controller. This system consists of DC motor to actuate the liquid container/tank to the prescribed location in the horizontal movement in the same time minimize the liquid slosh. The feedback signal from the encoder is used for developing the model-free PID controller. The experiment works is done by using LabVIEW and interfaced with hardware via data acquisition card. The performances evaluation of the liquid slosh suppression HIL system are based on the ability of the tank to follow the input in horizontal motion and liquid slosh level reduction. Based on the experimental results, the suggested model-free PID controller is capable to reduce the liquid slosh level up to 75% in the same time produces fast input tracking of the tank compared to system without PID.*

Keywords: *liquid slosh suppression, LabVIEW, myRIO, PID controller*

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I. Introduction

The movement of the container system which contains liquid inside it usually faced a problem due to motion of the free liquid surface as known as slosh. The main problem of liquid slosh is it produces an additional moments and forces which can disturb the performance of the system. Hence, liquid slosh suppression is essential to solve the problems in numerous areas. For instance, the dynamic behavior of the ship carried a partly liquid filled tank onboard, is always disturbed because of additional forces and moments produced by a liquid slosh [1]. Another example, the pouring work in metal industries usually done by human operator. As we know, human tend to do an error because of many factors such as tiredness and carelessness. Consequently, human can cause sloshing and the molten metal will spill out from the ladle [2]. Moreover, the dynamics of the moving liquid cargo also can be troubled by the liquid slosh forces and moments acted in vertical and horizontal directions [3]. Thus, it is vital to suppress this liquid slosh problem during the movement of the container.

The goal of this study is to design the controller for the liquid slosh suppression HIL system so the tank can follow the prescribed location precisely in the same time, minimize the slosh angle. In recent years, several studies have focused on the liquid slosh control. Due to constraints of liquid slosh measurement, several passive approaches are executed to control the liquid slosh. For instance, absorbers and baffles are used as a passive elements to reduce the slosh energy in the container [4] – [5]. The drawbacks of these approaches to the system are heavy, bulky, require much time to construct and complex. Several attempts have been made to suppress the slosh of the liquid in the container by using feed-forward controller. For instance, minimum time feedforward control [6], filtering techniques [7], hybrid command smoothing and input shaping [8] and input shaping technique [9] – [10] . These methods are used by generating the prescribed motion without using any feedback sensors, which reduced the residual slosh of the liquid generated in the tank. Disappointingly, feed-forward controllers are very sensitive to external perturbation occurred in the system. As an alternative, closed-loop control or feed-back control, which is popular with its robustness to external perturbation, has been applied to reduce the slosh of the liquid. For example, Variable Gain Super-twisting Algorithm (VGSTA) [11], sliding mode control [12], PID control [13] – [15], H_∞

control [16], active force control (AFC) [17] and single input fuzzy logic controller [18].

Most studies on the liquid slosh control have only been carried out in simulation works. So far, however, there are only a few studies in literature that deal with experimental works. As we know, practically, the traditional control techniques which depends on precise modelling of the system as known as model-based control, are hard to implement in the liquid container system because of difficulties to model the dynamic motion of the liquid and turbulent behavior of liquid slosh in the container. So, the more attractive approach which the controller design is done without knowing the precise model of the system as known as model-free control, has a good potential to implement in liquid container system for reducing the slosh. One of the model-free controller is Proportional-integral-derivative (PID) controller. PID is well known with its reliability and robustness and it has been widely used on the numbers of applications such as in [19] – [20]. It should be noted from the above literature review, however, that limited studies are available for liquid slosh control by using PID controller especially on experimental works and this has motivated this present study.

The main concern of the controller design is to minimize the liquid slosh when the DC motor actuates to the desired tank position. A liquid slosh suppression HIL system which consists of a DC motor will move the liquid tank horizontally. The feedback signal from an encoder is used for developing the PID controller. The effectiveness of the suggested approach is judged in term of input tracking capability of the tank and level of slosh reduction. The experiment works is done by using LabVIEW software for evaluating the performance of the proposed control approach. Lastly, it is determined that the suggested control approach promises the fast input tracking of the tank and minimize the liquid slosh.

The paper is organized as follows: Section II described the PID controller design, Section III explains the experimental setup, Section IV presents the experimental results and discussion and finally, Section V concludes this paper.

II. The Design of PID Controller

This section presents the design of proposed PID controller for liquid slosh suppression HIL system. The PID controller block diagram of the liquid slosh problem is shown in Fig. 1.

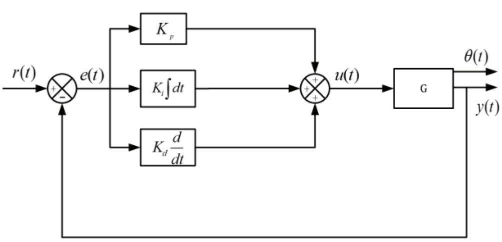

Fig. 1: PID controller block diagram of the liquid slosh problem

where $\theta(t), y(t), u(t), e(t)$ and $r(t)$ are the slosh angle, tank position, the control input, error and reference, respectively. G is the plant of the liquid tank system driven by DC motor. Transfer function of PID controller is given by (1).

$$TF_{PID} = K_p + \frac{K_i}{s} + K_d s \tag{1}$$

where K_p is proportional gain, K_i is integral gain and K_d is derivative gain.

The PID parameters are tuned by heuristic method based on PID behavior as shown in Table I [21]. This method is done by increasing the PID parameters independently and observed the response until the optimal performance is achieved based on time response specifications. For example, by increasing K_p, the rise time will decrease, same goes to steady state error but the overshoot will increase and just a small changed to settling time. So, to compromise with increasing overshoot, K_d is increased. The elimination of the steady state error is done by increasing the integral gain, K_i. This method is done heuristically until the best response is observed.

TABLE I
PID BEHAVIOR WITH RESPECT TO GAIN INCREMENT

PID Gain	Over-shoot	Steady state error	Rise Time	Settling Time	Stability
K_p	Increase	Decrease	Decrease	Small Change	Degrade
K_i	Increase	Eliminate	Decrease	Increase	Degrade
K_d	Decrease	No effect	Minor change	Decrease	Improve if K_d small

III. Experimental Setup

A. LabVIEW Setup

The experiment activities are done by using LabVIEW 2015 run in Microsoft Window 10, 8GB RAM and Intel Core i7-6700 Processor (3.41GHz) personal computer for assessing the performance of the proposed control scheme. Fig. 2 and Fig. 3 show the front panel and block diagram for experimental setup in LabVIEW software, respectively. Front panel consist of chart to display the encoder reading, image display to capture the image of liquid slosh, pointer slide as an input and PID gains for tuning the PID parameters. While, the block diagram in Fig. 3 consists of upper part and lower part. In upper part, there are PID controller with the input from pointer slide and feedback signal from an encoder reading. Then, the control input is send to analog output to control the DC motor. In lower part, it consists of vision functions to capture the image of liquid response in the tank.

B. Hardware Setup

Fig. 4 shows the hardware setup of liquid slosh suppression HIL system for experiment works. The hardware consists of data acquisition card (DAQ) NI MyRIO act as interfacing device between LabVIEW software and hardware. The DC motor is powered up by using 11.1V 2200mAh 3 cells LIPO battery. 5 megapixel Logitech web camera is used to capture the image of the liquid slosh in the tank. The CNC belt driven is used as a platform for the tank to move linearly in horizontal axis. To control the speed and direction of the DC motor, 40A motor driver with analog input is used. The whole system is actuated by 12V 66W DC motor integrated with 20 pulse/rotation rotary encoder for feedback signal of the tank position.

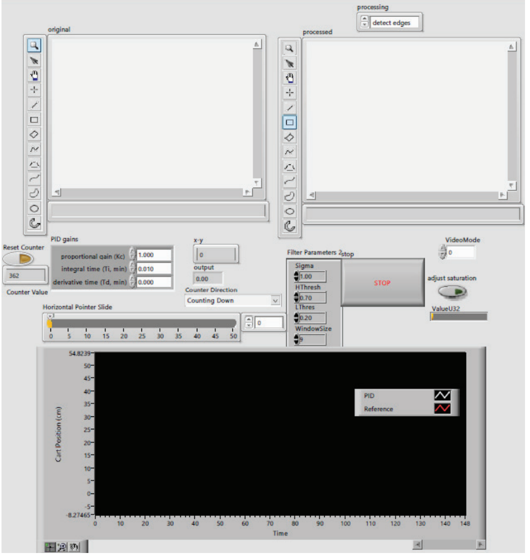

Fig. 2. Front panel in LabVIEW

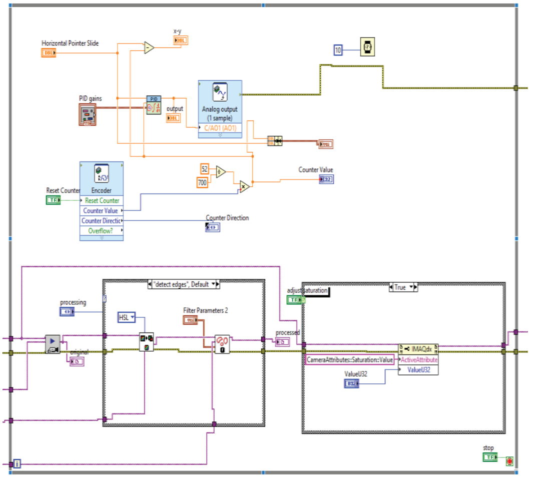

Fig. 3. Block diagram in LabVIEW

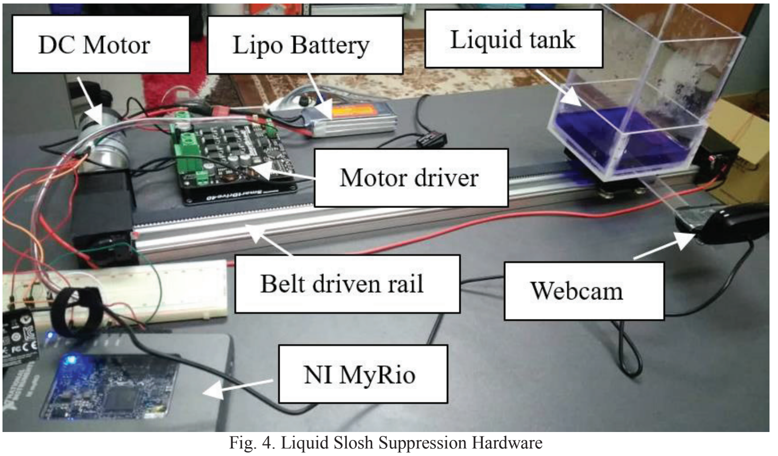

Fig. 4. Liquid Slosh Suppression Hardware

IV. Implementation and Results

This section presents the results of the control method for liquid slosh suppression HIL system. The proposed control scheme is designed to reduce the liquid slosh level from the system without PID and improved the input tracking capability of the tank in terms of time response specification. The PID gains is set heuristically as follows: K_p is set to 0.02, K_i is set to 0.04 and K_d is set to 0.001.

Fig. 5 shows the response of the liquid inside the tank when there is no controller applied to the system. As we can see, the liquid slosh response is very chaotic and turbulent behavior is happened in disorder manner. The maximum liquid slosh level as indicated in Fig. 5 is 5 cm from the water surface. To overcome this problem, PID controller is applied to the system. Fig. 6 illustrates the position of the tank for the motion from initial position, 0 cm to desired position, 45 cm. The result reveals that the tank follows the prescribed input well with zero overshoot, steady state error is 0.46 cm and settling time is 6 seconds. Fig. 7 shows the level of liquid slosh. Based on the result, the maximum slosh is about 1 cm from the water surface. There is very significant improvement in term of liquid slosh reduction as compared to system without PID where the slosh level is reduced from 4 cm to 1 cm for this particular movement which is contributed to 75% reduction. Meanwhile, Fig. 8 and Fig. 9 show the tank position and liquid slosh for motion from 45 cm to 0 cm, respectively. Fig. 8 shows the cart is move nicely with zero overshoot, steady state error is 0.41 cm and settling time is 6 seconds. Fig. 9 shows that the level of the liquid slosh is about 2 cm from the water surface. For this particular movement, the slosh level is reduced from 5 cm to 2 cm which is contributed to 60% liquid slosh reduction.

Fig. 10 shows the tank position with different input; 15cm, 30cm, 45cm, return back to 30cm, 15cm and to initial position. For the movement from 0 cm to 15 cm, there is no overshoot occurred and no steady state error. Next, for the movement from 15 cm to 30 cm, the response is worse with steady state error is about 3.35 cm. For the movement from 30 cm to 45 cm, the system significantly improved with elimination of steady state error. The response also able to track the input for movement from 45 cm to 30 cm with no steady state error, unfortunately, for the movement from 30 cm to 15 cm, the response produced a big steady state error which is 2.75 cm. Lastly, for the movement from 15 cm to initial position (0 cm), the cart stopped with small steady error which is 0.22 cm and no overshoot occurred. From all results, we can conclude that the system has a better performance when it runs for longer distance continuously compared to shorter distance. The time response specifications of cart position and maximum slosh angle is summarized in Table II.

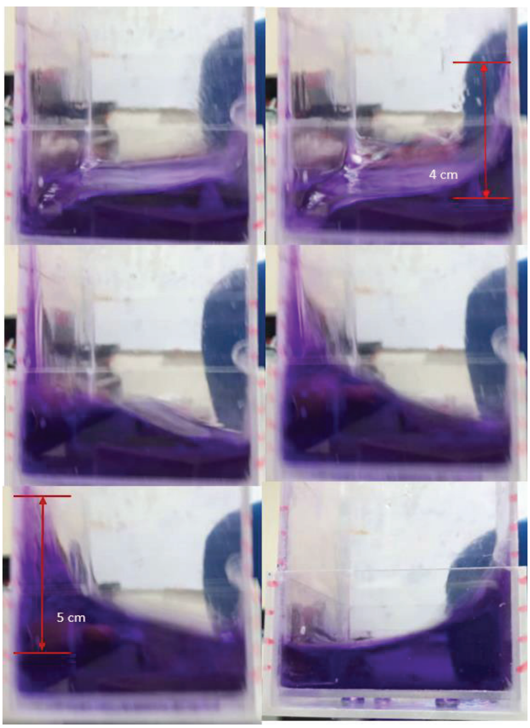

Fig. 5. The liquid slosh response without PID controller

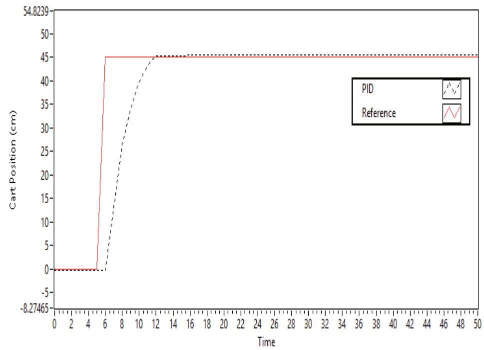

Fig. 6. The response of tank position for 45 cm

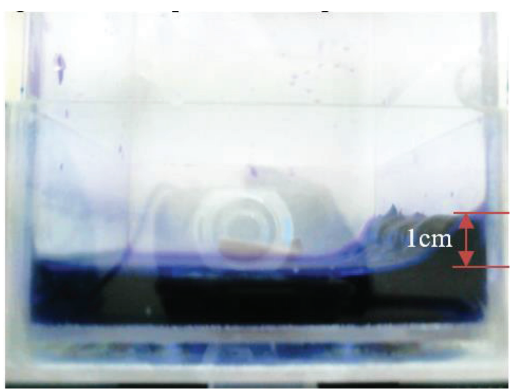

Fig. 7. The liquid slosh for 0 cm to 45 cm movement

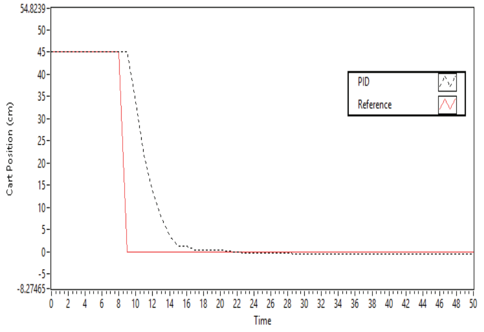

Fig. 8. The response of tank position for 0 cm

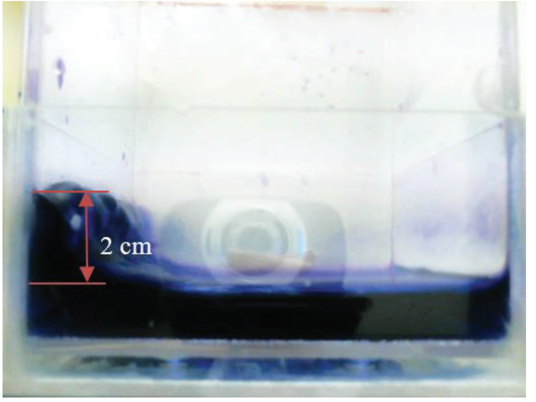

Fig. 9. The liquid slosh for 45 cm to 0 cm movement

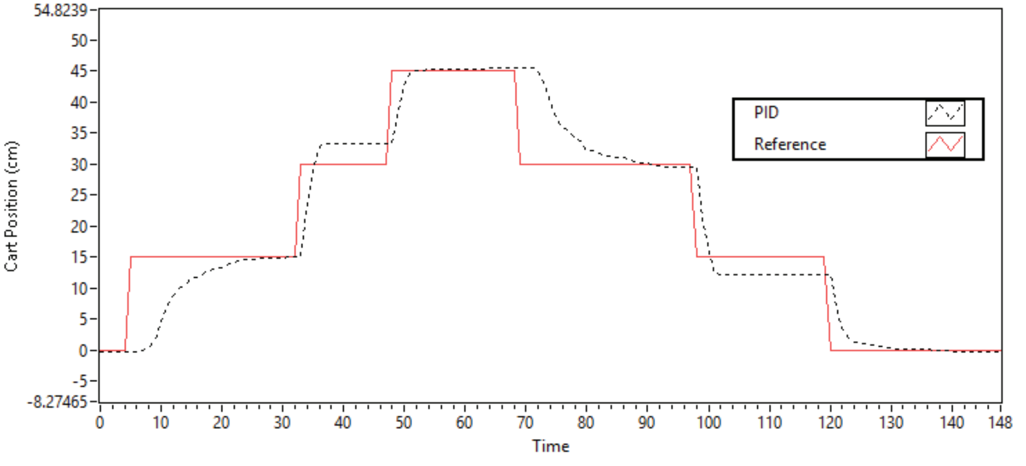

Fig. 10. The tank position response for different position

TABLE II.
THE RESULTS OF TIME RESPONSE SPECIFICATION OF THE SYSTEM

Position (cm)	Steady State error (cm)	Percentage Overshoot, %OS (%)	Settling Time, T_s (s)	Rise Time, T_r (s)
0cm to 45cm	0.46	0	6.0	4.8
45cm to 0cm	0.41	0	6.0	4.1
0cm to 15cm	0.00	0	20.0	12.0
15cm to 30cm	3.35	0	4.0	2.5
30cm to 45cm	0.00	0	2.0	1.0
45cm to 30cm	0.00	0	16.0	10.0
30cm to 15cm	2.75	0	4.0	2.5
15cm to 0cm	0.22	0	10.0	6.0

V. Conclusion

This project was undertaken to develop a liquid slosh suppression HIL control system by implementing model-free PID controller are investigated. The PID parameters are tuned heuristically by increment or decrement the PID gains based on the system behavior. The results of this investigation show that the suggested control method is capable in reducing the liquid slosh during the tank transition to the prescribed input. Therefore, this research will serve as a base for future studies in solving the problem of liquid slosh in aforesaid sectors. However, the tuning of PID parameters is very tedious task. What is now needed is a study involving the fine tuning of PID parameters using optimization algorithms to decrease the tuning time. Besides that, the development of control scheme with the feedback from the liquid slosh is needed for more robust system.

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