Design and Control of a Compliant Stage with Reconfigurable Dynamic Characteristics by Incorporated Rubber Shear Damper

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Abstract

This paper presents the dynamic analysis and control system design of a compliant stage with reconfigurable dynamic characteristics, consist of a notch-based structure and a mechanical amplifier. Generally, compliant stages are usually fabricated of metallic structures. Such an approach could yield excellent performance in many applications with simple feedback controls incorporated. However, the system dynamic cannot be changed once the geometry of the stages is designed. In this work, we propose a dynamic characteristics reconfigured approach by incorporating polydimethylsiloxane (PDMS) layer to modify the dynamic characteristics of compliant structures. In order to implement the approach, a compliant stage is designed and realized. Essential performance and dynamic tests are conducted to examine the functional performances and dynamic characteristics of both the original and PDMS-modified stages. The dynamic testing results indicate that the PDMS materials can significantly increase the stiffness and damping coefficient of the stage for 45% and 6.7%, respectively. Finally, for assessing the possible advantage in precision control by using this structural reconfiguration approach, controller systems are designed based on loop transmission shaping and positive acceleration, velocity and position feedback methods. The experimental results demonstrate that settling time is indeed improved from 55.3ms to 36.2ms after the dynamic characteristics are adjusted.

Keywords: Compliant stage, PDMS rubbers, Reconfigurable dynamics, Positioning control.

1. Introduction

Compliant stages are critical subsystems in precision motion control for various industrial applications ranged from machining tool handling to sub-micron metrology⁽¹⁻²⁾. Generally, they are fabricated by using conventionally machining methods such as wire cutting of metallic structures. Such an approach has advantages of high stiffness and high reliability and this could yield excellent performance in many applications with feedback controls incorporated. However, the dynamic characteristics is usually unalterable once the geometry of the stages is designed. For example, for increasing stiffness of compliant structure 200%, the structural length should be redesigned and decrease to 70% of the original one if the other parameters of geometry were fixed⁽³⁾. Note, the low adjustable capability of dynamic characteristics leads to a major challenge of operating stages in different applications. As far as the cost of stage fabricated is concerned, a low adjustable capability of dynamic characteristics provides only certain application and results in an increase in actual application costs. In this sense, the stage design with reconfigurable dynamic characteristics could be easier to achieve verities application requirement.

For past decades, many techniques have been proposed to reconfigure the dynamic characteristics of compliant stages⁽⁴⁻⁵⁾. However, it is challenging to add traditional dampers due to the spatial consideration in many small-scale ultra-precision applications. As a result, how to effectively enhance adjustable capability of the dynamic

characteristics of compliant stage under space constraint is a non-trivial issue in precision positioning control. Polydimethylsiloxane (PDMS), due to its low stiffness and high damping nature, can be incorporated into compliant structures to reconfigure the system dynamics⁽⁴⁾. It is worthwhile to mention that PDMS is generally applied as biomedical materials⁽⁶⁾ and has new interests as precision positioning application⁽⁷⁾, recently. Previously, Yu⁽⁴⁾ successfully verified the damping enhancement mechanism through 3D printing structure. It should be noted, PDMS has stiffness and damping which is similarly with the 3D printing materials. In this sense, PDMS would also affect the system stiffness of the 3D printing structure significantly.

Motivating by the literature mentioned above, a dynamic characteristics reconfigured approach of metallic structure is proposed by incorporating PDMS in this work. The overall research flow is shown in Fig. 1. The developed of this stage with revisable dynamic characteristics can be implement with three steps. First, essential performance and dynamic tests are conducted to examine the functional performance and dynamic characteristics of the stage containing the original one and the one with PDMS incorporated. Second, for verifying the proposed the dynamic characteristics reconfigured approach, a feedback controller is designed based on loop transmission shaping to conduct a series of position experiments. Finally, for obtaining a better performance of control system, positive acceleration, velocity and position feedback controller is designed and applied in this work.

Fig. 1. Overall research flow

The rest of this paper presents the testing, and control of the stage in detail. A brief description on the stage design, realization and PDMS filling is addressed in chapter II and followed by the preliminary dynamic characterization results and presented the preliminary dynamic behavior of stage integrated with rubber is demonstrated in Section III. Subsequently, feedback controllers are design in Section IV and Section V briefly discusses the experiment results. Finally, Section VI present the conclusion of this work and provides future perspective and concludes this work.

2. Approach

2.1 Stage design and realization

In this section, the well-defined compliant stage⁽⁸⁾ and the mechanical amplifier are brief presented for evaluating the proposed adjustable capability enhancement strategy. Here, the design of which the XY fully decoupled parallel stage shown in Fig. 2 consists of four individual limbs connected at the center point in parallel. Each limb provides essential compliance and serves as a displacement amplification mechanism. The final dimensions are listed in Table 1 and the schematic plot of the structure is shown in Fig. 3. Li⁽³⁾ et al. has already conducted numerical analysis about this displacement amplification for a complete compliance analysis based on the potential energy analysis and Castigliano's theorem, the derivation of the stiffness. The technical detail on design analysis can be found elsewhere^(3-4,8). A finite element analysis performed by Abaqus is conducted in this work for accessing the structural compliance and to evaluate the state of stress during operation. The material used for constructing the stage is the conventional Aluminum 5052 with a Young's modulus of 69.3GPa and a Poisson's ratio of 0.33. As shown in Fig. 4, the structure at notch hinges have the highest stress level as expected and the first three natural frequencies are 94.2, 130.36, and 151.24Hz. Since the second resonant frequency is much higher than the first, the stage can be treated as the equivalent of a single degree of freedom system during operation without loss of generality. The amplification ratio and input-output stiffness of structure are all obtain by finite element analysis, as listed in Table 2. The error may result from the non-ideal boundary. Although PDMS should be added in the portions where the maximum stress is observed for efficiently

dissipating energy to change dynamic characteristics of the stage, the PDMS is incorporated in the position shown in Fig. 5. in the work instead due to the spatial concern. During movement, this design will still generate a shear force on PDMS and the dynamic characteristics changing effect should be realized as expected.

Fig. 2. XY fully decoupled parallel stage⁽⁸⁾

Table 1. dimensions of the stage (mm)

r	t	l_x	l_y	w	h_l	l_l	l_2
8	1.2	60	5	10	5	14	37.4

Fig. 3. The schematic plot of the compliant structure

2.2 Experimental setup

A brief functional block diagram of the stage control is shown in Fig 6(a) and the entire experimental setup is

shown in Fig 6(b) containing two AVM40-20 voice coil motors of which maximum output force is 54N as the actuators, two ASP-10-CTR capacitive probes of which measurement range is 254 μ m, resolution is 10nm and bandwidth is 10kHz used for characterizing the input and output displacements, a compliant stage and a dSPACE controller with 14-bit A/D and 14-bit D/A for data acquisition and for sending out controlled output for controlling the motion and the experiments are all executed with sampling rate of 10kHz. The voice coil motors actuate the stage and the capacitive probes for sensing the input and output movement. Therefore, major performances such as input-output stiffness, amplification ratio, natural frequencies, and even damping ratio, can be obtained. Moreover, real time control system experiments are implemented by dSPACE FPGA controller. This test system is firstly used to obtain the system dynamics and then, for performing the evaluation on stage control for validating the proposed conceptual design.

Fig. 4. The finite element simulation of the stage. (a)The original mesh and the mode shapes of the first three modes and (b) The von Mises stress contour.

Table 2. The amplification ratio and input-output stiffness

	Amplification ratio	input-output stiffness
Finite element analysis	13.91	0.3829 (μ m/N)

Fig 5 the position of PDMs incorporated

Fig. 6. (a) Experimental setup and (b) Block diagram of the stage control

3. System dynamic and modeling

3.1 Original stage dynamics

The stage is modeled as a single degree of freedom vibration system with a mass, M , a damper with damping coefficient, C , and spring, K . By force equilibrium, it can be shown that the transfer function, $G_{stage}(s)$, of this stiffness element can be expressed as

$$G_{stage} = \frac{1}{Ms^2 + Cs + K} \quad (1)$$

The mass M in the model is taken as the mass of the aluminum stage, 446 g. The stiffness is $0.34 \mu\text{m/N}$ which is determined by examining the open-loop step response and

is closed to the one obtained by finite element analysis. The damping coefficient C is hard to be obtained analytically and is finally experimentally determined by frequency sweeping. Experimental results and simulations are shown in Fig. 7 and consider the actuator system as one order system which has the expression of

$$G = G_{act} = K_a \times \frac{2\pi \times 200}{s + 2\pi \times 200} \quad (2)$$

which K_a is the coefficient of amplifier. The transfer function of the entire plant can be finally expressed as

$$G_{plant} = \frac{a}{s^3 + bs^2 + cs + d} \quad (3)$$

which $a = 5.06 \times 10^8$, $b = 1278$, $c = 3.121 \times 10^5$ and $d = 3.584 \times 10^8$

Fig. 7. (a) Open-loop step response and (b) frequency sweeping

3.2 Dynamic characterization of modified stage

It is also important to perform dynamic characterization of the stage with PDMS incorporated. The stiffness and damping are obtained by the same method as of original stage. Here, a series of step response experiments are conducted to test the variety of the system dynamic to valid the concept that the dynamic characteristics is adjusted after PDMS incorporated with different preload pressure. From the results of step response test, the damping coefficients are obviously changed as shown in Fig. 8. Moreover, the stiffness of the system can be increased 280% from the original one. Nevertheless, the damping ratios aren't enhanced as well due to the increasing of stiffness. Although, there can be several models which altered from the original one, we first present one kind of dynamic characteristics reconfigured stage in this work. The corresponding preload pressure of PDMS is chosen with trial and error method. For a comparative study, the frequency sweeping experimental results of this adjusted model and the original one are shown in Fig. 9.

Fig. 8. Step response corresponding to different preload pressure of PMDS

Fig. 9. Frequency sweeping experiment of original model and dynamic characteristics reconfigured model

4. Control system design

In order to verify this approach, three feedback controllers are design and adopted. In this work, we first present typical PID controller. Second, a loop transmission shaping (L.T.) method⁽⁹⁾ which designed by shaping the loop transmission of the system in frequency domain is used to achieve better performance of close loop system. After shaping loop transmission into desired from, the performance of the close loop system can be predicted. Finally, the positive acceleration, velocity and position feedback (PAVPF) controller⁽⁵⁾ is applied to the systems to achieve better performance. The block diagram of the system with the loop transmission shaping is shown in Fig. 10. The loop transmission is defined as

$$T_{open} = C_{lt}(s)G_{plant} \quad (4)$$

where G and C are the transfer function of the system and the controller containing notch filter to reducing the lightly damped resonant vibration and PI controller to improve the control bandwidth. Therefore, the loop transmission controller has the expression of

$$C_{lt}(s) = K_p \left(1 + \frac{K_i}{s} \right) \left(\frac{s^2 + \frac{d}{c} \omega_{notch}s + \omega_{notch}^2}{s^2 + \frac{1}{c} \omega_{notch}s + \omega_{notch}^2} \right) \quad (5)$$

where K_p , K_i , d , c and ω_{notch} are adjustable parameters. For a comparative study and obtaining better performance of control system, the positive acceleration, velocity and position feedback (PAVPF) controller is incorporated to deal the low damping behavior. The block diagram of this concept is shown in Fig. 10 and the transfer function of the PAVPF controller can be expressed as

$$C_{damp}(s) = \frac{\Gamma_2 s^2 + \Gamma_1 s + \Gamma_0}{s^2 + 2\xi\omega_p s + \omega_p^2} \quad (6)$$

The technical detail on design analysis can be found elsewhere⁽⁶⁾.

Fig. 10. (a) The block diagram of L.T. control and (b) The block diagram of PAVPF control

5. Experiment results

5.1 Step responses

In this section, positioning experiments are conducted through the experimental setup as shown in Fig. 6. First, a series of typical step response experiments with PID controller for a $25.4 \mu m$ step command of the system with PDMS incorporated are conducted and discussed. The control parameters of PID controller are tuned by trial and error method as K_p ranged from 0.003 to 0.011, $T_i=2.53 \times 10^{-4}$ and $T_d=6.325 \times 10^{-5}$. The experimental results are shown in Fig 11. It's obviously that the controller performance with only PID isn't good enough for high bandwidth required situation although the responses have nearly low overshoot. Moreover, the system becomes unstable after increasing a little of the proportional gain of PID controller. Second, loop transmission shaping controller experiments are conducted to determine the parameters of controller for all model containing the original system and the systems after dynamic characteristics modified by PDMS. Finally, the experiments of PAVPF controller are conducted. The experiments of PAVPF controller begin with step response and frequency sweeping. Experiment results containing with the open loop systems, the system with the PDMS and the one with both PAVPF and PDMS are shown in Fig. 12. It is apparently that the damping ratio is enhanced. Meanwhile, the output stiffness is increased from 0.001 to 0101. It is worth noting that a L.T. controller is incorporated to deal with the tracking errors here. The detail of PAVPF controller parameters are list in Table 3 and the detail of the corresponding L.T. controller parameters are list in table 4. The experimental results of all step responses are shown in Fig. 13. For comparison study, all step responses are controlled to similar overshoot and rise time. Thus, we can distinctly identify how dynamic characteristics reconfigured affect the settling time. From experiment results, it is visibly that the systems with PDMS and PAVPF controller are less oscillated and the corresponding settling time are slightly shorter when they reach the destination. Moreover, compared with the PID controller, L.T. controllers have much shorter rise time. The detail of control system performance index of L.T. controller is listed in Table 4.

Table 3. The detail of PAVPF controller parameters

Γ_0	Γ_1	Γ_2	ω_p	ξ
8338	43.36	0.18	171.8	0.34

Fig. 11. Typical step response with PID controller

Table 4. Parameters of L.T. controller

	K_p	K_i	d	c	ω_{notch}
Original system	0.047	1100	0.007	0.3	534.07
System with PDMS	0.065	1470	0.03	0.3	609.47
System with PDMS and PAVPF	0.051	1300	0.1	0.55	578.05

Fig. 12. (a) Open-loop step responses of all systems and (b) Frequency sweeping results of all systems

Fig. 13. Step response experimental results

Table 5. Control system performance index

	Overshoot	Rise Time	Settling time
Original system	6.4 %	17.3 ms	55.3 ms
System with PDMS	6 %	15.3 ms	49.7 ms
System with PDMS and PAVPF	7.5 %	16 ms	36.2 ms

5.2 Sinusoid tracking experiments

After determined the parameters of the loop transmission shaping controllers, real-time sinusoid trajectories tracking experiments are conducted. Fig. 14 and Fig. 15 demonstrates the comparison of the sinusoid tracking performance within different system under 1 and 50 Hz, respectively. As Fig. 14 and Fig. 15 shown, it is apparently that the tracking error of the control system with the PDMS incorporated and the PAVPF controller is lower than the others. In this sense, the bandwidth of the control system with the PDMS incorporated and the PAVPF controller is higher than the others.

Fig. 14. Sinusoid tracking experiments under 1 Hz

Fig. 15. Sinusoid tracking experiments under 50 Hz

6. Conclusion

In this work, a compliant stage with alterable dynamic characteristics is proposed aiming for adjusting the system dynamics of compliant mechanism-based positioning stage for different applicated situations. By utilizing high material damping capacity of elastomers, PDMS, the stiffness is increased 45% without any geometry redesigned. Besides, after introducing PAVPF damping control system, it is possible to enhance the equivalent damping factor of the system. The process mentioned above leads to a better situation for controller design for achieving multiple application situation and better positioning performance. This study composed of a compliant amplifier design, the location of PDMS material researching and control system evaluating for verifying concept in adjusting the dynamic of the stage. The preliminary results indicate that the proposed method could effectively adjusting the dynamic characteristics of the stage. A two degree of freedom version design is underway for allowing a more practical evaluation. Meanwhile, it is suggested that the dynamic characteristics reconfigured concept can be integrated with CCD camera for certain high valued applications.

Acknowledgment

This work is currently supported by the Ministry of Science and Technology (MOST) of Taiwan under contact numbers MOST 105-2221-E-006-100-MY3, MOST 108-2221-E-006-209, MOST 108-2622-8-006-014 and MOST 108-2221-E-218-027. Contributions from Yi-Hsuan Yu, and Yu-Ching Li of National Cheng-Kung University (NCKU) during the early stages of this work are greatly appreciated.

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