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Control of Liquid Sloshing Container using Active Force Control Method

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Abstract. This paper presents a robust control method to relieve the sloshing of liquid container transport using Active Force Control (AFC) method. A model of two degree-of-freedom (2-DOF) liquid container transfer was implemented in this research as the main dynamical system to be controlled. The surface of liquid is maintained in a flat position, so that changes the slope of liquid surface countered by changing the acceleration of container. The focus of this research is how to use AFC method being applied to the system, so that it can suppress liquid sloshing. The control scheme were simulated, compare between PID-AFC and pure PID. Simulations has been conducted, the results show that the PID-AFC have superior performance to suppress the sloshing compared with pure PID, especially if disturbance occurred.

1. Introduction

Sloshing or oscillation of the free surface of the liquid may occur during transfer of container filled with liquid. The sloshing happens due to the acceleration or deceleration when the container moves. Sloshing is undesirable condition, too many sloshes may cause spill-over, temperature changes, vibration and induce contamination of the molten metal is transferred. Therefore, the slosh should be suppressed while maintaining a high transfer speeds container for reasons of productivity and safety, for example transfer the liquid metal in the casting process. One way to reduce liquid sloshing low as controlling the acceleration or deceleration in accordance with the speed of the container, so as not to cause a socking. This research considers the fluid transfer machine can move the slide horizontally from one side to the other. An Inertial Measurement Unit (IMU) sensor fitted to the system for measuring acceleration and socks liquid container caused a stir. The purpose of this study was to develop a transfer container spilled liquid that can be suppressed using active force control.

2. Previous Works

Several methods to suppress the liquid slosh have done intensive research. In the tracking and sloshing suppression control to the moving object using a 2-DOF control system, the filter gain a different time using polynomial time can dampen spilled liquid container, and a fast track to get the target. The experimental results obtained indicate that the proposed control system is useful for both of the tracking control to the moving object and the sloshing suppression control [1] [2]. Additional work is presented using a flexible container as absorbent spill. Numerical predictions presented in which the flexible container is set to benefit more rigid container for effective control [3]. Numerical predictions presented in which the flexible container is set to benefit more rigid container for effective control [3]. Some researchers have been developed input shaping method to absorb sloshing on transfer of liquid in container using multiple degree-of-freedom robot arms [4]. They have also developed a vibration parameter identification algorithm integrated with design input shaper. Its applications for vibration absorber control of the transfer of the manipulator robot arm have been done. Simulation and experimental results have shown good accuracy in estimating the natural frequency and damping ratio. The final performances of forming an input have been also verified [5]. Other researchers presented analysis of dynamic effects and control of liquid stirring for an infinite number of modes spill as well as theoretically and experimentally. There are two control methods were proposed to suppress spill infinite mode in away minimize the slosh. The first is creating smooth input, while the second is a combination of input-shaping and smoothing command scheme. Both smooth and a controller coupled to produce good control effect that reduces unwanted transients and stir remainder. However, the combined controller can be shorter in time than a smooth ride. Simulations and experiments results were used to prove the dynamic character and the efficacy of the proposed method [6]. The both robustness and perform ability of the proposed scheme is guaranteed the proposed solution based on sliding mode control. The controller is shown to direct the robot to restricted environment of origin.

Another researchers have been created robust control such as slide mode control, adaptive control, quantitative feedback theory, passivity based control, etc. Yet another type of powerful method known as a method of active power control (AFC) was first proposed by Hewitt and Burdess (1981) has proven to be very robust against interference and the uncertainty of the dynamic system. However, no research or studies that have not been that incorporate the scheme into the liquid spilled oppressive and investigated its effects. Other researcher has been also developed of hybrid control schemes for vibration suppression applied to suspension system. The control scheme is developed on the basis of the AFC collaborate with *input shaping* techniques and it has been simulated, implemented and tested in an experimental suspension system. The characteristic of resonance modes of vibration suppression is evaluated to obtain performance of the control scheme. Using the both control strategies, the vibration suppression results had been accepted. A comparative appraisal of the control techniques applied to suppression of the suspension has shown that AFCIS with 4 impulses scheme results is better performance than the pure AFC in respect of vibration [7][8].

Other people use active force control (AFC) strategy to absorb the vibration and squealing noise phenomenon in disc brake model using a robust feedback control method. A model of a two-degree-of-freedom (2-DOF) *Wagner* considered in this research as the main dynamic element that must be controlled. The durability and effectiveness in suppressing vibration and screaming was tested, by considering account a number of disorders that work on the system. There are three control schemes involving simulated and compared to classical controller proportional-integral-derivative (PID), pure AFC with crude approximation (AFCCA) and combination of AFC with fuzzy logic (AFCFL) scheme. AFC-based schemes shown excellent performance compared with the pure PID counterpart with the AFCFL method generate the best performance [9].

3. Control Design

When someone brings a glass of water on his hand while walk, automatically the hand will suppresses the sloshing of the water surface. The hand will control the speed or acceleration of the moving. Although the hand moves in high speed, however the hand will keep the acceleration low as possible. There are two censors is used by human to measure the water sloshing, namely eyes and nerve. Eyes see value of the sloshing by the tilt angle of water surface. While the nerve detect water sloshing by the change of inertia or shocking. When eyes see water is sloshing and almost spilled or nerve sense change of inertia, the hand will react by do change the acceleration. If the sloshing caused by high acceleration, the hand will decrease the acceleration. In what follows, the system consist of a tank, mounted on two parallel bars. The tank can slide horizontal as reciprocally on the parallel bars. The movement of the tank is driven by a DC motor, which slides as long as rig gear. The surface of liquid is flat, when the tank at idle condition. But, when the tank move will occur slosh being caused by acceleration or deceleration. A laboratory scale experimental has been built to simulate the real operation and all progress is presented as shown in Fig. 1.

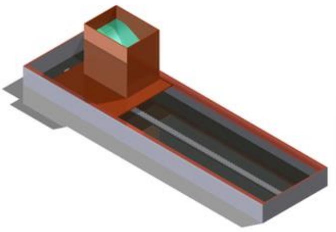

Figure 1. Design of liquid sloshing in container transfer

3.1. Sloshing Model

Sloshing in an open container as general can be well described by equivalent mechanical models, as well as a pendulum model or a spring-mass model [1]. One way is using a simple pendulum model, where one pendulum system is one mode. Slope magnitude of liquid surfaces similar with slope magnitude of vertical pendulum. The angle of liquid surface is similar to the angle of pendulum bar. The pendulum model is added a damper system to reflect the viscosity and friction of fluid with container walls. Given the fundamental mode only spill, which is dominant in the transfer container spilled, and next ignore other small modes, model of pendulum is shown in Figure 2 can adequately represent the dynamics spilling laterally.

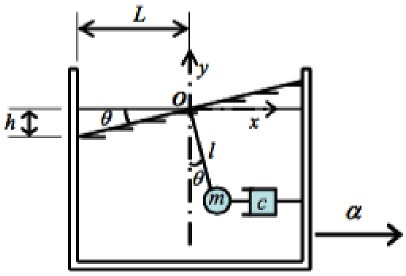

Figure 2. Pendulum model in liquid container transfer

The pendulum bar is perpendicular to the liquid surface, which tilts as the container accelerates or decelerates represent by α, configuring angle θ, which is angle of the horizontal lines and liquid surface. The container may slide to left or right direction, so that the angle θ has sign + or –, depend on the motion direction of container. The coefficient c is the constant damp of fluid viscosity and fluid friction with the walls of the container. The value of damper depends on the kind of liquid. Taking into account the balance of currents around the fulcrum of the pendulum, the dynamics of the model can be depicted by the equation:

$$J\frac{d^2\theta}{dt^2} = -c\frac{d(l\theta)}{dt}l.\cos^2\theta - mgl\sin\theta + m\alpha l\cos\theta \qquad (1)$$

Where J (ml^2) is the moment of inertia, m is mass of liquid, and l equivalent pendulum length (m) and coefficient of viscosity c (N.s/m). The high level of liquid h on the wall equals $l\cdot tan(\theta)$. In view of only small value of θ, linear approximation of the above non-linear model is described in 2^{nd} order equation as follows:

$$\ddot{\theta} = -\frac{c}{m}\dot{\theta} - \frac{g}{l}\theta + \frac{\alpha}{l} \qquad (2)$$

$$h = L\,\alpha \qquad (3)$$

The angular of acceleration will be integrated to the angular velocity, then integrate again will be obtained the value of angle θ. The transfer function relation between liquid high level h and translation acceleration α is described by the following equation:

$$\frac{h(s)}{\alpha(s)} = \frac{L/l}{s^2 + \frac{c}{m}s + \frac{g}{l}} \tag{4}$$

Sloshing occurs is caused from oscillation motion, so that its can be solved using vibration equation. The natural frequency ω_n and damping ratio ζ can be obtained by comparing the equation (4) to second-order damped linear oscillation:

$$\omega_n = \sqrt{\frac{g}{l}} \tag{5}$$

$$\zeta = \frac{c}{2m}\sqrt{\frac{l}{g}} \tag{6}$$

3.2. Active Force Control

AFC method has been applied to many kinds of experimental rig, such as robot arm and mobile robot. The aim of use AFC method is to suppress any known or unknown disturbances that may present in the system, so that the system effectively remains robust and steady during operation. The method has convenient application that is readily realized and implemented since it is primarily based on measured or estimated quantities. The advantage of AFC method is its ability to suppress some disturbances effectively and reliably, without use complex mathematical computation. Actually, AFC is a simple methods, the mechanism largely depends on the accurate measurements of two parameters related to the torque and acceleration of the physical system with an appropriate estimation of the inertia matrix of the dynamical system. The AFC principle can be simply traced back from the Newton's second law of motion for a rotating mass. The sum of all torque (T) acting on a body is the product of the mass moment of inertia (I) and the angular acceleration (□) of the body in the direction of torque applied, which can be expressed as:

$$\sum T = I\alpha \tag{7}$$

Assuming a DC motor being mounted under water tank system that has only rotary motion, the equation governing the applied AFC method is as follow as:

$$T + Q = I(\varphi)\alpha \tag{8}$$

Equation (8) is the most significant expression that describes the strategy AFC and thus should be critically and carefully treated, especially during the implementation phase as well as in simulation and experimental studies. The successful implementation of the strategy lies in the AFC precise estimate of the matrix of inertia of a dynamic system. The estimated of inertia matrix can be obtained from calculation. The estimated disturbance vector *Q** is traverse the transfer function *H(s)*, before the vector summed with the command *c* in summing junction. An appropriate choice of *G(s)* associated to an actuator device can cause the controlled output *q* to be made invariant with respect to the introduced disturbances *Q'*. For more detail of a schematic of the AFC scheme can be seen in Figure 3.

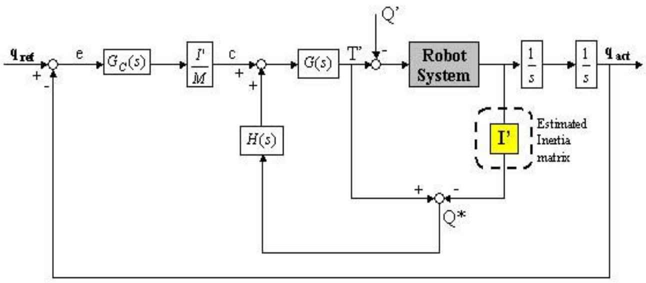

Figure 3. AFC schematic

Base on the schematic in Figure 3, outside the control loop transfer function $G_c(s)$ can be arbitrarily selected, the most common of which is the classical proportional-integral-derivative (PID) controller. The available of the inner control loop from *G(s)* to *H(s)* will localize the effect of the disturbances *Q'*, thus doing action necessary compensation. Choice of the appropriate *estimated inertia matrix I'* absolutely crucial and essential to ensure the effectiveness of the strategy of AFC. From the previous literature, a rough estimate of the approximate matrix of inertia, *IN* for a two-link robot arm and the Wheeled Mobile Robot (WMR) are expressed as:

$$IN = K_i H \quad (9)$$

Where K_i is a coefficient of the inertia matrix such that $0.5 < K_i < 1.5$, while *H* is the modelled inertia matrix that can be easily and directly obtained from the system equation of motion. This value obtained from trials, where the procedure has been also applied to the robot arm and mobile robot system. The main objective of using the intelligent means is to enable the computation of the required inertia matrix be made automatically, continuously and on-line.

4. Simulation Results

Simulations of sloshing control were conducted using MATLAB Simulink. For this simulation water thank can move slide along 120 cm, powered dc motor with constant motor torque (*Ktn*:0.263 N.m/s^2). Height of water tank 10 cm, and the mass of liquid about 1 kg. Maximum acceleration is set 2 m/s^2, whereas the initial speed is 0.5 m/s. The whole of simulation parameter is shown in Table 1.

Table 1. Parameter Values

Parameter	Value	Unit
Mass of liquid, *m*	1	kg
Initial velocity, *Vo*	0.5	m /s
Acceleration, *a*	0.8	m/s^2
High water level, *h*	10	cm
Coefficient of viscosity, *c*	1.02	N.s/m
Gravity acceleration, *g*	9.8	m/s^2

Firstly, simulation is conducted using PID controller, where Kp=10, Ki=0.4 and Kd=0.01. Disturbance is set 0, its mean no disturbance. The block diagram of suppress liquid control using PID controller is shown Figure 4.

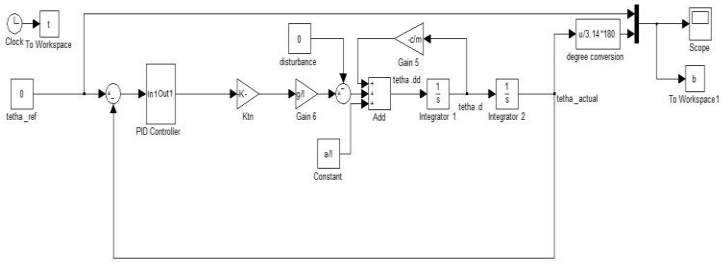

Figure 4. Simulation of suppress liquid control using PID controller

Secondly, simulation is conducted using PID-AFC. The gain controller is set same with the pure PID controller, and also without disturbance. The block diagram of suppresses liquid control using PID-AFC controller can be seen in Figure 5.

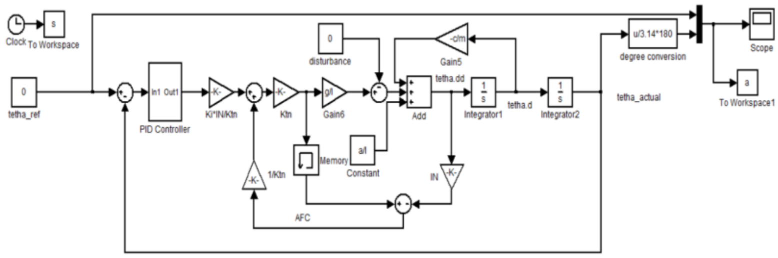

Figure 5. Simulation of suppress liquid control using PID-AFC controller

The result of simulation of PID and PID-AFC controller for 10 seconds can be seen in Figure 6. It can be seen that PID-AFC method more superior than pure PID method. The PID method occurs transient in the beginning and reachs steady state after 8 seconds, meanwhile the PID-AFC method reachs steady state from the strarting time.

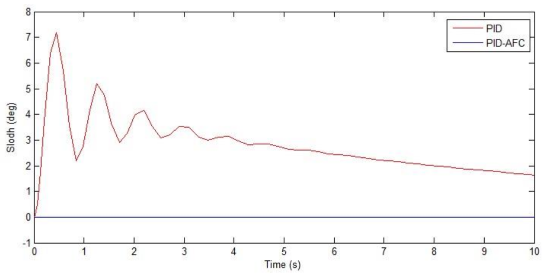

Figure 6. Simulation of suppress liquid control using PID-AFC and PID controller

The response of PID-AFC method in Figure 6 looks able to suppress slosh until zero. Actually, the slosh of PID-AFC method is not perfect zero, but vary in very small value such as shown in Figure 7.

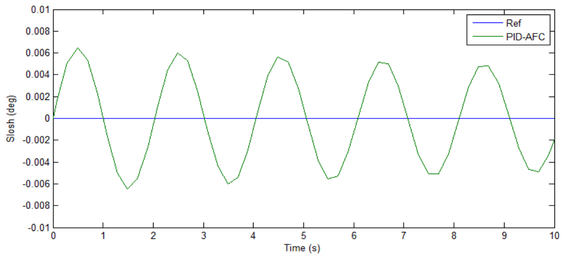

Figure 7. The result of simulation using PID-AFC controller

Third, simulation is conducted by giving constant disturbance. Using PID controller, disturbance give effect to the stability of system. Disturbance causes big slosh rising in early movement. The comparison results between no disturbance and using disturbance as shown in Figure 8.

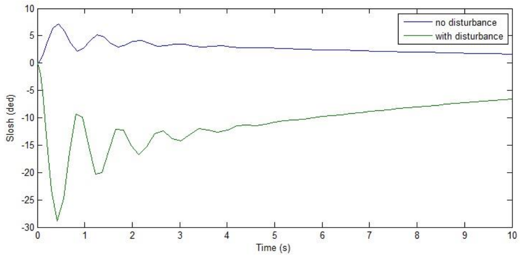

Figure 8. Simulation result using PID controller with disturbance

The next simulation is conducted using PID-AFC controller by giving disturbances. Either there are disturbance or no, the results is stable, the graph is almost same. While, the simulation time is extended to 100 seconds, precisely the sloshing toward to zero. The comparison results between no disturbance and with disturbance as shown in Figure 9.

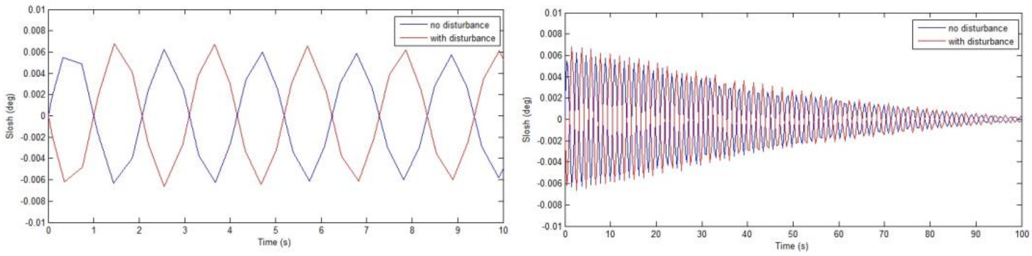

Figure 9. Simulation result using PID-AFC controller with disturbance

Conclusion

Simulations of liquid sloshing control have conducted. The simulation is conducted comparing between PID with PID-AFC control and also by giving constant disturbance. From the simulation result shows that using PID-AFC control be able to suppress the sloshing effectively than the PID control. The PID-AFC method reach steady state from the starting time. The simulation result clearly indicates that the proposed PID-AFC method performs more robust than PID method in the presence of disturbances. In the future work, we will focus in the experimental work.

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