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# Experiments on active precision isolation with a smart conical adapter

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ABSTRACT

Based on a conical shell adaptor, an active vibration isolator for vibration control of precision payload is designed and tested in this study. Flexible piezoelectric sensors and actuators are bonded on the adaptor surface for active vibration monitoring and control. The mathematical model of a piezoelectric laminated conical shell is derived and then optimal design of the actuators is performed for the first axial vibration mode of the isolation system. A scaled conical adaptor is manufactured with four MFC actuators laminating on its outer surface. Active vibration isolation efficiency is then evaluated on a vibration shaker. The control model is built in Matlab/Simulink and programmed into the dSPACE control board. Experimental results show that, the proposed active isolator is effective in vibration suppression of payloads with the negative velocity feedback control. In contrast, the amplitude responses increase with positive feedback control. Furthermore, the amplitude responses increases when time delay is added into the control signals, and gets the maximum when the delay is close to one quarter of one cycle time.



## 1. Introduction

Payloads in spacecraft are subjected to various dynamic loads during the launch, for example, ignition and shutdown of rocket engines, stage separation, aerodynamic load, mass reduction [1]. These dynamic loads are transmitted to the payload via an adapter. Severe dynamic loads may lead to overload or large deformation. These increase the possibility of accuracy loss, function failure or even damage to the spacecraft or payload.

Vibration isolation system can be used to improve the dynamic environment of the precision payload [2–4]. Many prototypes of vibration isolation systems have been developed in recent years, such as the SoftRide vibration isolation platform [5], launch vibration isolation system (LVIS) [6], vibration isolation and suppression system (VISS) and D-Strut element [7], Stewart platform [8–12] and so on. These vibration isolation systems can be classified into passive control (damping), active control (pneumatic, hydraulic, piezoelectric stack), and semi-active control (magneto rheological fluid). Active vibration isolation systems are adaptive and effective for lower frequency isolations. Because of the critical limitations on weight, volume, power consumption, etc., it is a great challenge to design an isolation system to protect the spacecraft or

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payload [13]. Thus, the vibration isolation systems are expected to be lightweight, less power consumption and higher performance.

Smart structures show great potentials in vibration control. Various materials have been used in smart structures as the intelligent part, such as piezoelectric materials, magnetorheological fluid and magnetostrictive materials [14–17]. Among them piezoelectric sensors and actuators get most attention because of their quick response and less energy conversion [18]. The direct piezoelectric effect means converting strain or deformation into electric signal, thus the piezoelectric material can be used as sensor or piezoelectric energy harvester. On the other hand, the piezoelectric material can generate strain with driving voltage, known as the converse piezoelectric effect, and the induced strain acting as control force or moment. By using the piezoelectric unimorph as an actuator, a 10 dB reduction of vibration level was achieved in a demonstrating active isolation system [19].

Generally, the payload adapter is of the shape of conical shell with light weight, high strength and stiffness. Recent researches show the possibility of using smart conical adapter as the active isolator, i.e., integrating piezoelectric materials as the sensors and actuators. Based on the constitutive equations of piezoelectric shells [20], the distributed sensing and actuation of conical shells was investigated and most researches emphasized on the shell without payload [21–23]. The sensing signal and control force depend on the location, size, geometry of actuators, mode shapes, and the structural and material properties. For example, the modal control force consists of four components inherited from bi-directional piezoelectric constants $d_{31}$ and $d_{32}$ [21,24]. The four components could have opposite phase that leading to force cancellations in some natural modes. In the circumferential direction, the modal control force varied sinuously with respect to the circumferential coordinate for transverse modes. In the longitudinal direction, the distribution is much more complicated. Thus, the smart conical shells can generate higher control force with careful designs. Furthermore, to avoid the force cancellation, one-dimensional piezoelectric actuators are expected. Macro-fiber composite (MFC) is a piezoelectric composite consisting of piezoelectric fibers and polymer matrix. MFC actuators exhibit single axial elongation or contraction and show the possibility to avoid force cancellation [25]. The MFC actuators are flexible and can be easily attached on shell surfaces [26,27]. The piezoelectric constants of MFCs are much higher than these of polyvinylidene fluoride (PVDF). This promises better performance as sensors and actuators for curvature structures.

This paper emphasizes the experimental study of active payload isolation under base excitation with MFC actuators. The modal control force is briefly presented. Based on the equations, the distribution of control force on the conical isolator is evaluated to locate the piezoelectric actuators placed on a laboratory physical model. Then the control model is developed and programmed into the dSPACE control board. The payloads are simplified to be a rigid cylinder, and two payloads with different weight are considered in laboratory experiments. MFC actuators are laminated on the outer surface of the conical isolator. The negative velocity feedback is used in the active vibration control. Experimental results show that the dynamic response of payloads can be effectively suppressed by the smart conical isolator.

## 2. Modal control force of distributed actuators

Dynamics of conical shells with various boundary conditions have attracted much research attention in last decades. Numerical methods and finite element methods have been proposed for vibration analysis of conical shells [28,29]. Dynamic analysis of conical isolation system is more complicated because of its payload, base excitation and boundary constraints. The resin shells used in following laboratory experiments are found to be non-uniform in longitudinal or circumferential directions, which resulting in errors between finite element solutions and experimental data. Thus, the analytical procedure [25] presented in this section is to determine optimal design and placements of MFC actuators in the experimental model used in laboratory testing.

For the isolation of precision load, special interest is on the vertical motion. The vertical motion is related to the axial modes of the adaptor, i.e., the compression and elongation along the centerline of the conical shell. In this research, only the first axial mode of the isolation system is considered. The rigid payload is fixed at the minor end of the thin conical adapter,

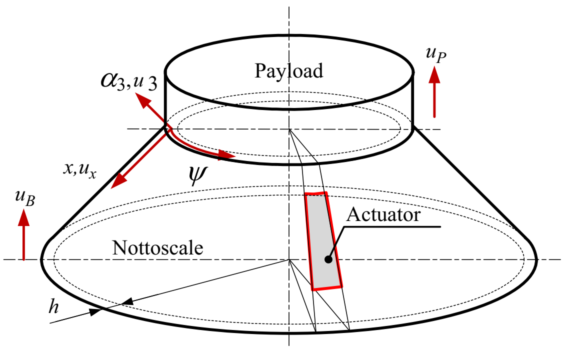


**Fig. 1.** Conical shell isolator with attached actuator.