A Model-Free PID Tuning to Slosh Control using Simultaneous Perturbation Stochastic Approximation

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***Abstract*— This paper addresses an initial study of a model-free PID tuning based on simultaneous perturbation stochastic approximation (SPSA) for liquid slosh control. The SPSA method is used to optimize the PID parameters such that the liquid slosh is minimized. In order to validate our model-free design, a liquid slosh model is considered to represent the lateral slosh motion. The simulation results demonstrate that the proposed model-free method has a good potential in reducing the liquid slosh without explicitly modeling the liquid slosh behavior.**

I. INTRODUCTION

Nowadays, slosh or oscillation of liquid inside a container often occurs in many cases. For example, ships with liquid cargo carriers are at high risk of generating sloshing load during operation [1]. In the metal industries, high oscillation can spill molten metal, which is dangerous to handle by the operator [2]. Meanwhile, sloshing of fuel and other liquids in moving vehicles may cause instability and undesired dynamics [3]. Hence, it is necessary to suppress this residual slosh induced by the container motion.

So far, various attempts in suppressing slosh are based on open-loop and closed-loop approaches. For example, input shaping scheme [4], [5] and some filtering techniques [6], [7] are used to generate a prescribed motion, which minimized the residual oscillation. These methods are able to reduce the slosh without needs for feedback sensors. However, these strategies are very poor in handling with any disturbances. On the other hand, closed-loop control or feedback control, which is well known to be less sensitive to disturbances and parameter variations, has also been adopted for reducing slosh. These include PID control [8], H_∞ control [9], sliding mode control [10] and iterative learning control (ILC) [11].

As shown in the above, many approaches use model-based control strategies, which are difficult to apply in practice. This is because their control schemes do not accurately consider the chaotic nature of slosh and the complex fluid dynamic motion in the container. Therefore, a model-free approach will be more attractive. On the other hand, a simultaneous perturbation stochastic approximation (SPSA) [12] would provide us a promising tool for the model-free approach. This is because the SPSA method is known to be effective for a variety of model-free optimization problems without require any explicit form of the objective function [13], [14]. However, it is not clear whether it works for liquid slosh problems since there are a few works in the literature have discussed the application of the SPSA to the problems.

This study aims to investigate the effectiveness of the model-free PID tuning for liquid slosh suppression based on simultaneous perturbation stochastic approximation. To evaluate the performance of the proposed model-free approach, a liquid slosh model in [15] which consists of a small motor-driven liquid tank performing a rectilinear motion is considered. Here, the SPSA method is used to tune a given PID controller such that the liquid slosh is minimized while achieving desired cart position. Then, the performance of the proposed method is assessed in terms of level of slosh reduction and cart's position tracking capability.

The rest of the paper is organized as follows. Section II formulates the problem of model-free PID controller tuning to slosh control. In Section III, the simultaneous perturbation stochastic approximation based method is explained. Simulation results and discussion are presented in Section IV. Finally, some concluding remarks are given in Section V.

Notation: The symbols $\mathbb{R}$ and $\mathbb{R}_+$ represent the set of real numbers and the set of positive real numbers, respectively. For the random variable V, the probability of event $V = a$ is represented by $\mathbb{P}(V = a)$. For $\delta \in \mathbb{R}_+$, $\mathrm{sat}_\delta : \mathbb{R}^n \to \mathbb{R}^n$ denotes the saturation function whose ith element given as follows:

$$\text{The } i\text{th element of } \mathrm{sat}_\delta(\boldsymbol{x}) = \begin{cases} \delta & \text{if } \delta < x_i, \\ x_i & \text{if } -\delta \le x_i \le \delta, \\ -\delta & \text{if } x_i < -\delta, \end{cases}$$

where $x_i \in \mathbb{R}$ is the ith element of $\boldsymbol{x} \in \mathbb{R}^n$.

II. PROBLEM FORMULATION

Consider the PID control system for liquid slosh problem depicted in Fig. 1, where $r(t)$, $u(t)$, $y(t)$, and $\theta(t)$ are the reference, the control input, the measurement of lateral position of the tank, and the measurement of slosh angle, respectively. The plant is the motor-driven liquid tank system G. The controller $K_i(s)$ $(i = 1, 2)$ is the PID controller

$$K_i(s) = P_i \left(1 + \frac{1}{I_i s} + \frac{D_i s}{1 + \dfrac{D_i}{N_i} s} \right), \tag{1}$$

where $P_i \in \mathbb{R}$ is the proportional gain, $I_i \in \mathbb{R}$ is the integral time, $D_i \in \mathbb{R}$ is the derivative time, and $N_i \in \mathbb{R}$ is the filter coefficient.

The performance index for the control system in Fig. 1 is given by

$$J(\boldsymbol{P}, \boldsymbol{I}, \boldsymbol{D}, \boldsymbol{N}) = w_1 \hat{e} + w_2 \hat{\theta} + w_3 \hat{u}, \tag{2}$$

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