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Research Article

A Study on Precision Stage with Displacement Magnification Mechanism Using Flexure-Based Levers

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Abstract: This study presents a precision stage driven by a piezoelectric actuator and equipped with a displacement magnification mechanism for the purpose of easy displacement measurement. The displacement magnification mechanism consists of flexible hinges and lever mechanisms. The developed stage is able to provide accurate measurement by virtue of the displacement magnification mechanism, but it is exposed to severe residual vibration. In order to overcome the drawback, this study develops a method for reducing residual vibration by using a simulation model for the stage system that takes into account the dynamics of the system and the hysteretic characteristics of the piezoelectric actuator. The Bouc-Wen model is employed to represent the hysteretic characteristics of the actuator. A comparison between simulation and experiment is made to find the best simulation model for the developed system. Input shaping is applied to eliminate the residual vibration from the stage. An improved input shaper is designed to overcome the ineffectiveness of input shaping due to the hysteresis by using the proposed simulation model. Simulations and experiments prove that the proposed simulation model is very useful to investigate the system and that the proposed stage can provide accurate positioning with small residual vibration.

Keywords: Displacement magnification mechanism, flexure-based lever, hysteresis model, input shaping, optimization, piezoelectric actuator

INTRODUCTION

This study presents a novel sub-micron stage of which displacement is magnified to be measured easily by using a low-cost displacement sensor. Unlike other measurement-assisting methods with displacement magnification (Ha *et al*., 2013), the proposed sub-micron stage, which was first introduced by Bae *et al*. (2009), is equipped with a displacement magnification mechanism based on levers with flexure hinges. It is well known that a combination of piezoelectric actuators and flexure hinges is of good use to secure high precision for positioning systems (Liaw and Shirinzadeha, 2008; Bae *et al*., 2009; Kim and Cho, 2009; Tian *et al*., 2009; Ha *et al*., 2013). However, piezoelectric actuator, in general, allows only limited range of stroke. Many research works have focused on how to extend the stroke of piezoelectric actuators (Chu and Fan, 2006; Choi *et al*., 2007; Bae *et al*., 2009). The previous experimental study has revealed that such a lever mechanism with flexure hinges can easily magnify the small displacement of piezoelectric actuator to hundreds microns but may be exposed to excessive residual vibration (Bae *et al*., 2009). The hysteresis inherent in the piezoelectric actuator also causes inaccuracy in the stage (Bouc, 1967; Wen, 1976; Sain *et al*., 1997; Chu and Fan, 2006; Choi *et al*., 2007; Kwok *et al*., 2007; Charalampakis and Koumousis, 2008; Fung and Lin, 2009; Fung *et al*., 2009).

The goal of this study is to make the proposed stage system more accurate and vibration-free. To this end, we develop a dynamic model for the proposed stage system and then improve its performance in terms of simulation and experiments. The dynamic model accounts for the dynamics of the system, as well as the hysteretic characteristics of the piezoelectric actuator. A hysteresis model, called Bouc-Wen model (Bouc, 1967; Wen, 1976; Sain *et al*., 1997; Kwok *et al*., 2007; Charalampakis and Koumousis, 2008), is employed to represent the hysteresis in the system. The parameters involved in the model are determined by correlating the simulation and experiment. Simulation is made to improve the performance of the stage. In this study, input shaping (Singer and Seering, 1990; Singhose and Seering, 2007) is applied for vibration reduction in the micro-stage. Input shaping has been widely used as an

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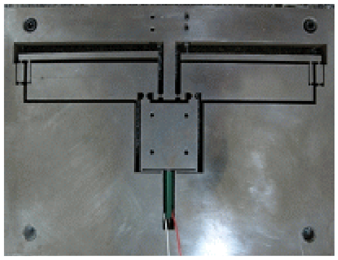
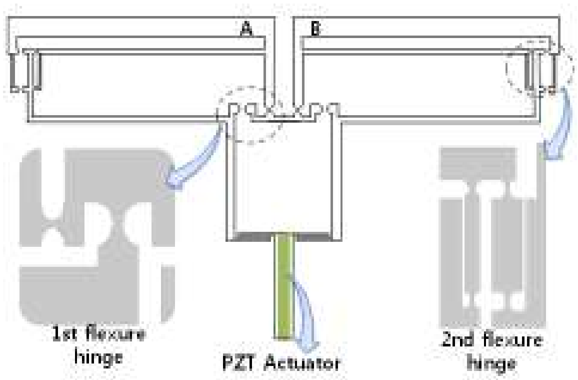


(a) Prototype



(b) Schematic diagram

Fig. 1: Experimental stage with displacement magnification mechanisms

effective tool for removing residual vibration, but there are few research results which focus on input shaping application to systems with hysteresis. To have better performance of input shaping in the presence of hysteresis, this study proposes an improved input shaper designed by virtue of optimization with the dynamic model. Experiments are performed to test the system performance and also demonstrate the improved input shaping on the micro-stage. The experimental results show that the proposed simulation model is very useful to improve the performance of the stage and that the proposed stage can provide very accurate positioning with small vibration.

MICRO-STAGE WITH DISPLACEMENT MAGNIFICATION MECHANISM

Experimental system: Figure 1 shows the experimental stage under consideration. This system employs a combination of levers and flexure hinges. Two identical two-step lever mechanisms are symmetrically placed to magnify the displacement of the piezoelectric actuator and also to secure linear motion. The flexure hinges as indicated in Fig. 1b serve as the hinge for lever motion and at the same time provide restoring force for the levers. The total magnification ratio of the current lever mechanisms is 30. The central part of the system is the stage that is actuated by a piezoelectric actuator. Then, the stage movement is magnified by the two-step lever mechanisms. A low-cost displacement sensor may be adopted to measure the displacement at the ends of the second-step levers (points A and B in Fig. 1b) so as to indirectly estimate the stage displacement.

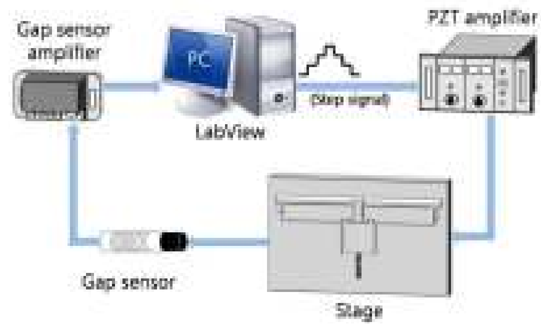
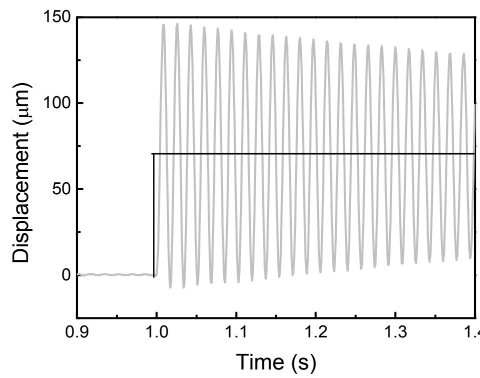
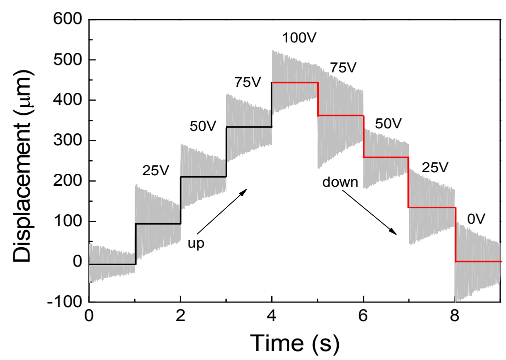


Fig. 2: Experimental setup



(a) Single-step response



(b) Multi-step response

Fig. 3: Experimental step responses

Figure 2 shows a schematic diagram of the experimental setup, which consists of the stage, a PC, a piezoelectric amplifier, an eddy current type displacement sensor and its associated amplifier.

Step responses of the system: Figure 3 shows experimental step responses of the system measured at point A, in the vicinity of the end of the upper lever bar where the displacement is maximized. Severe residual vibration is induced by a step input. Moreover, a bit of beating phenomenon occurs due to the presence of manufacturing imperfection in the two symmetrical displacement magnification mechanisms that are supposed to be identical in design. Figure 3b shows a multi-step response of the system. We can witness severe vibration due to the flexibility with light damping, as well as asymmetric behavior due to the hysteresis.

DYNAMIC MODELING AND ANALYSIS

Dynamic model: Figure 4 shows a schematic model for the proposed sub-micron stage system. The dynamic equation of motion for one lever part of the system can be written by:

$$m\ddot{x} + c\dot{x} + kx = k(d_e V - h) \tag{1}$$

or,

$$\ddot{x} + 2\xi\omega_n c\dot{x} + \omega_n^2 kx = \omega_n^2 (d_e V - h) \tag{2}$$

where,

- x : The displacement
- h : the hysteresis variable
- m, c and k : The mass, the viscous damping and the stiffness
- d_e and V : The piezoelectric coefficient and the input voltage for the piezoelectric actuator
- ω_n and ξ : The natural frequency and the damping ratio

The aforementioned experimental step responses showed that hysteresis plays a significant role in the dynamic behavior of the current system, especially when a large input is applied. For the purpose of investigating the dynamic characteristics of the system, a hysteresis model, called Bouc-Wen model (Bouc, 1967; Wen, 1976; Sain *et al*., 1997; Kwok *et al*., 2007; Charalampakis and Koumousis, 2008), is employed in this study. Equation (3) is a first order nonlinear differential equation that describes the hysteretic relationship between the hysteresis variable h and the voltage rate $\dot{V}$:

$$\dot{h} = \alpha d_e \dot{V} - \beta |\dot{V}| h |\dot{h}|^{n-1} - \gamma \dot{V} |h|^n \tag{3}$$

For this model, there are four parameters to be determined: α is related to the amplitude, β and γ are related to the shapes of the hysteretic curve and n is an integer constant which is relevant to the transition from elastic to post-elastic branch (Kwok *et al*., 2007). In general, n is selective number based on the severity of nonlinear characteristics. In the study, n is selected 1. Then, Eq. (2) is simplified as:

$$\dot{h} = \alpha d_e \dot{V} - \beta |\dot{V}| h - \gamma \dot{V} |h| \tag{4}$$

Equations (2) and (4) should be solved together in order to simulate the system time responses.

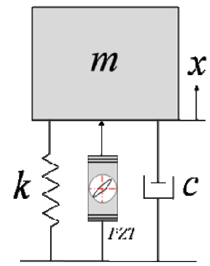


Fig. 4: Conceptual dynamic model of the system

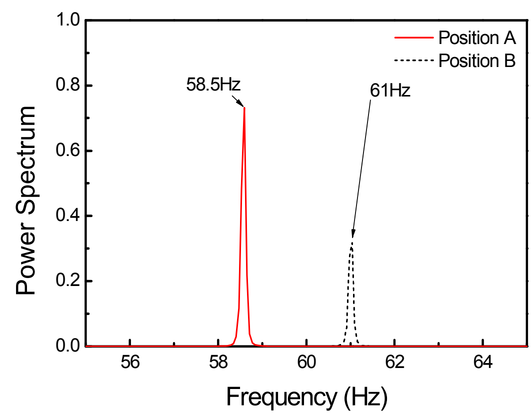
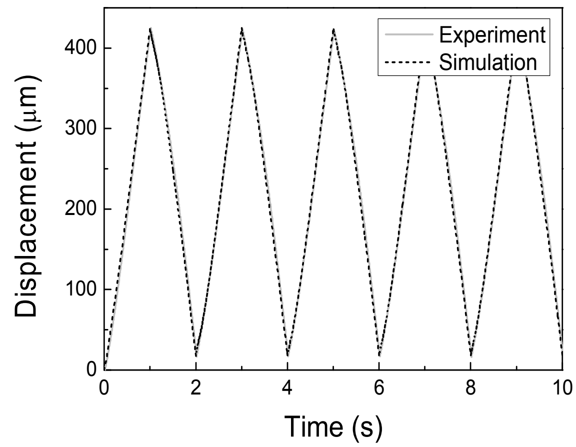


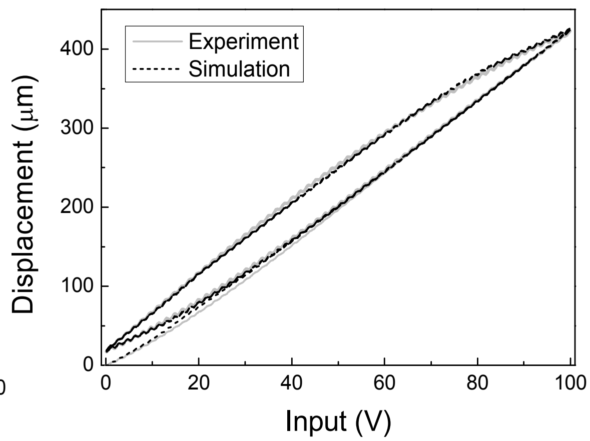
Fig. 5: Power spectral density functions from step responses

Parameter identification and validation: The first step to simulate a system with hysteretic model is to identify the parameters associated with the system model. It is easy to identify the natural frequency and damping ratio from Fig. 3a. Figure 5 shows the power spectral density functions from the experimental step responses. Two distinct peaks are observed: these two peaks are relevant to the natural frequencies for the two lever mechanisms.

For identifying the unknown parameters involved in Eq. (4), experiments and simulations are performed for the case when a triangular type input is applied to the system. The three parameters of the hysteresis model, α, β and γ in Eq. (4) are estimated by minimizing the difference between the measured and simulated responses. Figure 6 shows the measured and simulated time responses and their associated hysteresis loops with the triangular input.

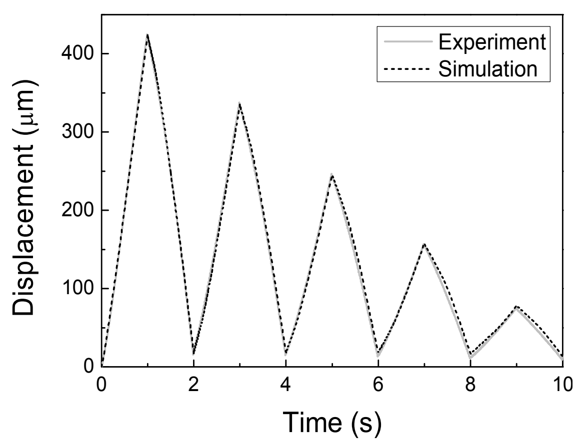


(a) Time response

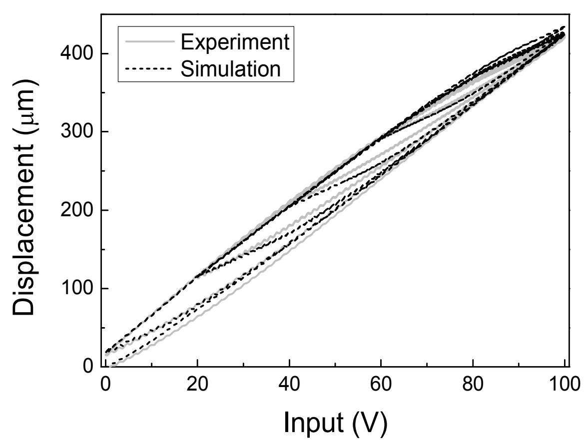


(b) Hysteresis loop

Fig. 6: Comparison of measured and simulated time responses and hysteresis loops for the system

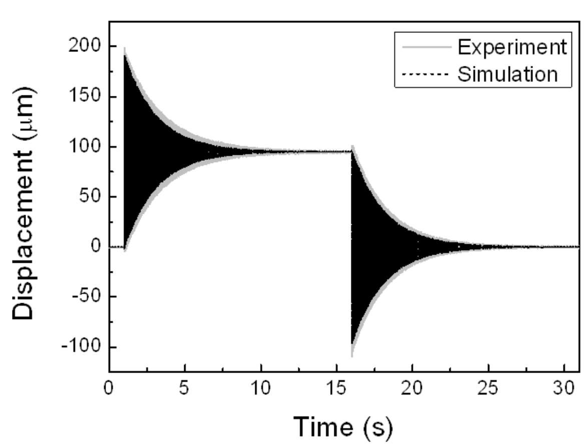


(a) Time response

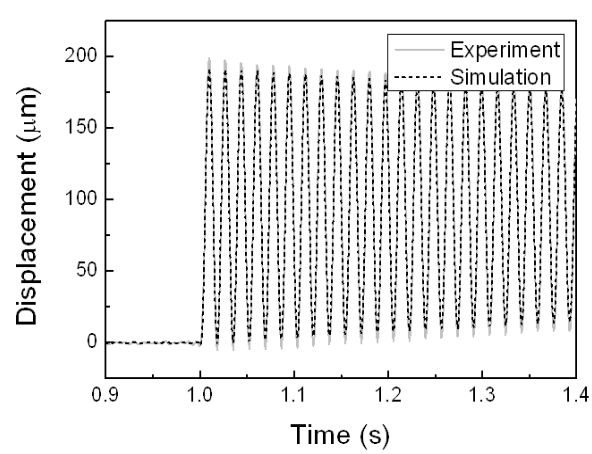


(b) Hysteresis loop

Fig. 7: Comparison of measured and simulated time responses and hysteresis loop for the system with triangular input of which amplitude changes with time



(a) Wide



(b) Zoomed

Fig. 8: Comparison of simulated and measured step responses

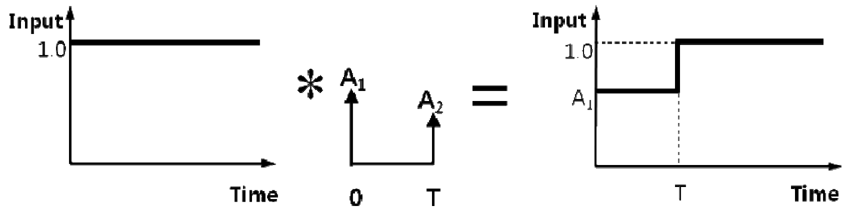


Fig. 9: Illustration of input shaping process with a ZV input shaper

In order to validate the proposed hysteresis model and identified parameters, a simulation result is compared with the experimental result for a triangular input whose magnitude is a function of time. Figure 7 shows the measured and simulated responses for the system. The good agreement between the measured and simulated results may lead to a conclusion such that the proposed hysteresis model can well represent the experimental system.

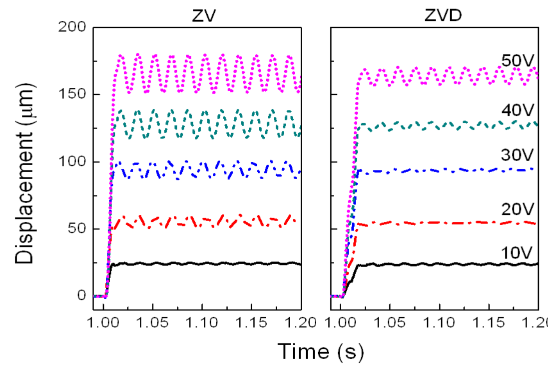
Figure 8 compares measured and simulated step responses when an input of 30 V is applied to the piezoelectric actuator. The measured and simulated responses are very close to each other. The slight difference between the measured and simulated responses is due to the beating phenomenon associated with the vibration coupling between two parallel lever mechanisms.

INPUT SHAPING FOR RESIDUAL VIBRATION REDUCTION

As observed in the experimental step responses, the proposed system manifests severe residual vibration. To reduce such residual vibration, we apply input shaping.

Conventional input shaping: Figure 9 illustrates an input shaping process with a simple input shaper, called ZV (Zero Vibration) (Singer and Seering, 1990; Singhose and Seering, 2007) shaper, for reducing residual vibration. Figure 10 shows experimental step responses for several different input magnitudes when the ZV and ZVD (Zero Vibration and Derivative) (Singer and Seering, 1990; Singhose and Seering, 2007) input shapers are applied to the system. It is obvious from the figures that the ZV shaper does not work well when the system is subjected to high-magnitude input. The ZVD shaper is more robust than the ZV shaper against the inaccuracy in natural frequency or damping ratio. Apparently, the ZVD shaper shows better performance than the ZD shaper. This implies that, to a certain extent, robustness of input shaper can alleviate the ineffectiveness of input shaping due to the nonlinearity by hysteresis.

More robust shapers such as EI (Extra-Insensitive) shaper (Singhose and Seering, 2007) can further reduce the residual vibration of the system, however, with the sacrifice of the rise time. It is always desirable to minimize the rise time and make the command simple



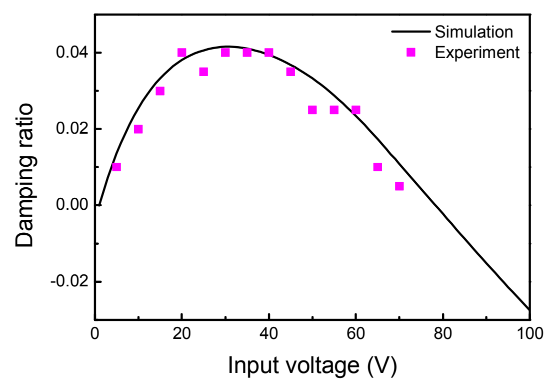
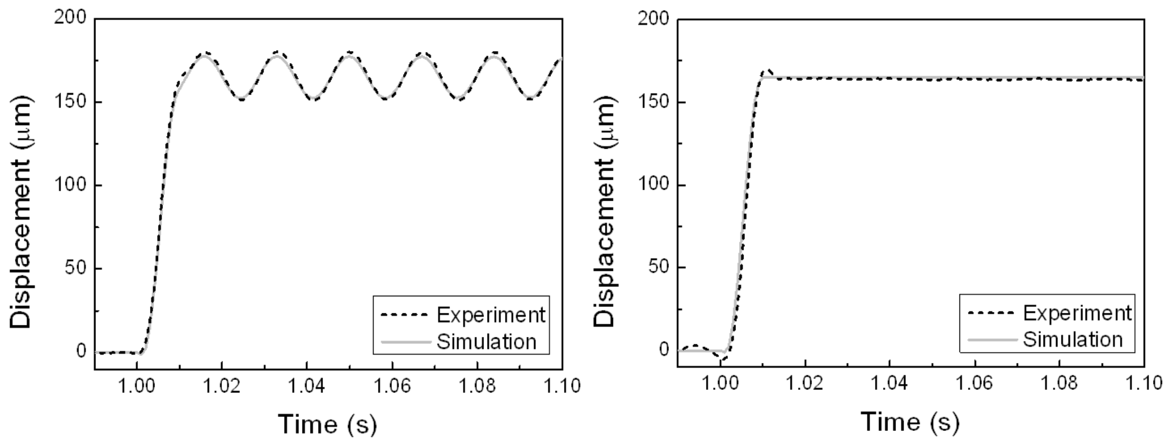


Fig. 11: Optimal damping ratio as a function of input voltage

in most applications. In the next section will be discussed how to improve the simplest shaper, ZV shaper, to work well for a wide range of input magnitude.

Improvement of input shaper: Several input-shaping approaches have been developed to cope with residual vibrations in non-linear systems (Kinceler and Meckl, 1995; Dimitry and George, 1998; Lawrence *et al.*, 2005; Stergiopoulos and Tzes, 2005; Smith *et al.*, 2002; Daqaq *et al.*, 2008; Blackburn *et al.*, 2010a, b). However, there are few reported results for input-shaping applications to non-linear systems due to hysteresis. In the case of slightly non-linear systems, robustness of input shapers can overcome the system non-linearity so as to reduce the residual vibration quite well. For most non-linear systems, however,



(a) ZV (b) Optimal

Fig. 12: Comparison of measured and simulated step responses when the ZV and optimal ZV shapers are applied (50V input applied)

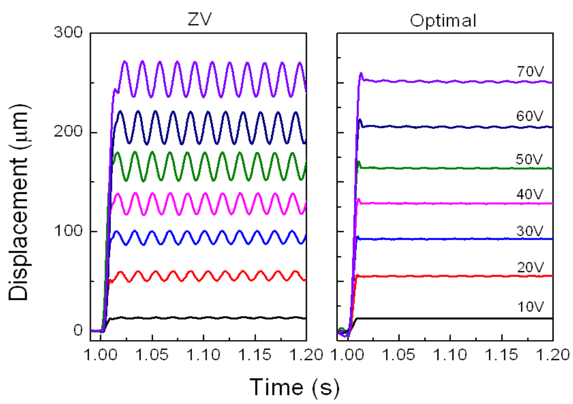


Fig. 13: Experimental step responses when the ZV and optimal ZV shapers are applied

conventional input-shaping techniques are not straightforward to apply. Here, we modify the ZV shaper to be able to account for the hysteresis.

Here, we treat the damping ratio for generating the input shaper as a design variable. Then, we search for the optimum value to suppress the residual vibrations. To this end, the following cost function representing the amount of residual vibration is defined:

$$J(\varsigma_s) = abs\{y_{peak} - y_{valley}\} \quad (5)$$

where, y_{peak} and y_{valley} are the first peak and valley of the time response to the applied input right after the command duration is over. Figure 11 compares the theoretically and experimentally obtained optimal damping ratios for shaper design as a function of input voltage. Notice here that the optimal damping ratio may become negative for high voltage input. This implies that the second impulse magnitude becomes greater than the first one. In other words, the second impulse contributes the response greater than the first impulse at the time of second impulse. This is very unlikely for linear time-invariant systems. Figure 12 shows typical results of experiment and simulation with the conventional ZV and the optimal ZV when 50 V is applied as a step input. The experimental results are in good correlation with the simulation results. The optimal ZV shaper results in almost zero residual vibration. Figure 13 compares the experimental step responses with the ZV and the optimal ZV when the step input magnitude varies. The optimal shaper leads to excellent results over the entire range of input while the ZV shaper deteriorates as the input magnitude increases.

CONCLUSION

This study presented a novel micro-stage that is actuated by a piezoelectric actuator and equipped with a displacement magnification mechanism to easily measure its displacement. The displacement magnification mechanism consists of lever mechanisms and flexure hinges. A dynamic model for the stage is developed to simulate and enhance the vibration and precision. A hysteresis model, called Bouc-Wen model, is employed which accounts for the hysteretic characteristics inherent in the piezoelectric actuator. The hysteretic parameters were identified and validated for the developed system through correlating the simulations and experiments. Simulations and experiments were also made to improve the performance by introducing input shaping. An improved input shaper was designed by means of optimization based on the system model. The simulations and experiments proved that the developed model can well represent the developed micro-stage system and that the proposed stage can provide accurate positioning with negligible residual vibration.

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