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AIAA/AFOSR WORKSHOP ON MICROGRAVITY SIMULATION IN GROUND VALIDATION TESTING OF LARGE SPACE STRUCTURES, FINAL REPORT

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This report summarizes the proceedings of the Workshop on Microgravity Simulation in Ground Validation Testing of Large Space Structures. The workshop was conceived and organized as a follow-on activity to an earlier study sponsored by the Air Force Office of Scientific Research. The objective of the initial study was to provide a cursory review of available techniques against assessed needs in the specific area of dynamic testing of large space structures. The intent of the workshop was to broaden the scope of this initial investigation by involving national experts in areas relevant to issues identified in the initial study.

The workshop focused on present and future needs. Participants from the Government (both Air Force and NASA), universities, and private industry were invited to give presentations on research in which they were actively involved, including both analytical and experimental work. An overview session covering both military and civil space objectives was presented first. This overview was followed by a session on Space Structures Experimental Programs and Facilities, sessions on On-orbit Dynamics Modeling and Simulation, and sessions on Advanced Suspension Devices and Systems. The workshop concluded with a panel discussion which addressed Current Issues and Needs.

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SUMMARY

The AIAA/AFOSR Workshop on Microgravity Simulation in Ground Validation Testing of Large Space Structures was held on November 1-2, 1989, at the Hyatt Regency Hotel in Denver, Colorado. Invited participants from the Government, universities and private industry offered state-of-the-art presentations covering a broad scope of topics in the subject area. The workshop consisted of six regular sessions containing nineteen presentations, followed by a panel discussion.

This report contains abstracts of all nineteen presentations, followed by a summary of issues and needs identified during the course of the two-day workshop, including the panel discussion. Appended to the report are the final program and registration list. Proceedings of the workshop containing copies of the viewgraph presentations with facing page text are bound separately.

1. INTRODUCTION

The Workshop on Microgravity Simulation in Ground Validation Testing of Large Space Structures was conceived and organized as a follow-on activity to an earlier study sponsored by the Air Force Office of Scientific Research.[1] This study grew out of a need for documentation of the current state-of-the-art in ground simulation of the microgravity environment in space. The objective of this study was to provide a cursory review of available techniques against assessed needs in the specific area of dynamic testing of large space structures. The intent of the workshop was to broaden the scope of this initial investigation by involving national experts in areas relevant to issues identified in the initial study.

The workshop focused on present, as well as anticipated future, needs. Participants from the Government (both the Air Force and NASA), universities, and private industry were invited to give presentations on research areas in which they were known to be actively involved. These research areas included both analytical and experimental efforts. An overview session covering both military and civil (NASA) space objectives was presented first. This overview was followed by a session on Space Structures Experimental Programs and Facilities, and sessions on On-orbit Dynamics Modeling and Simulation, and Advanced Suspension Devices and Systems. The workshop concluded with a panel discussion which addressed Current Issues and Needs.

This report briefly summarizes the contents of the workshop and attempts to draw into sharper focus the major issues and viewpoints which were expressed. It contains abstracts of the presentations and a summary of identified issues and needs. Abstracts submitted by the authors were used when available. In a few cases, where authors' abstracts were not available, abstracts were prepared by the editor based on author-furnished materials.

Copies of the complete presentations consisting of the viewgraphs used in the presentations along with facing page text are separately bound.

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[1] "Microgravity Simulation in Ground Validation Testing of Large Space Structures", by A.K. Amos, M. L. Zeigler, S.E. Lamberson, V.B. Venkayya, T. Strange, and W.L. Haskin, Draft Report Prepared for the Air Force Office of Scientific Research, November 1988.

2. ABSTRACTS OF PRESENTATIONS

2.1 Overview

"Military Space Objectives," David Finkelman, US Space Command and NORAD

Space systems vastly expand military capabilities and enable new missions. The United State Space Command (USSPACECOM) has responsibility for the employment of all dedicated military space systems in support of terrestrial operations and for maintaining sovereignty through the use of space. USSPACECOM provides surveillance, communications, and navigation capabilities as well as launch services. USSPACECOM is responsible for executing ballistic missile warning and defense and is the proponent for anti-satellite capabilities. Future capabilities often rely upon exploiting the micro-gravitational environment. For example, the accuracy of space based radars depends upon the performance of large structures in orbit. Space based wide area surveillance also requires large, precision structures whose performance cannot be assessed easily under normal gravity. If near earth space is legislated nuclear free, the stability of large solar arrays will be an important issue for the future. The structural response of satellites which maneuver rapidly to evade anti-satellite weapons must be documented. Our objectives in space demand better understanding of the micro-gravitational characteristics of large structures.

"NASA Space Objectives," Larry Pinson, NASA Langley Research Center

Several space missions involving large structures have been proposed including lunar and Mars outposts and Mission to Planet Earth. These missions must be thoroughly planned and high confidence must be developed in both projected structural precision and deployment and assembly procedures. This confidence is developed mostly through extensive, valid ground tests accompanied by very infrequent orbital flight tests with limited instrumentation. To achieve this confidence an ability to perform ground and flight tests must be developed. As a result, portions of several NASA space technology programs are aimed at the development of test methods which provide for simulation of important microgravity features in ground testing, extraction of the most information from limited flight test information, and development of the ability to function effectively in the construction process on orbit.

An overview of NASA fundamental research programs is presented along with a brief description of the focused technology programs Civil Space Technology Initiative (CSTI) and Pathfinder. Other presentations focus on various specific programs and studies in detail. The intention here is to provide a broad view of the program to show relevance to the overall NASA direction in space.

"Microgravity Simulation Issues," A.K. Amos, The Pennsylvania State University

In Aircraft design (the conventional approach), Ground Testing plays a supporting role to Flight Testing in the validation of new system designs. It is complemented in this role by analytical simulations which use test data and validated analytical models to identify potentially critical operational conditions to be flown during flight testing. Spacecraft systems with large physical dimensions or high flexibility do not lend themselves to design validation by the conventional approach. Additionally, flight testing is not usually feasible for economic reasons. Thus a different approach to design validation has been evolving to handle such systems. In this approach, analytical simulation plays a more direct role in the decision to commit a design to flight. Simultaneously, the type of ground testing possible is undergoing radical changes in directions that make it subordinate to analytical simulation. The design validation process for Large Space Structures can therefore be characterized as primarily one of analytical simulation supported, as appropriate, by experimental data.

This presentation addresses two major issues in microgravity simulation. The first is assuring that vibrations during the testing do not involve participation by any restraining systems, and are sufficiently long in duration to achieve steady-state vibrations and permit meaningful measurement. The second has to do with the effective treatment of nonlinear effects in the analytical simulation of on-orbit dynamics. A critical assessment of current methods related to both issues is presented.

2.2 Space Structures Experimental Programs and Facilities

"Air Force Programs and Facilities," Alok Das, Air Force Astronautics Laboratory

Air Force Programs and Facilities have been established to meet the DOD need for precision structures. This need has grown out of proposed space systems which are very large and inherently flexible. Missions call for extremely precise acquisition, slewing, pointing, tracking and figure control. The combined impact of structure, mission and environment requires a significant "leap" beyond current capabilities.

This presentation discusses current Air Force Programs and Facilities involving both ground experiments and flight experiments. Ground experiment programs, including the Passive and Active Control of Space Structures (PACOSS) Program, the Advanced Space Structure Technology Research Experiments (ASTREX) Program, the Embedded Sensors and Activators Program and the Multibody Dynamics Experiment are discussed. Discussion of Flight Experiments covers the LACE Flight Dynamics Experiment, Reduced Gravity Aircraft Experiments, Shuttle Based Experiments (Mid Deck Experiment and Get-Away-Special) and the Inexpensive Structures and Materials Flight Experiment (INFLEX).

"NASA Programs and Facilities," Jerry Newsom, NASA Langley Research Center

Spacecraft components, such as booms, solar arrays, and antennas, are often quite flexible and can interact with the spacecraft control system. This interaction, commonly referred to as controls-structures interaction (CSI), can reduce spacecraft performance or restrict operations. Designing to avoid CSI generally requires either stiffening the structure (costly in increased weight) and/or slowing down the control system (costly in performance capability). CSI technology involves the capability and confidence to integrate the structure and control system so as to avoid interactions that cause problems, and exploit interactions that have the potential to increase spacecraft capability.

Future NASA missions are likely to increase the need for CSI technology because of the increased size of distributed-mass components, greater requirements for surface and pointing precision, increased use of articulated moving components, and increased use of multi-mission science platforms with their associated multiple control systems.

A NASA program has been initiated to advance CSI technology to a point where it can be used in spacecraft design for future missions. This program, which is a restructuring of NASA's Control of Flexible Structures (COFS) program, consists of a balance between analysis and design methods development, ground test methods development, ground experiments, and in-space flight experiments. The CSI technology program is a multicenter program utilizing the resources of the Langley Research Center (LaRC), the Marshall Space Flight Center (MSFC), and the Jet Propulsion Laboratory (JPL).

The purpose of this paper will be to describe the ongoing activities, results to date, and future activities of the CSI technology program with particular emphasis given to the activities at the LaRC. Activities include CSI concepts and configurations, integrated analysis and design, ground test methods and experiments, and in-space flight experiments.

2.3 On-orbit Dynamics Modeling and Simulation

"Modeling Techniques for the Dynamics and Control of Large Flexible Orbiting Systems," Peter Bainum, Howard University

The steps involved in the development of mathematical models used to simulate the in orbit dynamic behavior of large flexible systems are reviewed. A general continuum formulation approach is compared with the hybrid coordinate formulation and finite element representation of the system. Numerical techniques employed to synthesize shape and attitude control laws are summarized with emphasis placed on modeling errors resulting from the simulation of rapid near-minimum time maneuvering based on an application of Pontryagin's maximum principle. The resulting two-point boundary value problem is then solved by using the quasilineariza [illegible] nique and the near minimum time is obtained by sequentially shorten [illegible] ing time until the controls are near the bang-bang type. The results ind [illegible] at the flexible modal responses for the nonlinear system model can be notic [illegible] ably different from those of the linear system model - even for the case where vibration suppression is achieved during the maneuver. Finally, the problem of modeling environmental disturbance torques due to the interaction of solar radiation pressure on vibration and thermally deflected systems is reviewed. This effort involves the prediction of the open-and-closed loop dynamics of large space structures after the onset of thermal shock as well as during steady state thermal conditions.

"Modeling and Control of Coupled Structures: Recent Developments," P.S. Krishnaprasad, University of Maryland[2]

The dynamics of very lightly damped structures may be sufficiently approximated by Hamiltonian systems. The rich geometric and group theoretic features of Hamiltonian systems may then be exploited to reveal the qualitative and quantitative aspects of the dynamics. In this talk we shall discuss recent progress along these lines towards a better understanding of the modeling, stability and control of coupled structures. Our work also has led to new insights into computational mechanics.

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[2] A copy of this presentation was not submitted by the author and is, therefore, not included in the proceedings.

"Rapid Generation of Special Purpose Simulation Programs," David A. Levinson, Lockheed Palo Alto Research Laboratory

This talk is about AUTOLEV, a new concept for solving problems in dynamics. AUTOLEV is an interactive, PC-based, symbol manipulation capability that one can use to formulate explicit equations of motion for dynamical systems and write corresponding complete, fully-formatted, FORTRAN simulation programs, all very rapidly. AUTOLEV differs from conventional dynamics programs in that it takes over burdensome analytical and coding tasks from the user without imposing stifling restrictions on either the kinds of systems that can be accommodated or the creativity of the user. AUTOLEV contains built-in "help" commands for all of its functions, and can be applied to any type of system of rigid bodies and particles, such as complex multibody spacecraft, robotic manipulators, and mechanisms, including nonholonomic systems and systems containing closed loops of bodies. Thus AUTOLEV is particularly useful to microgravity researchers interested in simulating behavior of either on-orbit systems or ground test devices.

"Multi-flexible-body Dynamics Capturing Motion-induced Stiffness," Arun K. Banerjee and Mark E. Lemak, Lockheed Missiles and Space Company

This paper presents a multi-flexible-body dynamics formulation incorporating a recently developed theory for capturing motion induced stiffness for an arbitrary structure undergoing large rotation and translation accompanied by small vibrations. In essence, the method consists of correcting prematurely linearized dynamical equations for an arbitrary flexible body with generalized active forces due to geometric stiffness corresponding to a system of twelve inertia forces and nine inertia couples distributed over the body. Equations of motion are derived by means of Kane's method. A useful feature of the formulation is its treatment of prescribed motions and interaction forces. Results of simulations of motions of three flexible spacecraft, involving stiffening during spinup motion, dynamic buckling, and a repositioning maneuver, demonstrate the validity and generality of the theory.

"On-orbit System Identification of Adaptive Structures for Precision Systems," Ben K. Wada, C. P. Kuo and G. S. Chen, Jet Propulsion Laboratory

The paper will present ground modal test data on flight systems which would help establish the accuracy to which large structures vibrating in the micron displacement range can be determined by current ground test approaches. Limited data will also be presented on flight systems when tested to the lowest possible excitation level. Based upon the available data, the authors believe that the current ground test approaches cannot satisfy the validation requirements for large precision structures. Since a ground test program is required to validate the structure prior to flight, a dilemma exists.

An approach incorporating Adaptive Structure in the design is presented which would help in the achievement of the structural requirements as well as alleviate the accuracy requirements of the ground test validation program. The active members which are integrally a key element of Adaptive Structures can then be effectively utilized to excite the structure in space to measure the dynamic characteristics in the micron displacement range. Preliminary experimental results will be presented.

The active members used for the system identification can then be used to adjust the structural geometry and/or characteristics to meet the structural performance requirements.

"Low Gravity Free Surface Fluid Motions and Propellant Management," Franklin T. Dodge, Southwest Research Institute

In-space microgravity experiments on propellant management will be reviewed. Such experiments are needed both to develop technology for planned and future missions and to acquire fundamental fluid mechanics understanding and modeling. Two general topics will be discussed: (1) requirements for propellant dynamics experiments, such as low-g sloshing, fluid transfer, fluid reorientation, and motions in spinning tanks; and (2) requirements for the development and verification of propellant management devices and systems for cryogenic liquids.

The discussion will include a listing of the requirements for needed experiments and a review of experiments currently in the planning or development stage.

"Dynamics and Kinematics of Satellite-Mounted Robots," Richard Longman, Columbia University

The topics covered in this presentation include the following:

- Robot forward and inverse kinematics on satellites with the attitude control system (ACS) on;
- Robot forward and inverse kinetics and workspace with the ACS off;

- Computation of reaction moments and forces on a satellite due to "robot" motion (both rigid body and flexible body cases); and

- Effect of robot flexibility on attitude control.

Three standard problems in robotics are the forward kinematics, inverse kinematics, and workspace. When a robot is mounted on a satellite with an attitude control system in operation, there is a new space-based forward kinematics problem and a new inverse kinematics problem. But the inertial position of the end-effector is still purely a function of the robot joint angles, (i.e., they are still kinematics problems). When the robot is mounted on a satellite that has the attitude control system turned off, then the end-effector position becomes a function of the whole history of the robot joint angles. Hence, we coin the terms: forward kinetics and inverse kinetics.

When a robot is operated on a satellite base, the motion induces forces and torques on the satellite. Methods are discussed to predict these forces and torques both for rigid robot links and for robots with structural flexibility.

The robot workspace is generated for robots mounted on satellites with the attitude control system off. The workspace is found to be often larger than for an earth-based robot, and is a perfect sphere.

2.4 Advanced Suspension Devices and Systems

"A Second Generation Zero Spring Rate Support System," T. Jeffrey Harvey, AEC-Able Engineering

The fidelity and speed of dynamic testing of satellite structures on earth can be improved by the use of low stiffness suspension points to more closely simulate the boundary conditions of zero gravity. In 1988 a device called a zero spring rate mechanism (ZSRM) was developed in an attempt to provide low stiffness suspension points for the Freedom Space Station scale model. While the ZSRM was successful in meeting performance objectives it was large and, by design, sensitive to small changes in its payload requiring complex and time consuming manual adjustment. A second generation ZSRM (ZSRM2) which addresses the shortcomings of the first unit has been designed and tested.

The design objective of the program was to take the ZSRM from a testbed model to a prototype with features wh[illegible]ould make it more versatile and user friendly. The most challenging modi[illegible]n was an automated load-centering system, which allows fast, reliable and [illegible]ote centering of the unit over a large payload range. Additionally, the ZSRM2 is smaller and has a larger payload range than its predecessor. Finally, provisions for centering of multiple ZSRM's in a structurally indeterminate configuration have been incorporated. Test results and a system description will be presented.

"A Pneumatic/Electric Suspension Device for Very Low Frequency Dynamic Testing," David A. Keinholz, CSA Engineering, Inc.

A new suspension device is described for simulating unconstrained boundary conditions in ground vibration testing of low frequency structures. Developed under the NASA/LaRC Dynamic Scale Model Technology Program it is designed for test articles having flexural modes as low as 1 Hz. The device supports its payload from above by a cable such that simple pendulum action can provide soft restraint in the horizontal directions. Gravity offloading with very low stiffness in the vertical direction is provided by a combination of a passive pneumatic system and an active electromechanical system. Payload range for the current design is 30 to 340 lb per device. Stiffness of the passive pneumatic system varies automatically with payload and, by itself, produces a vertical suspension frequency of about 0.1 Hz at maximum payload. Load position is held within the working stroke of the device by an active system which provides a static stiffness adjustable electronically from zero to 2.0 lbf/inch. Loop compensation causes the active stiffness to drop away rapidly with increasing frequency to less than one-fourth its static value for frequencies above 1 Hz. Breakaway friction is less than 0.002% of payload. Acceleration feedback is used to actively cancel the mass of the moving part of the device. A single unit may be used by itself or a number may be used together, controlled remotely from a central panel, to support a single, flexible test article. Continuing development is described, including a derivative of the existing device which will support its payload from below using a flat air bearing to allow unconstrained horizontal motion.

"Zero Gravity Suspension Systems," Paul Lynn, NTS Engineering

An innovative magnetic suspension system to counteract the pull of gravity has been devised by the NTS Engineering personnel. The suspension system produces a constant uplift force, and keeps additional stiffness, viscous damping, and material mass coupled to the flexible test structural systems to a minimum level. It can be used in a vacuum chamber and controlled electronically to input/output experimental data.

The suspension force formula was derived, and theoretical and experimental analyses were performed. For experimentation of the zero-gravity suspension system, two prototypes were built. The suspension system consisted of two interpenetrating solenoids.

The performance characteristics studied include: (a) selection of a proper magnetic material; (b) the stability of the uplift force; (c) the determination of the range of the suspension system's vertical displacement for which the lifting force remains constant and equal to the weight of the structure (d) identification of design improvements and areas requiring further investigation.

A solenoid design, for future implementation has been proposed. A conceptual zero-gravity vacuum test facility has also been suggested.

"Location of Attachment Points and Distribution of Suspension Forces for a Microgravity Suspension System," T. K. Hasselman, Engineering Mechanics Associates, and Richard Quartararo, SPARTA, Inc.

Microgravity suspension systems for testing large space structures will require numerous attachment points so that gravity-induced stresses in the structure are minimized. The number of attachment points will be limited, and their locations restricted to accessible regions of the structure. Questions arise as to how many attachment points are needed, where they should be located, and how a particular selection will affect the behavior of the structure. An optimization approach is suggested as a means of answering these questions. Objectives under consideration include minimizing strain energy, and minimizing the difference between the eigenvalues of a structure suspended in a one-g environment and those corresponding to a zero-g environment where no external forces act on the structure. The formulation of the problem along with simple examples demonstrating concepts and solution procedures will be discussed.

"Assembly and Suspension Issues for the DSMT Pathfinder Scale Model," Marc J. Gronet and Rick G. Brewster, Lockheed Missiles and Space Company; and Edward F. Crawley, Massachusetts Institute of Technology

The ground testing of planned low-frequency space structures challenges the state-of-the-art in suspension system technology. In many cases, the fragility of these structures will also pose challenges in the assembly of the suspended test article and in overall safety. This paper explores general assembly, suspension, and testing issues associated with the use of suspension devices to simulate 0-gravity during the ground vibration testing of low-frequency space structures.

Specifically, approaches to these problems developed as part of the DSMT Pathfinder Space Station Scale Model program at NASA/LaRC are discussed.

These include optimization and evaluation of suspension system performance, selection of cable attachment locations on the test article, development of safe assembly and testing procedures, and modeling of suspension interactions. Assembly procedures and analysis results from the DSMT Pathfinder program are provided as examples.

"Large Motion Suspension Devices for Flexible Structures," Victor M. Cooley, NASA Langley Research Center

Suspension research at NASA Langley Research Center (LaRC) has the general objective of developing and demonstrating suspension systems for ground testing of large flexible structures. Such systems will typically involve the use of one or more Advanced Suspension Devices (ASD's). The structures to be ground tested typically will have natural frequencies on the order of 1 Hz. or less. The motion of the structure during test will consist of vibrations, and in the case of articulating structures, rigid body articulations.

In addition to the in-house work at LaRC, several private sector research and development contracts are underway. These are sponsored, all or in-part, by LaRC Spacecraft Dynamics Branch, Structural Dynamics Division. The Dynamic Scale Modeling Technology (DSMT) program employees ASD's for use in modal testing a scale model (one-tenth length scale) of the NASA space station. This program has funded the research and development of two ASD's -- a passive Zero Spring Rate Mechanism (ZSRM) and an active pneumatic spring device. Both ASD's will be evaluated at LaRC in the first half, 1990.

Another research contract underway is jointly funded by the Air Force Astronautics Lab and LaRC. This work has produced a survey of applicable devices, and selection and development of a promising concept is forthcoming. A component of this work focuses on an ASD system for structures undergoing large motion.

As a Guest Investigator of the Control/Structure Interaction (CSI) program at LaRC, Dynamic Engineering Inc. is conducting R&D of a vertical/lateral/torsional 3 degree-of-freedom ASD. This device has application to the suspension of horizontally oriented, long beams vibrating in bending and torsion.

In-house Research and Development of ASD's at the LaRC Spacecraft Dynamics Branch has focused on a combined ZSRM/air table to allow vertical vibration and horizontal slewing of articulating structures.

This briefing will review the objective of ground test suspension research and discuss models and facilities available at LaRC. The two ASD's not covered elsewhere in these proceedings, the vertical/lateral/torsional device and the combined ZSRM/air table, will be described. Additionally, a technical note on the eigenvector sensitivity for closely spaced modes will be noted.

"Structural Testing Using the KC-135 In-flight Microgravity Simulation Facility," Al Janiszewski, Wright Research and Development Center

The Structures Division of the Flight Dynamics Laboratory has established an aggressive in-house program for the exploratory development of vibration suppression technologies for space systems. The two primary objectives of the Large Space Structures Technology Program (LSSTP) are first, to evaluate and experimentally quantify anticipated synergies between active and passive control; and, second, to qualify ground test techniques for appropriate simulation of the micro-gravity environment. The current testbeds for these studies include two 12m trusses with tailorable levels of passive damping -- from approximately .25% to 5% for first bending, to as much as 40% for first torsion. These trusses have undergone detailed modal surveys, both cantilevered and pseudo free-free suspended from zero spring rate mechanisms. Prior to initiating active/passive trade studies on these trusses, further validation of the suspension method will be attempted by flying a full 12m truss aboard NASA JSC's reduced gravity KC-135. Preliminary flights of a 2m version of this truss were accomplished in late March '89 to help assess rigid body dynamics, instrumentation and the overall test environment. Details of these flights and future plans are presented.

3. IDENTIFIED ISSUES AND NEEDS

Following the presentations made during the first day and a half of the workshop, a panel discussion was held to try to bring into focus the particular issues and technology needs associated with microgravity simulation. The following subsections attempt to recap the highlights of the panel discussion as well as major points emphasized during the presentations and related discussions. In some cases, comments and recommendations could be attributed to particular individuals; in others cases, they could not since the workshop proceedings were not recorded. This section should, therefore, be read as an editorialized version of workshop proceedings.

3.1 General Observations

The ability to simulate a microgravity environment in ground validation testing of large space structures is important for the accomplishment of a broad range of military and civil space objectives. To achieve these objectives, large space structures must be deployed and/or assembled on orbit, shapes must be controlled, attitude maneuvers executed and various on-orbit operations successfully managed. These needs have driven the state-of-the-art in both the dynamic analysis and experimental verification of large space structures. The potential payoff of technology development in this area is an estimated 100% to 500% improvement in the ability to predict in-space performance, and a 50% reduction in cost and time for verification of space hardware (Pinson 1-2).[3] Current costs for control-structure interaction (CSI) flight experiment studies range from approximately $6M for a shuttle mid-deck experiment, to $30M for a shuttle remote manipulator system (RMS) based experiment, to $100M for a CASES-type experiment (Newsom, 3-2).

Some of the structures under consideration are hundreds of meters in dimension and will be required to maintain shape and alignment to within microns. These structures will have to be actively controlled, both statically and dynamically. Natural frequencies may be on the order of 0.01 Hz or less. Shape and alignment control will probably be accomplished by active structural members with low force output. It will be impossible to simulate the microgravity environment in ground tests for some of these structures.

Other types of structures will be smaller, stiffer, and will be required to slew rapidly, achieve pointing accuracies on the order of microradians, and limit

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[3] Where reference is made to a particular presentation, it is cited with the author's last name, followed by the session number, a dash, and paper number as it appears in the Final Program contained in Appendix A.

jitter to nanoradians. These structures may be tens of meters in dimension and have frequencies on the order of 10 Hz. Slew control will be accomplished by thrusters which apply large external forces. The transient nature of these forces will induce structural vibration which must be actively damped. The damping or "settling" of these slew-induced structural vibrations may be accomplished by a combination of external thrusters and internal actuators.

In general, ground validation tests can have different objectives, as suggested by Slimak in the panel discussion. Examples are technology validation versus system risk reduction. A technology validation test may employ a subscale model of a generic structure which is heavily instrumented. A test conducted for purposes of risk reduction, on the other hand, would involve flight hardware or protoflight hardware, and be more limited in scope, (e.g., to provide experimental verification that a particular boom will deploy). One type of test may not suffice for the other, there being differences in scale, differences in instrumentation, and differences between generic and specific hardware. Microgravity simulation could be approached very differently in these two cases, emphasizing the fact that varied approaches should be explored.

3.2 Current Issues

A number of current issues were identified during the workshop. They are listed below and discussed in the paragraphs which follow.

1. Integration of design, analysis, ground test and flight test.
2. Limitations of ground test methods.
3. Critical assessment of current methods for nonlinear dynamic analysis.
4. Effects of geometric stiffness.
5. Inclusion of electronics in experimental work.
6. Design, analysis and test of fluid systems.
7. Environmental disturbances and effects.

Issue #1. Integration of design, analysis, ground test, and flight test.

This issue appears central to all other issues related to the subject of the workshop. Different positions and opinions were expressed. There was no formal debate of the different positions, nor should there necessarily have been. All have validity depending on the particular circumstances being considered. The key to the issue is the word "integration", and how integration might be approached under various circumstances. The different positions are summarized below:

One position was that analytical simulation is of primary importance with experimental verification playing a supporting role (Amos, 1-3). As explained by Amos, this is a departure from the "conventional approach" used in aircraft design where ground testing plays a supporting role to flight testing in the validation of new system designs, and is complimented in this role by analytical simulation. Amos points out that spacecraft systems with large physical dimensions or high flexibility do not lend themselves to design validation by the conventional approach due to facility size limitations, gravitational distortion effects, or both.

Newsom had a different opinion. He thinks that the pendulum has, perhaps, swung too far toward analysis, citing poor comparisons between NASTRAN model predictions and experimental observations in some cases.

Wada (4-2) also pointed out that one of the primary reasons for testing is to measure the unexpected structural characteristics, which by definition are not modeled. Wada went on to emphasize, however, that it is not possible to measure the microgravity performance of some precision space structures in ground tests because of their size and/or the overwhelming effect of gravity on their performance which must be controlled to within microns. He proposes an approach incorporating adaptive structures in the design. This approach, he contends, would help in the achievement of structural requirements as well as alleviate accuracy requirements on the ground test validation program by adjusting the structure's geometry and/or characteristics on orbit to meet performance goals.

Another position was taken by Dodge (4-3) whose presentation addressed the difficulty of modeling and testing "low gravity free surface fluid motions and propellant management". Dodge pointed out that we presently do not have a general capability for analyzing fluids, and we can't afford to test every configuration in space. He suggested that generic designs be thoroughly analyzed and space-tested so that they may be used as "building blocks" for fluid systems.

A fifth point of view was offered by Ryan in the panel discussion. Ryan suggested that neither analysis, ground testing nor flight testing alone, are adequate for design validation, and that all three should be integrated on the basis of sensitivity analysis. Presumably, sensitivity analysis would help to define the interfaces among the different activities, and thereby facilitate their integration. Sensitivity analysis expands the knowledge associated with a particular analysis or experiment, provides direction for parameter searches which are used to bring analysis into agreement with experiment, and is used in quantifying the residual uncertainty in a verified analysis.

Issue #2. Limitations of Ground Test Methods

Amos (1-3) stated that a major issue in microgravity simulation is assuring that vibrations during the testing do not involve participation by any restraining systems, and are sufficiently long in duration to achieve steady-state vibrations and permit meaningful measurement. He lists the major drawbacks of the traditional schemes as follows:

- Cable suspension: Isolation of structural modes from cable axial and pendulum modes
- Drop tower suspension systems: Limited duration of test and sophisticated instrumentation requirements
- Aircraft parabolic flight maneuvers: Short test duration and heavily confined volumetric space
- Neutral buoyancy techniques: Hydrodynamic drag, limited space, and dynamic scaling distortions due to buoyancy requirements

Issue #3: Critical assessment of current methods for nonlinear dynamic analysis

Taking the position on analysis vis a vis testing discussed under Issue #1, Amos (1-3) asserts that analytical simulation should be capable of representing all major events of a mission "at a level of realism comparable to flight testing". Many of these events involve coupled rigid body and flexible body dynamics which is highly nonlinear. Amos calls for a critical assessment of current methods as a prelude to the development of improved capabilities. He suggests that such developments would be "greatly enhanced by heightened appreciation for nonlinearity pathologies like bifurcations, jumps, chaos, etc." Hybrid simulation involving combined use of physical and mathematical models may be needed to solve some of these problems.

Issue #4: Effects of geometric stiffness

"Geometric stiffness" is the term given to that portion of the stiffness representation of a structure which arises from "preload" on the structure. In linear finite element analysis, it may be the result of thermal loading or gravity loading, for example. In static structural analysis, it is used in formulating the buckling problem. In dynamic analysis, it affects the modal characteristics of a structure to the extent that it augments the elastic stiffness matrix. For space structures undergoing large rotations, it may result in stiffening during spinup motion, or dynamic buckling.

Two presentations addressed problems related to geometric stiffness. Banerjee (4-1) discussed a multi-flexible-body dynamics formulation incorporating a recently developed theory for capturing motion-induced stiffness for an arbitrary structure undergoing large rotation and translation accompanied by small vibrations. He claims that premature linearization in existing codes leads to "wrong equations." A consequence of these wrong equations is that existing codes, "such as DISCOS and TREETOPS" can predict dynamic softening during spinup where dynamic stiffening should occur.

In another presentation, Hasselman (5-4) showed that gravity-induced geometric stiffness can have a significant effect on where attachment points are selected for suspending a structure in ground vibration testing. Improperly located attachment points can cause the structure to buckle or introduce unwanted pendulum-type modes. A distribution of suspension forces optimized to minimize the strain energy in a structure can cause rigid body modes to become unstable.

Issue #5: Inclusion of electronic control loops in experimental work.

Several individuals mentioned the need to include electronics in experimental work on structures. Finkelman commented on the interaction of the Space Based Radar structure with its electronics. Newsom emphasized the importance of electronics in experimental work on the CSI Evolutionary Structure, and Wada suggested using active structures for system identification. Experimental verification of actively controlled structures with the control loops operating is an essential part of CSI technology verification. The microgravity environment will have to be simulated during ground testing of these structures.

Issue #6: Design, analysis and test of fluid systems.

The presentation by Dodge (4-3) was the only one addressing the unique problems of designing, analyzing and testing fluid systems. He stated that the physics of fluid motion and fluid-solid interaction are not well understood and, therefore, cannot be modeled. Nor is damping due to surface tension hysteresis understood very well. Fluid sloshing is characterized by very large excursions of the C.G. accompanied by low damping, implying that large rigid body excursions of the structure may occur. Frequencies may be on the order of 0.004 to 0.02 Hz with dynamic forces of 0.004 Newtons, peak to peak. Dodge said there is a need for liquid-vapor sensors which can detect whether a liquid or vapor is present at the sensor location.

As mentioned previously under the discussion of Issue #1, Dodge recommends that since fluid behavior cannot be analyzed (in general) and it would be too costly to test every configuration in space, that generic designs be thoroughly analyzed and space-tested for use as "building blocks" for fluid systems.

Issue #7: Environmental disturbances and effects.

This issue surfaced several times during the course of the workshop. Both static and dynamic environmental disturbances were mentioned. For example, Bainum (2-1) pointed out that it can require a larger control effort to compensate for static disturbances like solar radiation pressure than it does for vibration effects. On the other hand, it would seem that static-type corrections like the reorientation of solar sails could be used to compensate for changes in solar pressure. Other examples of environmental disturbances and effects were given by Pinson. One was a thermal flutter problem with a boom on the Voyager spacecraft. Another was a frequency error on the Galileo spacecraft attributed to gravity effects and model reduction. In the Galileo case, a structural frequency occurred within the bandwidth of the controller, which had not been predicted. Bainum mentioned that the Russians also appear to be very interested in environmental disturbances.

3.3 Identified Needs

The following is a list of needs distilled from the previous discussion of current issues and the workshop proceedings themselves. There is clearly overlap with previous sections of the report. However, some of the needs mentioned during the oral presentations and discussion do not appear in the written proceedings, nor were they brought out in the discussion of current issues.

Current and furture needs were identified as follows:

- Nonlinear analytical simulation capabilities for analyzing all major events of a mission (e.g., orbit insertion, assembly/deployment dynamics, orbital maneuvers, attitude maneuvers, on-orbit operations) at a level of realism comparable to flight testing.
- A hybrid simulation capability for the combined use of physical and mathematical models.
- An evaluation of alternative system identification methods.
- Improvement of on-orbit performance prediction capabilities for linear, as well as nonlinear, dynamics.
- Development of improved ground test methods for validation of on-orbit performance prediction.
- Cost reduction of validation procedures.
- Adaptive structures to achieve on-orbit performance goals.
- Design criteria for adaptive structures (i.e., the range of performance they must be able to correct for or adjust to).
- Verification of generic designs for fluid subsystems for use as "building Blocks" in assembling fluid systems.
- Liquid - vapor sensors for observation of fluid behavior.

3.4 Other Observations and Comments

This section contains miscellaneous observations and comments which were noted during the two-day workshop and judged to be worth mentioning but not otherwise reported.

- The textbook, Kinematic Geometry of Mechanics by K.H. Hunt was recommended by Krishnaprasad.
- It is possible to rotate a structure by 180° without external forces, while preserving conservation of momentum. The classic example of this is a cat, which when dropped upside down, will land on its feet.

- JPL has plans to evaluate alternative methods for modal parameter estimation including sine dwell, ERA (eigenvalue realization algorithm) and polyreference methods. They also hope to validate a NASTRAN model using model parameter estimation.

- When designing a microgravity suspension system, consideration should be given to optimizing the distribution of suspension stiffness as well as the distribution of suspension forces.

- Thought should be given to the characterization (modeling) of suspension elements so that even the small effects of a microgravity suspension system can be analytically removed from a model after experimental verification.

4. CONCLUSIONS

This report has attempted to document and summarize both the written and oral proceedings of the two-day workshop. The workshop included nineteen presentations and a panel discussion. Abstracts of all nineteen presentations are contained in this report along with a copy of the Final Program and the names and addresses of the 35 workshop participants and attendees. Copies of viewgraph transparencies used in the presentations, most with facing page text, are bound separately.

In addition to presenting abstracts of the nineteen papers, this report includes a discussion of the current issues raised in the workshop, and a list of identified needs for advancing microgravity simulation technology. The scope of the workshop was intentionally broad and appears to have covered the subject area reasonably well as judged by favorable comments from a number of the participants at the conclusion of the workshop.

APPENDIX A: FINAL PROGRAM

Opening Remarks, A.K. Amos, The Pennsylvania State University

Session 1: Overview
Chairman: Alok Das, Air Force Astronautics Laboratory

1. "Military Space Objectives," David Finkleman, US Space Command and NORAD
2. "NASA Space Objectives," Larry D. Pinson, NASA Langley Research Center, and Robert J. Hayduk, NASA Headquarters
3. "Microgravity Simulation Issues," A.K. Amos, The Pennsylvania State University

Session 2: On-orbit Dynamics Modelings and Simulation 1
Chairman: Major Al Janiszewski, Wright Research and Development Center

1. "Modeling Techniques for the Dynamics and Control of Large Flexible Orbiting Systems," Peter Bainum, Howard University
2. "Modeling and Control of Coupled Structures: Recent Developments," P.S. Krishnaprasad, University of Maryland
3. "Rapid Generation of Special Purpose Simulation Programs," David A. Levinson, Lockheed Palo Alto Research Laboratory

Session 3: Space Structures Experimental Programs and Facilities
Chairman: Ben K. Wada, Jet Propulsion Laboratory

1. "Air Force Programs and Facilities," Alok Das, Air Force Astronautics Laboratory
2. "NASA Programs and Facilities," Jerry Newsom, NASA Langley Research Center

Session 4: On-orbit Dynamics Modeling and Simulation II
Chairman: V. Venkayya, Wright Research and Development Center

1. "Multi-flexible-body Dynamics Capturing Motion-induced Stiffness," Arun K. Banerjee and Mark E. Lemak, Lockheed Missiles and Space Company

2. "On-orbit System Identification of Adaptive Structures for Precision Systems," Ben K. Wada, C.P. Kuo and G.S. Chen, Jet Propulsion Laboratory

3. "Low Gravity Free Surface Fluid Motions and Propellant Management," Franklin T. Dodge, Southwest Research Institute

4. "Dynamics and Kinematics of Satellite-Mounted Robots," Richard Longman, Columbia University

Session 5: Advanced Suspension Devices
Chairman: M.J. Gronet, Lockheed Missiles and Space Co.

1. "A Second Generation Zero Spring Rate Support System," T. Jeffrey Harvey, AEC-Able Engineering

2. "A Pneumatic/Electric Suspension Device for Very Low Frequency Dynamic Testing," David A. Kienholz, CSA Engineering, Inc.

3. "Zero Gravity Suspension Systems," Paul Lynn, NTS Engineering

4. "Location of Attachment Points and Distribution of Suspension Forces for a Microgravity Suspension System," T. K. Hasselman, Engineering Mechanics Associates, and Richard Quartararo, SPARTA, Inc.

Session 6: Suspension System Development
Chairman: Richard Quartararo, SPARTA, Inc.

1. "Assembly and Suspension Issues for the DSMT Pathfinder Scale Model," Marc J. Gronet and Rick G. Brewster, Lockheed Missiles and Space Company; and Edward F. Crawley, Massachusetts Institute of Technology

2. "Large Motion Suspension Devices for Flexible Structures," Victor M. Cooley, NASA Langley Research Center

3. "Structural Testing Using the KC-135 In-flight Microgravity Simulation Facility," Major Al Janiszewski, Wright Research and Development Center

Panel Discussion: Current Issues and Needs
Moderator: T.K. Hasselman, Engineering Mechanics Associates

A.K. Amos, The Pennsylvania State University
Larry Pinson, NASA Langley Research Center
L. Kevin Slimak, Astronautics Laboratory
P.S. Krishnaprasad, University of Maryland
Richard Longman, Columbia University
Robert S. Ryan, NASA Marshall Space Flight Center

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