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RECENT PROGRESS IN ADAPTIVE STRUCTURES FOR SPACE

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Abstract

Within the past 10 years, substantial research in Adaptive Structures is evident and continues its integration into various space experiments and missions. The rapid integration is attributable to solutions Adaptive Structures potentially provides to many anticipated spare challenges in large precision space structures and commercial availability of reliable actuator materials. The emphasis of the paper is on space experiments related to Adaptive Structures within the past two years.

Introduction

This paper provides an update on space experiments in Adaptive Structures since the overview papers [1,2] in 1993 and its potential value to meet challenges of large and small space structures[3]. Within the past ten years, substantial growth in Adaptive Structures research is evident along with various space applications and experiments in US and in France. The relatively rapid insertion of the technology to space application is attributable to its potential solution to space challenges and the availability of commercially available actuation materials compatible with space requirements. Additionally, many of the initial research activities included extensive testbeds and experiments to establish and demonstrate feasibility. The emphasis is to describe recent space flight experiments and those in development.

Although solutions to challenges related to large precision structures provided the initial motivation of Adaptive Structures, the technology is applicable to the new focus of small inexpensive spacecraft. Adaptive Structures promises to reduce the cost while improving reliability by introducing approaches for robust design. Robust design reduces cost of engineering and process control of many critical variables that could affect the performance of the final system. The NASA ORIGINS program starting in the next millennium requires large deployable precision structural systems

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with linear dimensions up to 100 meters and maintaining relative position of optical elements on the structure to about 1 nano-meter. The capabilities of Adaptive Structures promise to help meet many of the challenges of the ORIGINS program.

Space Requirements

Actuators

Adaptive Structures require the integration of many functions such as structures, sensors, actuators, controller, and power. Although the recent availability of sensors (e.g., non-contacting displacement sensors and interferometers with resolution about 1 nano-meter), low power miniaturized controllers, and power supplies are invaluable, the critical component are the actuators. The basic parameter for Adaptive Structures is strain. The actuator resolution must be compatible with the adverse strains within the structure during its operation. The attainment of precision of large space structures is achievable by controlling very small levels of strains ($\leq 1\ \mu m/m$) or strain energy, which becomes the required sensitivity of the actuator. Fortunately, commercial actuator material compatible with space requirements, namely piezo-electric and electrostrictive materials are commercially available.

The two basic approaches to integrating piezo-electric (PZT) actuator materials to date are to place the actuators in parallel with the structures (e.g. bond the actuator on the surface of the structure or embed the actuator within the composite materials) and to place the actuator in series (in-line actuator) with the structure. In both approaches, the design must provide for efficient transfer of strain from the actuator material to the structure while maintaining the linearity characteristics. The STRV-1b(4) flight experiment includes surface mounted and in-line actuators PZT actuators. The Advanced Control Technology Experiment I (ACTEX-I)(5) imbeds PZT actuators within the graphite epoxy composite structure. The apparent advantages of a design with actuators in parallel with the structure are its ability to transmit large loads and retain structural load transmission capability with a broken actuator. The apparent advantages of an in-line design are the capability to incorporate design approaches to attain large displacements and actively adjust the stiffness of the actuator using precision and small displacement PZT actuator materials. Space applications require actuators with both capabilities.

Currently quasi-static large motion precision actuators exist and are in development that consists of a rapid series of small motions, like a Burleigh inch-worm actuator or a linear actuator using surface waves(6). Another approach to develop precision, soft, and large stroke actuator with active stiffness control is to design mechanical amplifiers. One expandable design approach (7) is in Figure 1; the prototype shown amplifies the actuator motion by a theoretical factor 36:1 with a test validated mechanical efficiency of about -10%. The unique features of the design are redundancy, compactness, high internal actuator resonant frequency, and variable low stiffness.

'1'0 (km, the actuator requirements are achievable through application specific mechanical designs using commercially available 1'7,'1' and electrostrictive actuation materials.

Technical Challenges

The technical challenge for both small and large precision structure is to achieve a robust structural(3) design, namely an approach to reliably achieve the final mission objectives without critical dependency on the numerous design and validation parameters. In many cases the approach for a robust structure can significantly reduce both cost and schedule resources by reducing the requirements on analysis, development testing, hardware, processes, testing, and quality control. The concepts of Adaptive Structures provide solution alternatives to enable or simplify 1) ground validation testing of large precision structures, ?) reliable deployment or assembly of structures in space, 3) linearization of the structure by removing joint slippage, 4) in-space system identification, 5) static adjustment, 6) dynamic modifications, and 7) mechanical reliability.

Space Experiments

Role

The introduction of new technology into space missions often progresses from laboratory demonstration to space flight experiments to mission critical roles. For selected applications of Adaptive Structures, the major developments in the past few years are the large number of space flight experiments. The most significant non-technical justification of a flight experiment is to demonstrate its feasibility on a flight mission to provide confidence in the new technology for future missions, The technical Justification is to establish approaches and designs to integrate the new technology to the space system that often limits space, volume, weight, power. temperature bounds, computer power, data storage, data format and access. The total system must be capable of withstanding the ground tests, launch environment and the space environment.

Space Technology Research Vehicle-1b (STRV-1b)

The STRV-1b(4) spacecraft is a joint US/UK mission developed in about a 12 month period and launched on an Ariane-4 launch vehicle on June 17, 1994. The official mission was 12 months in duration, but the STRV-1b spacecraft current plan is to operate until the summer of 1997. A major experiment on the STRV-1b spacecraft was to actively suppress the tip motion of a mechanical cooler oyt)-cooler finger. The mission constrained volume, weight and power for the experiment. Two sets of actuators for the system consisted of three stacked actuators controlling the motion of the entire cyro-cooler tip and three PZT strips bonded to the base of the cryo-finger itself to control the cryo-cooler tip motion in the three transitional directions. See Figure 2. Schedule constraints did not allow for an adequate power system to meet the 700v voltage requirement for the bonded PZT and thus it was not effective in flight. The high voltage is necessary to drive a short 1'7,'1' to higher amplitudes because the PZT is limited to a small zone at the base of the cryo-cooler finger that is close to room temperature and to maintain low conductance from the base to the tip. The performance of the PZT degrades with decreasing temperature. The tip of the cryo-cooler finger is at about 80°K.

The stacked PZT actuators (20 volts) are capable of suppressing the vibration motion of the fundamental and the first 4 higher harmonics ranging from about 60Hz to 300 Hz. The control system suppressed the rms motion of the 5 harmonics of the cryo-cooler tip by a factor of about 80 to less than 0.1 micron over 200 times since the initial launch. The challenges of developing high voltage, low mass, efficient power supplies compatible with spacecraft power supplies became evident.

Middeck Active Control Experiment (MACE)

The MIT/NASA MACE[8,9] experiment was flown in the Space Shuttle middeck on STS-67 in March 1995. The objective of the experiment is to demonstrate high authority active structural control of flexible structures in zero gravity conditions based on analysis, ground testing, and on-orbit control redesign. The two basic configurations tested in space is in Figure 3. In each configuration, active struts are in the structure. The active struts in the High Authority Control/Low Authority Control (HAC/LAC) architecture are to add robustness to the closed-loop control system. A low authority controller consisting of two independent integral feedback controllers between the two axes of the active strut. For robustness, the local control loops add damping to the 10, 17 and 25 Hz modes. The in-space system performance was similar to those determined during ground testing. Some of the unexpected results of the experiment are the unexpected low frequency tether modes, nonlinearities in the system and the controllers based upon the identified dynamics did not perform better than those based on the analytical model.

Advanced Control Technology Experiment-I (ACTEX-I)

The TRW/AF/BMDO ACTEX-I[illegible] experiment was launched during the Spring of 1996. The specific objectives of the experiment are: 1) demonstrate integrated active/passive damping using piezoceramic sensors and actuators embedded within the lay-up of graphite epoxy tubes, 2) provide a capability to test vibration suppression algorithms in space using active structural components, sensors, and passive damping, 3) validate preflight design and performance prediction tools by performing on-orbit system identification and health monitoring experiments, 4) demonstrate the concept of Adaptive Structures using control laws that can be updated from ground, and 5) collect data on the long term effects of space environment on the active and passive control components. The experiment is in Figure 4. From the ground tests, a strain rate feedback control law increases the 0.8% open loop to 22% closed loop in the primary bending modes and from 0.5% open loop to 6% closed loop in the torsional mode. Flight data from the experiment are not available at this time.

The development and integration of the entire experiment to the spacecraft occurred within a fourteen month period. The hardware successfully passed a qualification test program.

Advanced Controls Technology Experiment 11 (ACTEXII)

The objectives of the TRW/AF/BMDO ACTEX 11 experiment are: 1) demonstrate the use of multichip module structural control electronics using high density chips, 2) demonstrate use of 2000 gate Field Programmable Gate Arrays enabling a 2Mbit/sec serial data bus, 3) demonstrate vibration suppression of a flexible appendage with realistic parasitic strain energy losses, 4) use innovative ground station laptop control computer using on-orbit system identification with closed loop design, simulation, and experiment upload programming capability. The experiment is in Figure 5 and represents a structure similar to a solar array. Graphite polycyanate beam with imbedded PZT actuator/sensors, passively damped viscoelastic joints, and constrained layer passively damped strut with fiberglass/graphite/VEM co-cured layers are at the base of the experiment.

The experiment launched in 1995 never reached its intended orbit.

Suppression of “Transient Acceleration by Levitation (STABLE)

The MDA/MSFC STABLE(11) system experiment was completed in 1995 on STS-73 Shuttle Mission. The objective of the experiment was to isolate sensitive microgravity science payloads from vibration due to on-board machinery or crew activity. The entire isolation system fits in a single middeck locker aboard the Shuttle and meets International Space Station requirements. The objective is to provide vibration isolation for experiments to limit the acceleration to about one μ-g from about .01 to 200 Hz. The electromagnetic actuators has a stroke of ± 1 cm. The space station requirements, the predicted non-isolated environment, and the environment with the isolation system are in Figure 6. Evaluation of a limited amount of flight data indicates STABLE is able to substantially attenuate the accelerations of over the frequency range of interest and comfortably meets the ISS requirements. The current plans are to isolate many of the experiments on ISS using the Active Rack Isolation System; however STABLE provides an alternative to isolate experiments flown by international partners on ISS as well as Mir and Shuttle.

Inflatable Antenna Experiment (IAE)

The L'Garde/JPL/NASA IAE(12) demonstrate feasibility of large inflatable precision structures in space in May 1996. The antenna fits in a 7 X 3X 1.5 foot box inflating into a 50 foot diameter offset parabolic surface on three 92 foot long struts. During the experiment the IAE is on the Spartan launch by Space Shuttle. The inflatable part of the system with the inflation Nitrogen gas weighs 132 pounds. The inflated antenna is space is in Figure 7. The antenna successfully inflated but the deployment sequence of the antenna was a surprise. Figure 8 shows one frame of the antenna during deployment. The data to establish the desired surface accuracy goal of” several mm rms is currently in evaluation. However the picture of the antenna shows visible surface roughness that indicates an incompletely pressurized system. The IAE technology demonstration experiment's design life was for about a few hours; the antenna jettisoned about 1.5 hours after initiation of the deployment re-entered the earth's atmosphere a few days later.

ChAracterization of STructures in Orbit (CASTOR)

The CNES experiment CASTOR[13] Is currently in development for a 1996 experiment on the MIR station, The objectives of CASTOR are to validate analysis and test procedures for prediction of advanced precision space structure dynamics and demonstration of zero gravity passive and active damping active members. Validation of analysis and test includes 1)ground test of elements and system, 2) modeling of passive and active damping, 3) model updating, 4) modeling of gravity effects, 5) performance prediction, and 6) comparison of ground and flight test results. A schematic of the approximately 15kg and 180cm long flight hardware with three active members is in Figure 9. The active members are low voltage Physik Instrument piezo-electric members.

Ground tests to date demonstrate the capability of substantially increasing the damping of the global resonant frequencies of the system below 100 Hz.

Vibration Isolation, Suppression and Steering (VISS)

The Honeywell/JPL/AF/BMDO VISS experiment currently in development is part of the Structural Test Research Vehicle 2 (STRV-2) program scheduled for launch in 1997. The objective is to combine functions of some of the above experiments into one subsystem, namely isolate the vibration from a “noisy” base to the precise instrument, suppress the vibration on the precise instrument (cryo-cooler), and steer the precise instrument.

During the initial JPL study[14], requirement included a PZT actuator. The goal was to establish a design for 20db vibration isolation above 2 Hz, 15db vibration suppression of disturbances at about 60 and 120 Hz, and ±0.3° steering at 2 and 4 Hz of an Mid Wave Infra-Red (MWIR) weighing about 40 pounds without its electronics. its dimensions are about 8.0” in diameter by 30” in length. The goals are only achievable with a long stroke and low stiffness PZT actuator[7]. Six of the long stoke, low stiffness, compact and redundant actuators provide the control of the six rigid body degrees-of-freedom. To simplify the development of the experiment within the 18 month period, the goal was to control each of the objectives independently; namely independent sensors and controllers but with a common set (actuators.

The current VISS is being developed by Honeywell/JPL/AF where Honeywell is developing the VISS hardware, JPL is developing the flight computer algorithms, and AF is the program manager. The Honeywell actuator is a combined passive damper (like a D-Strut actuator) and active voice coil.

Summary

Adaptive Structures provide solution options to meet many of the technical and cost challenges for future space missions, especially precision requirements, by providing use of robust design approaches. The large number of Adaptive Structures flight experiments is essential to validate the technology and necessary resources for future program managers. The activities within the past two years are possibly an indication of the near term insertion of this technology for future missions. Near term applications will include actuators unique to an application using existing PZT type materials.

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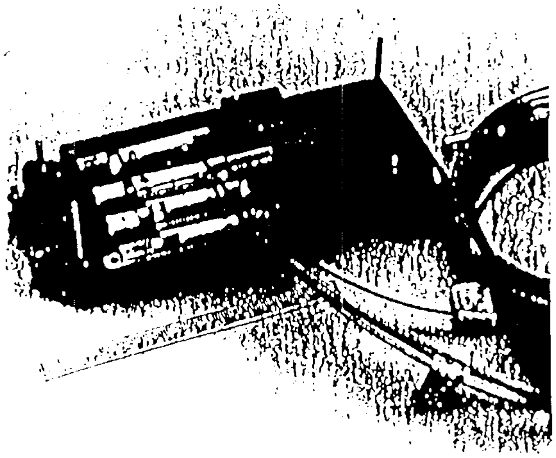


Figure 1. Long Stroke PZT Actuator

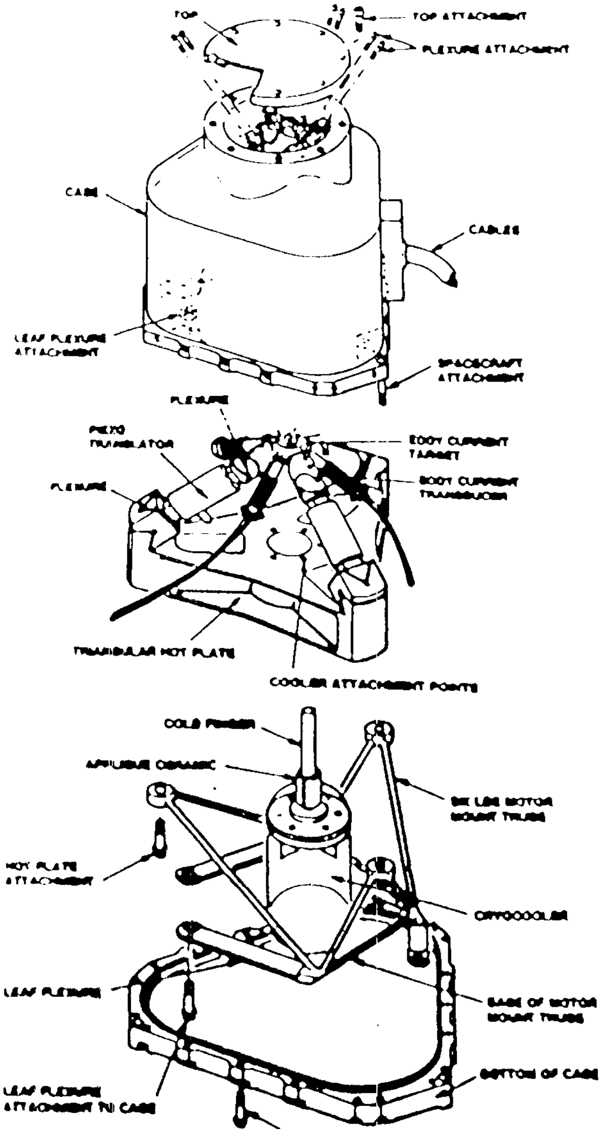
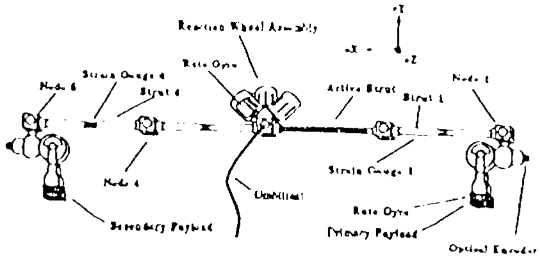
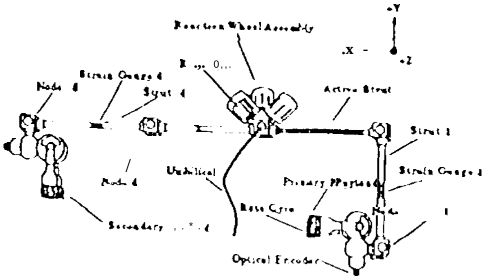


Figure 2 STRV-1b Cryo-cooler Vibration Suppression Experiment



(a) MACE Configuration I



(b) MACE Configuration II

Figure 3 MACE Configurations

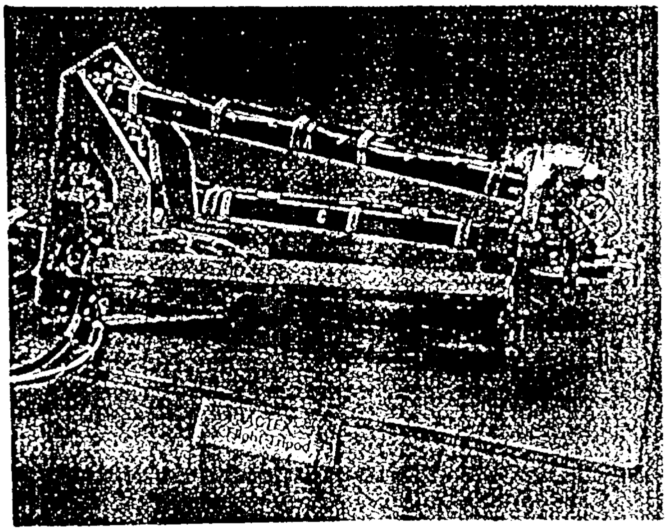
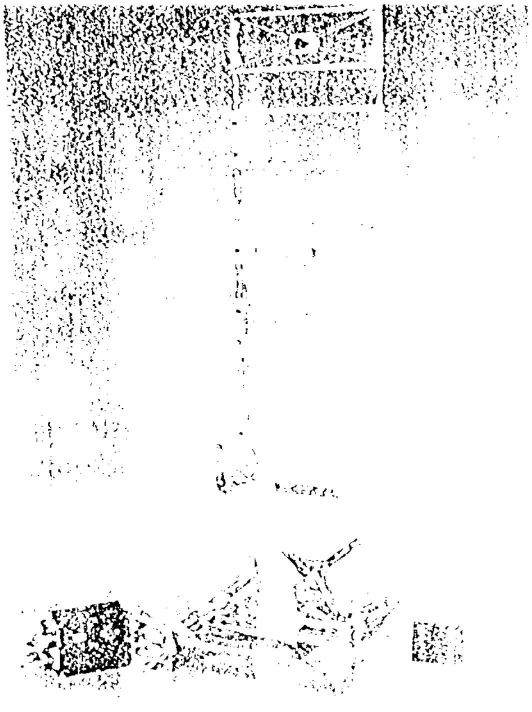


Figure 4. ACTEX-I Experiment



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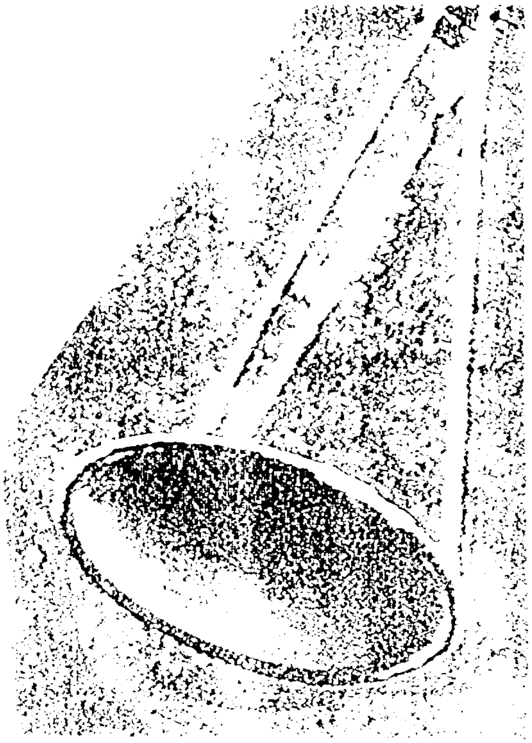

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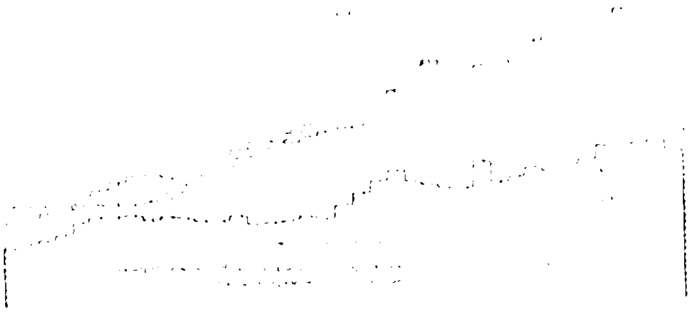

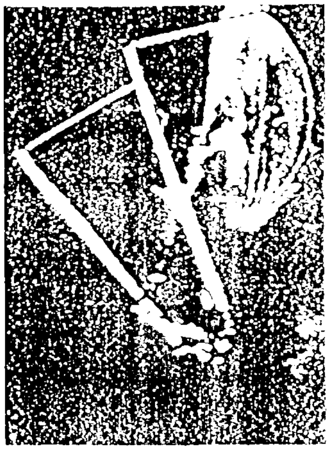

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