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ACTIVE VIBRATION ISOLATION SYSTEM USING THE PIEZOELECTRIC UNIMORPH WITH MECHANICALLY PRE-STRESSED SUBSTRATE

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ABSTRACT

In this paper, a pre-stressed piezoelectric unimorph made by a new fabrication method in room temperature, and an active vibration isolation system using the pre-stressed unimorph actuators are introduced. The fabricated piezoelectric unimorph, called PUMPS (piezoelectric unimorph with mechanically pre-stressed substrate), is an actuator in which actuation level is enhanced by displacement amplification mechanism that converts piezoelectric extension and contraction to large bending/pumping motion without sacrificing the actuation force. Preliminary vibration tests were performed to check the performance of PUMPS as actuators for active vibration control in a lab environment. Two feedback control schemes, the positive position feedback (PPF) and negative velocity feedback (NVF), were applied for active vibration control. Using a smart vibration isolation system with improved load capacity obtained by stacking pre-stressed piezoelectric unimorph actuators, about 10dB vibration reduction of the system was achieved near the resonant frequency region. With the preliminary vibration test results showing promising performance of PUMPS actuator in active vibration control, an integrated active vibration isolation system composed of PUMPS actuators is developed. The developed system contains compact analogue circuits and a sensor for PUMPS actuation and control, and power is supplied by Li-Polymer battery which means the system is completely standalone and portable. In addition, an integrated jitter isolation demonstration system was developed to demonstrate the degrading effect of jitter and the effectiveness of the developed integrated active vibration isolation system in improving the performance of optical payloads. Comparison of image qualities taken before and after the operation of vibration control system indicates that effective suppression of vibration disturbances can be achieved using the developed vibration isolation system with PUMPS actuators.

INTRODUCTION

A recent move towards the development of high performance observation and communication satellites has brought much emphasis on vibration isolation of payloads to achieve improved performance. Tasks such as taking high resolution images and communicating at high data rates require the payloads to remain relatively motionless, which unless satisfied, may result in significant degradation of performance and loss of data. For example, 10 microradian (0.00057 degree) angular vibration corresponds to 50m in the field of view at a distance of 500 km [1]. Fig. 1 illustrates how microvibration can cause a significant change in the line of sight and the resulting degradation in image quality. Although some of the jitter induced effects can be corrected through signal and image processing, removing vibration induced motion of the system to begin with is a better and, often, the preferred solution.

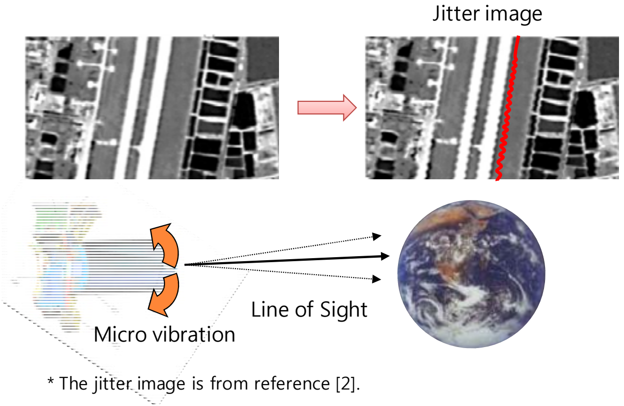


Fig. 1 Image degradation due to microvibration.

The sources of the unwanted performance degrading vibrations include operation of other critical components of the satellite such as reaction wheel assembly (RWA), control moment gyroscope (CMG) and thrusters for altitude control, cryocoolers for heat control, solar array drives and other scanning components, etc. Since these vibration disturbances cannot be avoided during the operational lifetime of a satellite, the key to the improved performance of vibration sensitive payloads depends on limiting the disturbances transmitted to them.

There are various ways to limit vibrations transmission to sensitive payloads but vibration isolation of the disturbance source or the sensitive component is the most common approach. Vibration isolation can be realized using passive or/and active components. Purely passive isolation systems require no input power and can attenuate high frequency disturbances but tend to aggravate vibrations at lower frequencies and often require some type of release and deployment device to survive harsh launch environment. For cases with stringent performance demands that cannot be satisfied by passive systems alone, higher isolation performance can be attained with active systems but at the expense of increased complexity and cost as input power and control system are required. Table 1 compares various vibration control schemes.

In this research, an active vibration isolation system utilizing smart material is tested for attenuation of vibration disturbances. Piezoelectric actuator is chosen after comparing merits and demerits of various smart materials apt for active vibration control. An Integrated active vibration isolation system is developed using piezoelectric actuators in multilayer stack configuration, and vibration tests are conducted to check and demonstrate its effectiveness in improving the performance of optical payloads by attenuating jitter.

ACTIVE VIBRATION SUPPRESSION SYSTEM USING SMART MATERIALS

Traditional actuators such as hydraulic, pneumatic and electromagnetic actuators that compose the bulkiest component of the active vibration isolation systems are now being replaced by smart material actuation. Some candidates include piezoelectric materials, shape memory alloys (SMA), electroactive polymer (EAP), etc.

Piezoelectric actuators, due to excellent frequency bandwidth, power density, good linearity and lightweight characteristics, have received much spotlight as a candidate to substitute conventional actuators. However, one major drawback of general monolithic piezoelectric actuators is limited level of actuation, typically a maximum of 0.1–0.2% of the induced piezoelectric strain in a longitudinal direction [4]. Research on increasing the level of actuation have resulted in the development of various externally leveraged [5, 6], internally leveraged [7-12] and frequency leveraged amplification actuators [13]. Numerous studies [14-18] using piezoelectric actuators in active vibration isolation have been conducted since Forward [19] reported a preliminary experimental demonstration of the feasibility of using piezoelectric transducers to damp mechanical vibrations in optical systems. Recently, piezoelectric actuators have been utilized as active components in the Satellite Ultraquiet Isolation Technology Experiment (SUITE) [1] and Miniature Vibration Isolation System [20] for the on-orbit jitter isolation of satellite payloads.

SMA actuators possess extremely high force-to-weight ratio and can be very simple and compact. However, many disadvantages also exist including low bandwidth and operation efficiency and that SMA actuators are difficult to control. Studies regarding development of SMA actuators include work by Gorbat and Russel [21], Mosley and Mavroidis [22] and Grant and Hayward [23]. SMAs in vibration control has been used mainly as a passive element [24, 25] but their role as active component is recently being reported [26, 27].

Table 1 Comparison of vibration control methods [3]

	Passive (P)	Active (A)	Semi-active
External energy requirement	Not required	Required	Little/Negligible
Components that provide forces	Nonadjustable passive elements	Active actuators	Adjustable passive elements
Forces provided to the isolated object	Forces are functions of the states of the system	Forces can be arbitrarily applied	Forces are (adjustable) functions of the states of the system
Simplicity	Simple	Complex	Between P and A
Weight	Heavy	Light	Between P and A
Cost	Inexpensive	Expensive	Between P and A
Typical components	- Rubber - Coil spring - Viscoelastic tape - Tuned mass damper - Shunted piezoelectric - SMA isolators	- Hydraulic actuator - Pneumatic actuator - DC motor - Various smart materials including PZT, EAP, SMA, …	- Variable orifice pneumatic damper - Tunable dampers - ER/MR damper - Adaptive piezo-shunt

As actuators EAPs are light, mechanically compliant and flexible, but have low actuation force, mechanical energy density and robustness. Due to EAP's similarities with biological tissues, especially in terms of force and stress characteristics, they are often called artificial muscles. Studies regarding vibration control using EAP actuators have been performed by Bandopadhya, Bhattacharya and Dutta [28, 29]. EAP actuators have also been applied to control space inflatable structures [30].

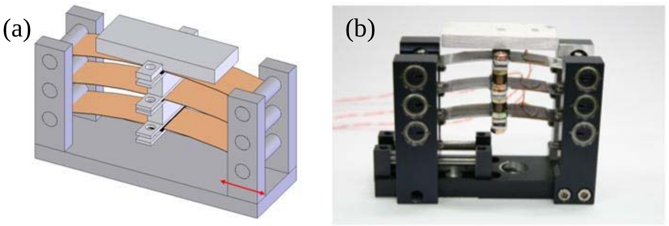


Fig. 2 An actuator module with three-layered PUMPS: (a) prototype design; (b) fabricated force amplification device.

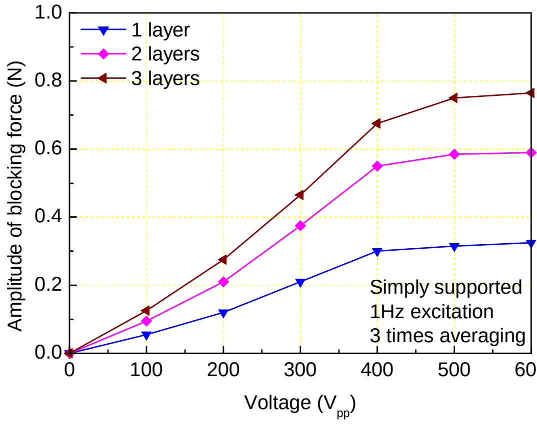


Fig. 3 Actuation force of the actuator system against the number of stacks.

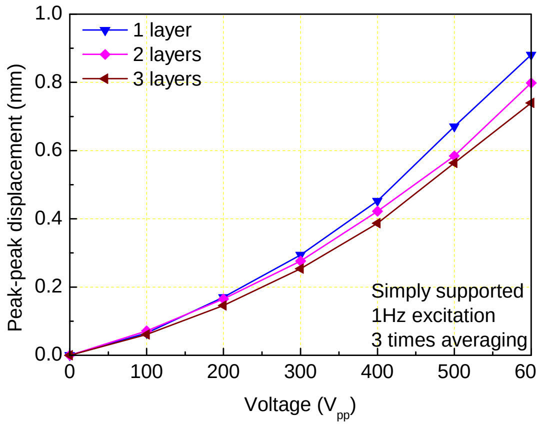


Fig. 4 Actuation displacement of the actuator system according to the number of stacks.

Among currently available smart materials applicable for active vibration control of structures, piezoelectric actuators possess most favorable characteristics and, for that reason, have been most widely used. The author's group has developed piezoelectric unimorph called PUMPS [31] which has high displacement and force performance. Thus, PUMPS is opted as piezoelectric actuator for active vibration control system, and its performance in isolating jitters is experimentally evaluated.

DESIGN AND EVALUATION OF THE ACTIVE VIBRATION ISOATIOR USING PUMPS ACTUATORS

In this section, PUMPS actuators with improved load capacity are presented and their potential in active vibration control is checked through a preliminary vibration test. PUMPS actuator is a unimorph actuator in which actuation level is enhanced by displacement amplification mechanism that converts piezoelectric extension and contraction to large bending/pumping motion without sacrificing the actuation force. However, higher load bearing capacity is required to apply the PUMPS actuator to active vibration isolation system. To achieve larger actuation force, three PUMPS actuators were assembled in a multilayer stack configuration as shown in Fig.

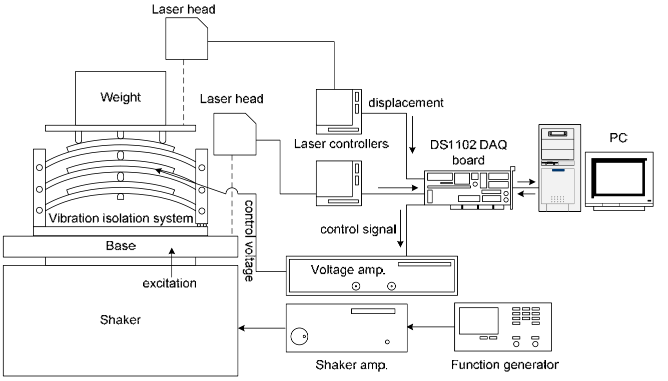


Fig. 5 Schematic of test setup for vibration control.

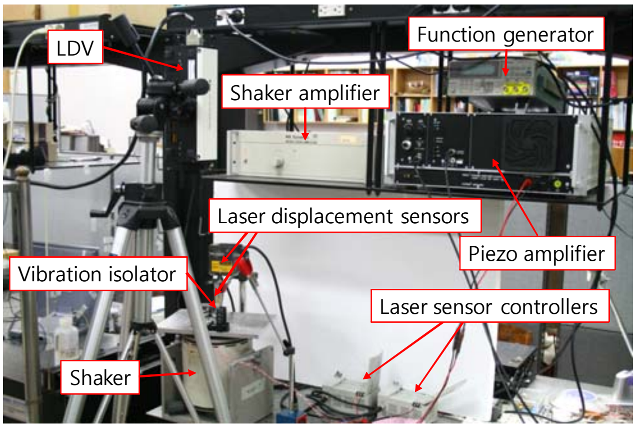


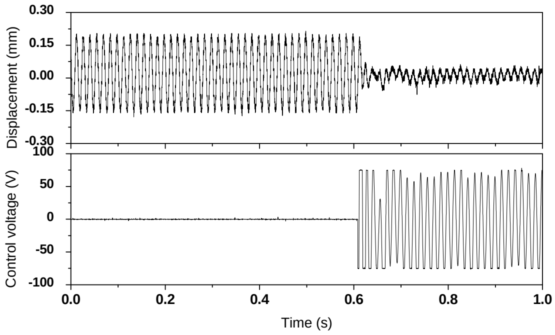
Fig. 6 Experimental setup for vibration control.

2. Using this design scheme, the force level of the isolator with three layers is increased up to about 150% compared with the isolator with a single layer as shown in Fig. 3. On the other hand, displacement level of the isolator with three layers is decreased a little compared with the isolator with one layer under same condition as shown in Fig. 4. In order to generate larger displacement, vibration isolator allowing free rotation at both ends and free translation at one end was constructed.

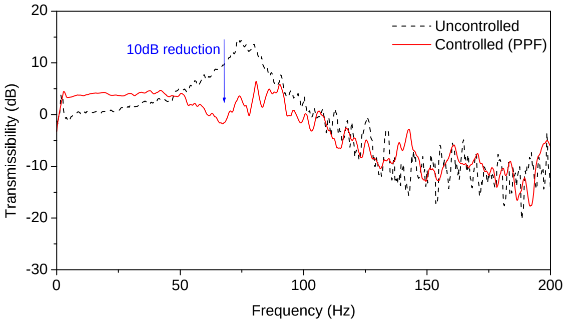
In order to investigate the vibration characteristics of the present vibration isolator, vibration test setup was prepared as shown in Figs. 5-6. The Experimental setup includes multilayered vibration isolator, shaker, amplifiers and data acquisition system in a laboratory environment. Preliminary test was performed using laser displacement sensors and piezoelectric amplifier. The dominant dynamics of the vibration isolator can be assumed as a single degree of freedom system, and two feedback control schemes, the positive position feedback (PPF) and negative velocity feedback (NVF), were applied for active vibration control. The designed PPF controller for resonance frequency is,

$$H_{PPF}(s)=\frac{K\omega_f^2}{s^2+2\varsigma_f\omega_f s+\omega_f^2} \qquad (1)$$

where ζ_f is a filter damping ratio, ω_f is the filter resonance frequency and K is a control gain. Using the presented PUMPS actuators, about 10dB vibration reduction of the system was achieved near the resonant frequency region as shown in Fig. 7.



(a) time domain results



(b) frequency domain results

Fig. 7 Vibration control results using the active vibration isolator with PUMPS actuators.

INTEGRATED ACTIVE VIBRATION ISOLATION SYSTEM

With the preliminary vibration test results showing promising performance of PUMPS actuator in active vibration control, an integrated active vibration isolation system using PUMPS actuators is developed. The developed system contains compact analogue circuits and an accelerometer for PUMPS actuation and control, and power is supplied by Li-Polymer battery. This means the system is completely standalone and portable and, thus, its use is not confined to laboratory environment. There is no need for external amplifiers or digital signal processing (DSP) board used in the preliminary vibration test.

Another vibration test is conducted to demonstrate the effectiveness of the integrated vibration isolation system in improving the performance of optical payloads degraded by jitter. For this purpose DC motor, flywheel, CCD camera, target image and power systems is added to the developed integrated active vibration isolator system to form a compact integrated jitter isolation demonstration system as shown in Fig. 8 Rotating disk operated using DC motor produces vibration disturbances with characteristics that resemble those generated by RWA. When the flywheel is rotated at full speed, the vibration has a certain peak frequency (~80Hz). Therefore, the PPF controller can be implemented to effectively suppress the vibration. In addition to PPF controller, PID controller was also applied to the vibration isolation system. Images taken by CCD camera provide straightforward demonstration of the effect of jitter and vibration control. Fig. 9 shows the overall test setup using integrated jitter isolation demonstration system.

The results of active vibration control test using the integrated jitter isolation demonstration system is shown in Fig. 10. Two images were taken using the CCD camera before and after the vibration control. Blurred image shows the detrimental effect of jitter in the performance of optical payloads. On the other hand, image taken during the operation of active vibration control system has much better quality, indicating that the developed integrated active vibration isolation system with PUMPS actuators can be effectively used to isolate jitter sensitive payloads from vibration disturbances.

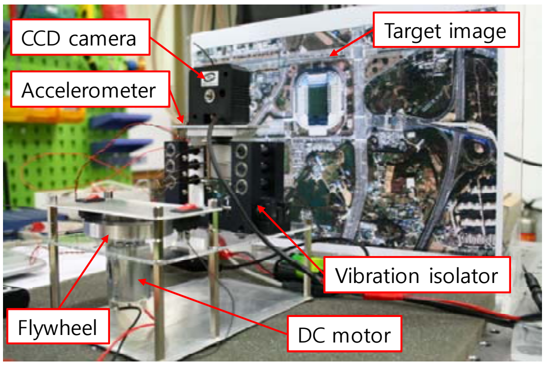


Fig. 8 Integrated jitter isolation demonstration system.

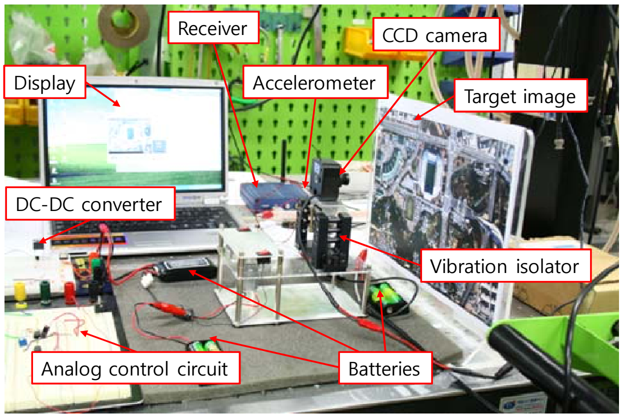


Fig. 9 Overall experimental setup.

(a) controller off

(b) controller on

Fig. 10 Captured images without and with vibration control.

CONCLUSIONS

A pre-stressed piezoelectric unimorph made by a new fabrication method in room temperature, and its application in active vibration isolation system were introduced and demonstrated through experiments. Enhancement of PUMPS actuator performance in terms of load capacity was realized by using three PUMPS actuators in a multilayer stack configuration. By stacking three pre-stressed piezoelectric unimorph actuators, the force level was significantly increased compared with isolator with one layer.

Preliminary vibration tests were performed to check the applicability of PUMPS as actuators for active vibration control in a lab environment. Two feedback control schemes, the positive position feedback (PPF) and negative velocity feedback (NVF), were chosen and the vibration tests showed about 10dB vibration reduction near the resonant frequency region.

With the preliminary vibration test results showing promising performance of PUMPS actuator in active vibration control, an integrated active vibration isolation system composed of PUMPS actuators was developed. The developed system contains compact analogue circuits and an accelerometer for PUMPS actuation and control, and power is supplied by Li-Polymer battery. This means the system is completely standalone and portable and, thus, its use is not confined to laboratory environment. There is no need for external amplifiers or digital signal processing (DSP) board used in the preliminary vibration test.

In addition, an integrated jitter isolation demonstration system was developed to demonstrate degrading effect of jitter and the effectiveness of the developed integrated active vibration isolation system in improving the performance of optical payloads. Comparison of image qualities taken before and after the operation of vibration control system indicates the developed integrated active vibration isolation system with PUMPS actuators can be effectively used to isolate jitter sensitive payloads from vibration disturbances.

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