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ADVANCED SHAKE TABLE CONTROLER DESIGN USING MODEL PREDICTIVE CONTROL STRATEGY

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Abstract

Shake table testing is one of the most realistic experimental methods to evaluate the seismic resistance of a structure. In most practice, conventional shake table control relies on the use of linear controller, such as proportional-integral-derivative (PID) controller, to regulate the motion of the table. However, due to the nonlinearity in the hydraulic actuator dynamics and specimen's nonlinearity, the tracking performance and stability of such linear control approach can be seriously degraded. To address the above shake table control issue, this paper adopts the hierarchical control architecture and model predictive control (MPC) strategy to regulate the shake table movement. The MPC predicts the response of the shake table using an numerical model. On the other hand, the low-level controller execute the control commands generated by the high-level controller by dealing with the local system dynamics of the hydraulic actuators. In this paper, a shake table system model was developed using the experimental data collected from a large scale shaking table at the University of British Columbia (UBC). Comparative simulation and experimental results are presented to demonstrate the feasibility using the proposed shake table control approach.

Keywords: Shake Table Testing; Model Predictive Control; Hierarchical Control

1. Introduction

The shake table test is one of the most common experimental methods to evaluate the structural response during earthquake shaking. Conventional shake table control relies on the use of linear control method, such as PID, to regulate the motion of the table. However, due to nonlinearities in the specimen behavior and the hydraulic actuator dynamics, it is very difficult to achieve good tracking performance using linear control approaches [1]. To address this issue, Yang et al. (2015) proposed a hierarchical control approach to regulate the shaking table [2]. The hierarchical control approach consists of a high-level sliding mode controller (SMC) and a low-level controller to regulate the actuator servo control. The high-level controller takes the system dynamics (specimen and the shake table) into account and then generate the control signal without consider the local actuator dynamics. While the low-level controllers take the command signal from the high-level controller to regulate the actuator without consideration of the global system dynamics. The hierarchical control architecture provides flexibility for adapting different controllers to different specimens and simplifies the shake table control problem by separating the control goals into high and low level controllers.

In this paper, a hierarchical control framework, as shown in section 2, is proposed to regulate the shake table. The hierarchical control framework adopted the Model Predict Control (MPC) as the high level controller, while basic PID controller as the low level controller. In order to develop the MPC-based shake table controller, experimental data collected from a large scale shake table test at the University of British Columbia (UBC) were used. Detailed system identification procedure and the development of the MPC shake table controller design are described in section 3 and 4, respectively. The performance assessment of the MPC-based hierarchical control shake table controller is presented in section 5. Finally, concluding remarks are presented in section 6.

2. Hierarchical Control

A hierarchical control system is a form of control system in which a set of devices and governing algorithms are arranged in a hierarchical tree. Fig. 1 shows the general hierarchical control architecture. In this control architecture, a high-level controller and one or multiple low-level controller(s) are employed. The high-level controller, which is designed based on the shake table system model, aims to control the movement of the table to track the desired reference signal, while the low-level controller(s) are used to regulate the command generated by the high-level controller. The main advantage of such hierarchical control approach is that it can separate and simplify complex shake table control problems into two levels of control tasks to be executed by the high-level and low-level controllers, respectively. The high-level controller governs the shake table motion to handle the overall control system stability and reference signal-tracking requirements. On the other hand, the low-level controller functions as the actuator servo controller to perform displacement, velocity, acceleration or force tracking according to the high level control command. Unlike the traditional linear shake table control approach, in which the actuator servo control, table motion tracking and stabilization in the face of nonlinearities of the specimen and actuator dynamics are all dealt with by the linear controller, the hierarchical control strategy is able to make the controller design and implementation easier. Such design architecture can also be easily adapted for multi-directional shake table control by changing the high-level controller without significantly changing the low-level controllers.

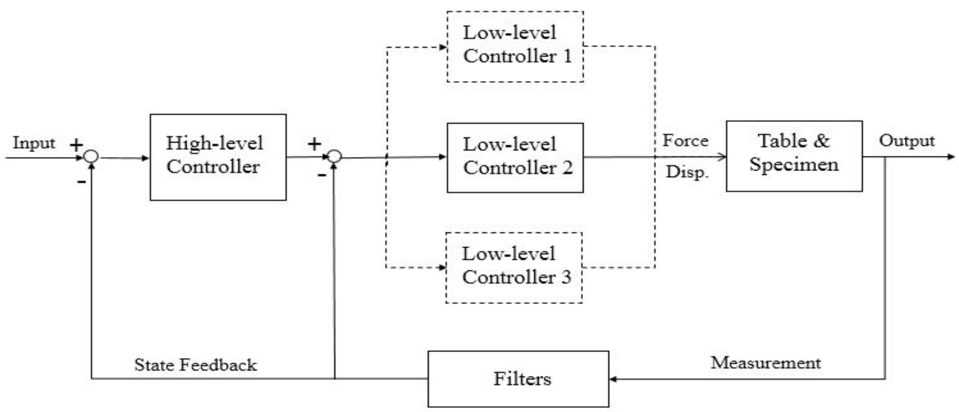


Fig. 1 Hierarchical control architecture of the shake table test

In this paper, a hierarchical control architecture as presented in Fig. 2 is adopted. In this model, the ground displacement was used as the reference signal. A Model Prediction Control (MPC), as described in section 4, is used as the high-level controller. The PMC-based high-level controller is used to track the desired reference signal, while the low-level controller was used to regulate the hydraulic actuator by adjusting the comment voltage to the servo valve.

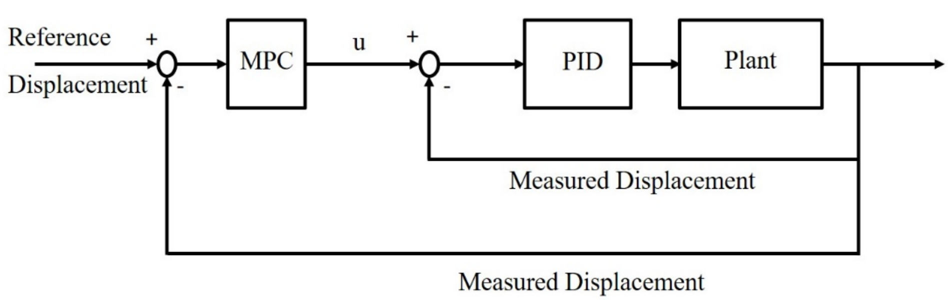


Fig. 2 Adopted hierarchical control structure for the uni-directional shake table control

3. System Identification of the Shaking Table System

A large-scale single-degree-of-freedom (DOF) shake table in the University of British Columbia, as shown in Fig. 3, was used. The shake table has the stroke limit of +/- 300 mm and a weight of 10 tons. The shake table has a build-in linear variable differential transformer (LVDT) and an accelerometer to measure the displacement and acceleration of the table, respectively. The shake table control platform was built by the ACTS Technologies Inc. which was able to provide real-time implementation of the developed control algorithms.

Fig. 3 Large scale shake table at UBC

System identification was performed for the shake table, the results of the system identification was used to develop a shake table model for controller deign in this paper. Since the open-loop shake table system tends to be unstable, the closed-loop system identification technique was applied [3]. The developed numerical model of the shake table system including the hydraulic actuator and the table is modeled as the *plant* in the block-diagram shown in Fig. 2. In performing the closed-loop system identification, a proportional-integral (PI) controller was used to obtain the input-output experimental data of the *plant*. The ground motion displacement data were used as the reference signals for the PI controller, which directly controls the voltage input to the servo valve of the actuator, and the output response of the table was recorded. Based on the collected input and output data of the shake table system, the open-loop model of the *plant* can be obtained. Fig. 4 shows the obtained Bode diagram of the open-loop shake table system. Based on this Bode diagram, the transfer function, G_{vd}, for the *plant* can be derived as shown in Eq. (1).

$$G_{vd} = \frac{-22.14s^7 + 144.3s^6 + 3.816*10^4 s^5 + 1.929*10^6 s^4 + 5.474*10^6 s^3 + 3.994*10^6 s^2}{0.135s^8 + 17.09s^7 + 736.4s^6 + 1.562*10^4 s^5 + 4.547*10^4 s^4 + 1.942*10^4 s^3 - 2.298*10^4 s^2 - 519.8s} \quad (1)$$

Fig. 5 shows the pole-zero map for the open-loop shake table system model. This plot shows that the open-loop shake table system has one right hand plane zero, which results in the non-minimum phase problem, including the phase delay, of the open-loop system. It should be noted that the right-hand plane zero of the open-loop system will attract the pole of the closed-loop system as the control gain becomes larger and makes the system become unstable. This explains why a traditional linear shake table controller tends to cause instability. Since the non-minimum phase system is hard to be dealt with by a simple linear controller, such as the PID controller, the more advanced controller is required to achieve satisfactory tracking performance.

Moreover, it should be noted that, in order to well describe the frequency response of the system in a wide frequency range, the order of the transfer function of the system cannot be arbitrarily reduced; thus, the resulting transfer function model has a high order. This also makes it difficult to apply a low-order linear controller to achieving robust tracking performance and stability.

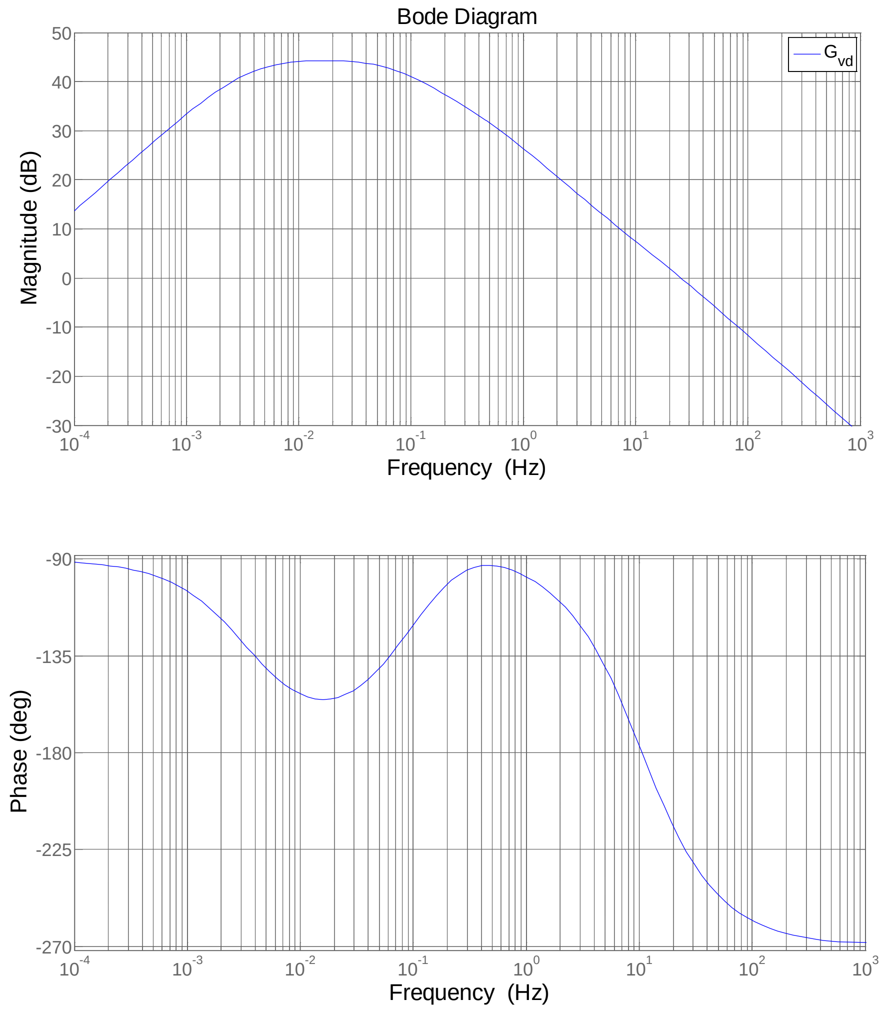


Fig. 4 Bode diagram of the open-loop shake table system

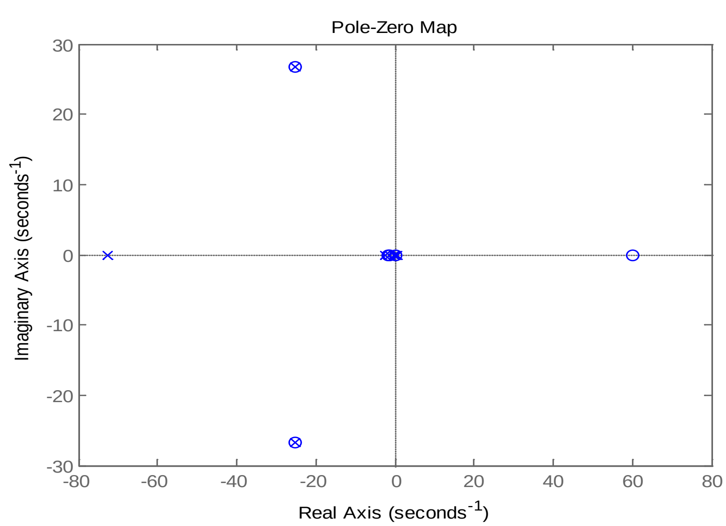


Fig.5 Pole-zero map for the open-loop shake table system

In this paper, a PID controller, which is described by Eq. (2), is designed using the above transfer function model.

$$C = \frac{-0.00131\left(s-90.97\right)\left(s+0.1317\right)}{s} \qquad (2)$$

where s denotes the complex variable in the Laplace domain.

The performance of this controller was compared with the MPC-based hierarchical controller. Fig. 6 shows the frequency response of the open-loop system, PID controller, *C*, and the closed-loop system compensated by the PID controller. As shown in the Bode plot in Fig. 6, the closed-loop system compensated by the PID controller has the bandwidth of ~3 Hz, which implies that the chosen PID controller is able to achieve good tracking performance for the reference signal with the frequency up to 3 Hz. Since the ground motion data of the earthquake normally contains frequency components above 3 Hz, this PID controller cannot fulfill the shake table testing need. A high-level MPC controller will be added and integrated with the low-level PID controller.

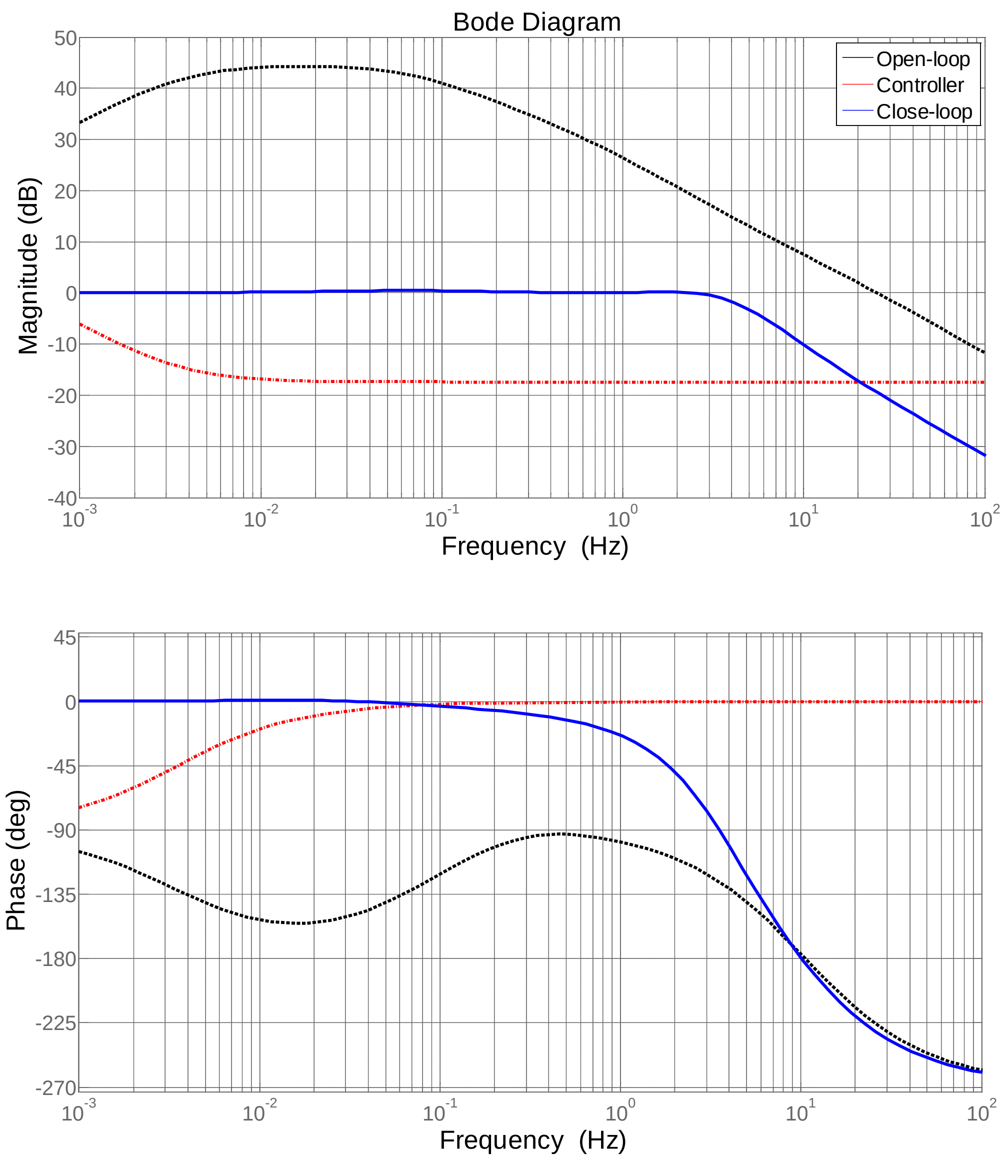


Fig.6 Frequency response of open-loop system, closed-loop system and the designed PID controller

4. Model Predictive Controller Design

The Model Predictive Control (MPC) was originated in the late 70s. Its control technique has been developed considerably since then. MPC is an optimization-based control method, it normally requires large computation power to resolve the constrained optimization problem, which is one of the major hurdles for its real-world applications, especially in the application of real-time control for nonlinear systems. With the advancement in the computer hardware, practical applications of MPC become more prevalent. MPC relies on the dynamic model to predict the system's behavior and makes the optimal decision for the control input to regulate the shake table. The main advantage of MPC is that MPC has the ability to predict system response, and it can correct the control actions accordingly [4].

Fig. 7 shows the control architecture for the MPC-based shake table control. The processing model (P) represents the close-loop servo control system, which is the shake table system compensated by the low-level controller. The goal for MPC is to generate an optimal input sequence to regulate the system output to track the reference input data in the finite horizon length (also called prediction horizon). Fig. 8 shows the relation between MPC input sequence and predicted output. The future outputs for a prediction horizon N are predicted at each instant t using the process model. These predicted outputs y (t + k | t) for k = 1. . . N depend on the known values up to instant t (past inputs and outputs) and on the future control sequence u (t+k | t), k = 0…N-1, which are those to be sent to the system and calculated.

At every time interval, MPC will base on the predicted system output and the cost function to generate an optimal control sequence with a selected length (control horizon) and implement the first step of the control sequence. At the next time interval, MPC will calculate the new optimal control sequence since the new output signal at the next time step is back and the predicted system output should be changed. The design of MPC can be divided into the following three parts: Model, Cost Function and Control. The whole design procedure will be presented in this section.

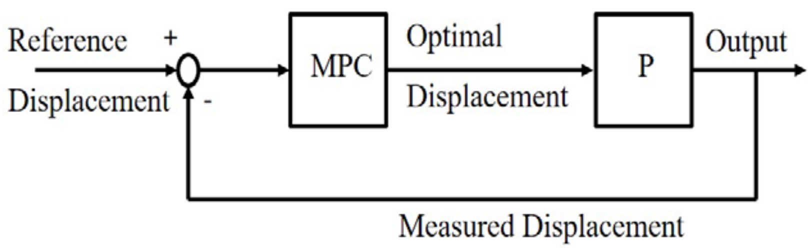


Fig. 7 Proposed MPC-based shake table control structure

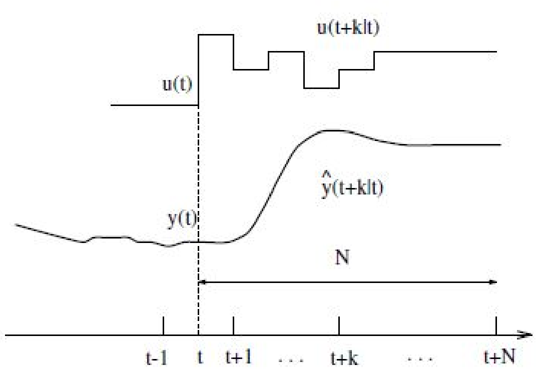


Fig. 8 Relationship between the MPC input sequence and predicted system output

4.1 Model

The first step in designing a MPC is to build a numerical model of the plant. In this paper, the input and output of the process model are chosen to be the reference displacement signal and the measured displacement of the table, respectively. The process model for the MPC design is actually the closed-loop system model compensated by the PID controller, and it is described in by Eq. (3). Since the compensated system has good displacement tracking performance in the low-frequency range (below 3 Hz), the main function of the MPC is to improve the tracking performance of the PID-compensated system in the high-frequency range (above 3 Hz).

$$P = \frac{-16.32s^8 - 189.3s^7 + 3.002*10^4 * s^6 + 1.932*10^6 s^5 + 2.987*10^7 s^4 + 7.942*10^7 s^3 + 6.288*10^7 s^2 + 6.9526*10^6 s + 8.961*10^{-11}}{s^9 + 125.3s^8 + 7164s^7 + 2.276*10^5 s^6 + 4.004*10^6 s^5 + 3.506*10^7 s^4 + 8.14*10^7 s^3 - 6.032*10^7 s^2 - 6.894*10^6 s} \quad (3)$$

4.2 Cost Function

The cost function as shown in Eq. (4) used to evaluate the performance of MPC,

$$\mathrm{J} = w_{disp}(r_{disp} - y_{disp})^2 + w_u \Delta u^2 \quad (4)$$

where r_{disp} is the reference displacement, y_{disp} is the displacement measurement feedback, w_{disp} and w_u are the weighting factors for penalizing the displacement tracking error and the input change rate, respectively. The constraints in the physical system should also be considered and the above cost function needs to be subject to these constraints. For example, the length of the actuator stroke limits the displacement signal in a bound, and this restriction can be imposed to the MPC by setting the limit on the displacement control input.

4.3 Control

The goal of MPC is to calculate the control input sequence to reduce the cost function value to the minimum in a finite horizon. Since the adopted process model is linear and the cost function, i.e. Eq. (4), is in the quadratic form, the resulting MPC is also linear and the optimal control input can always be obtained by using the convex optimization method. The control law of MPC can be represented by Eq. (5).

$$u^*(k) = \arg\min_u J(k) \quad (5)$$

where the length of control input sequence is defined as the control horizon.

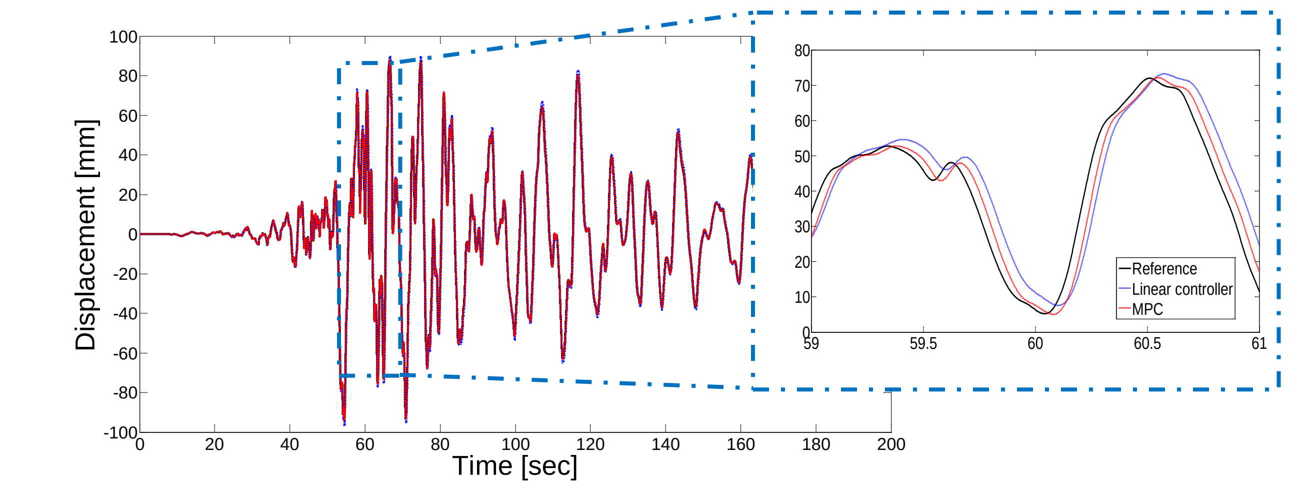
At the next time step, the algorithm will compute the new optimal control input sequence based on the measurement at current time step and new prediction of the model output. The proposed MPC controller and the shake table model obtained in section 3 are implemented in Simulink [5] and compared with the traditional PID controller. Table 1 shows the controller parameters used in the MPC setup. It should be noted that the selection of the prediction horizon and control horizon will affect the computation load and performance of the MPC, and they should be adjusted if the computing time is too long or the control performance is not acceptable.

Table 1. MPC parameters

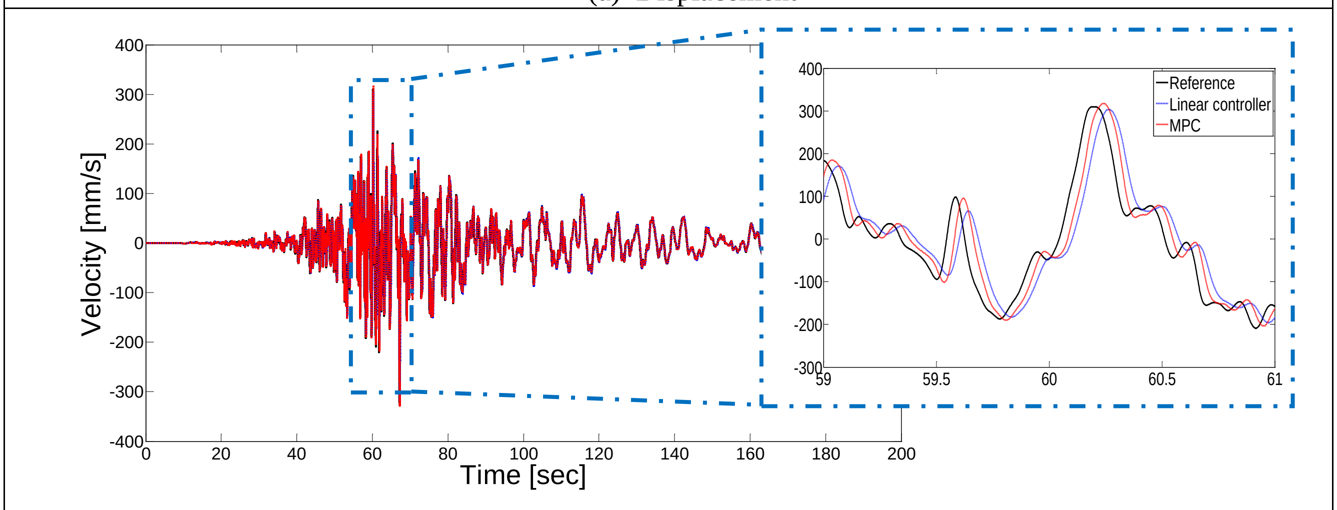
Control interval	0.002
Predict horizon	35
Control horizon	4
Control input Maximum	300(mm)
Control input Minimum	-300(mm)
Output weight (w_{disp})	4.95
Input rate weight (w_u)	0.02

5. Simulation Results

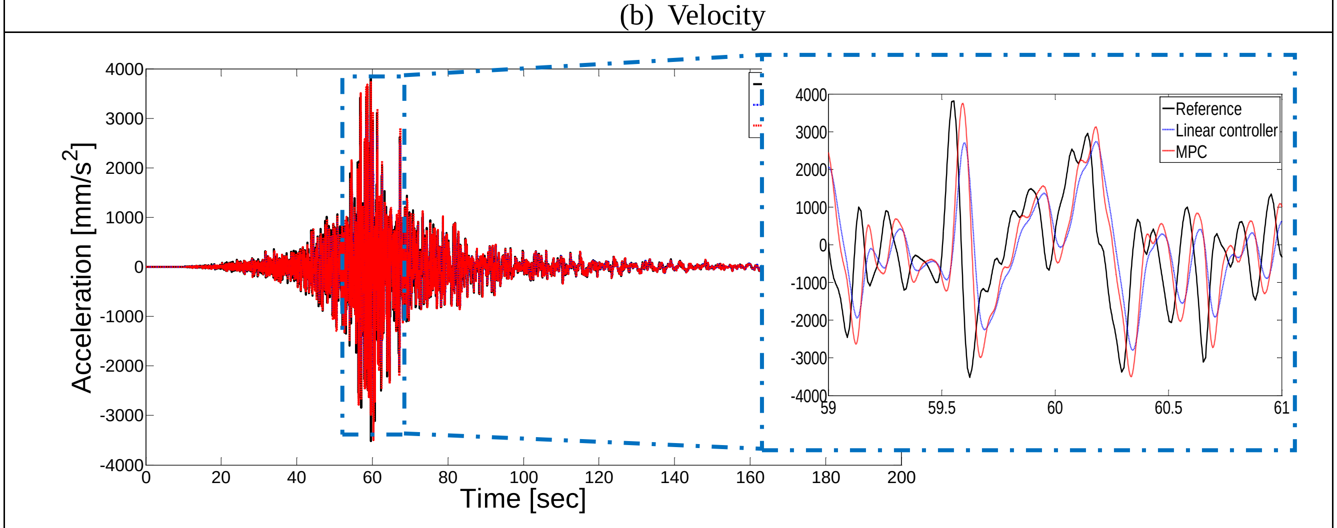
The performance of the proposed MPC-based shake table controller is verified through simulation using the earthquake time-history records. Fig. 9 shows the simulation results obtained using the 2003 Hokkaido Japan earthquake record as the reference signal. Fig. 9(a) shows that the MPC reduces the tracking error and the phase delay in the displacement response. Fig. 9(b) and (c) show that the MPC has slightly better tracking performance in velocity and acceleration tracking.



(a) Displacement



(b) Velocity



(c) Acceleration

Fig. 9 Comparison of the table performances

In order to further investigate the acceleration tracking performance, the spectrum analysis of the acceleration response is performed and shown in Fig. 10. The result shows that the MPC has better acceleration tracking performance than the PID controller, in particular, in the high frequency range. These simulation results demonstrate that the proposed MPC, which is built using the hierarchical control framework, can outperform the traditional PID shake table controller, and has very high potential for the development of the high-performance shake table control system.

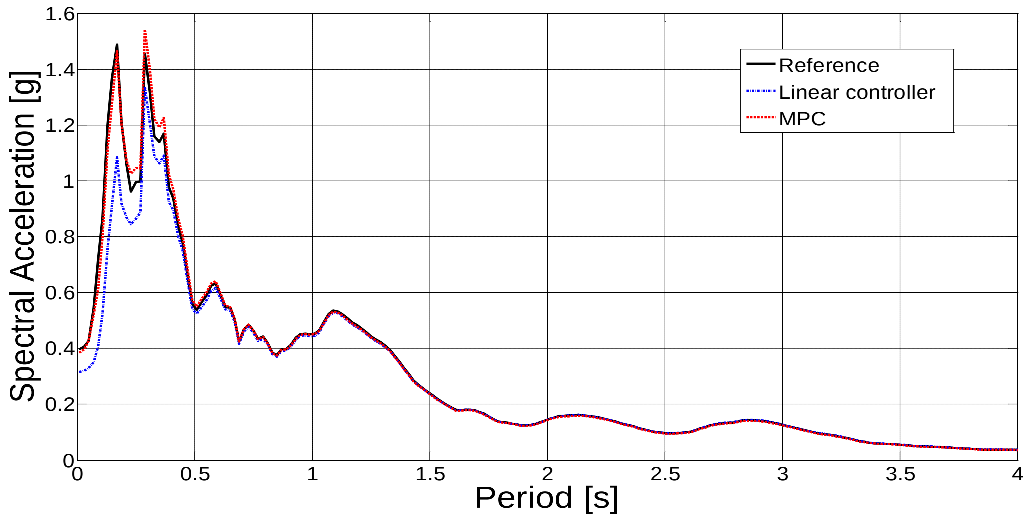


Fig. 10 Spectral acceleration

6. Conclusion

In this paper, a hierarchical control framework with model predict controller was used to regulate the shake table control. Closed-loop system identification is performed, and the model for the open-loop shake table system is derived. The low-level controller is then designed using the PID controller. Based on the closed-loop system model, a hierarchical control framework with MPC controller is formulated. The results show that the proposed hierarchical control framework with MPC controller can improve the acceleration tracking performance compared to the PID controller along. Hence, the feasibility of the proposed hierarchical MPC-based shake table control method is demonstrated.

7. References

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