NASA CSI Suspension Methods Overview

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Introduction

New suspension techniques will be necessary for ground testing the flexible spacecraft anticipated in NASA's future space activity. The most complex spacecraft involve nonlinear maneuvering (i.e. large angle slewing) with articulating substructures such as remote manipulating systems. The NASA CSI Ground Test Method team has begun researching and developing methodology to suspend the future class of spacecraft. This overview describes the work completed thus far.

As indicated in the outline below the research objective and technical approach will be presented first. Second, will be a suspension device overview followed by an assessment of existing hardware. Two different mechanical zero-spring-rate mechanisms will be compared for optimal performance. Next, will be a description of how existing hardware can be evolved to meet more general suspension requirements. A comparison of suspending articulating structures overhead vs underneath will follow. After a few experimental results from the zero-spring-rate mechanism/air suspension cart will be concluding remarks and future work.

Outline

- Objective
- Technical Approach
- Suspension Device Overview
- Assessment of Existing Hardware
- Zero-Spring-Rate Mechanism Optimization
- Suspension Device Evolution
- Suspending Articulating Systems
  Overhead vs Underneath
- Zero-Spring-Rate Mechanism/Air Suspension Cart
  Experimental Results
- Concluding Remarks/Future Work

Research Objective

The ultimate goal of advanced suspension system research is to simulate flight boundary conditions for ground testing flexible space structures. To achieve such a goal a suspension system must counteract gravity loads while allowing a structure to have unconstrained motion. The research objective is to develop and demonstrate suspension systems for CSI ground testing. The suspension problem concerns developing suspension systems for vibratory motion superimposed on large rigid body motion. These large rigid body motions could be large angle slewing or articulating substructures such as a remote manipulating system. Vibratory motion is inherent in the flexible spacecraft under consideration.

A suspension system must be considered as an integral part of the structure itself. However, it should be designed such that the dynamics of the system are dominated by the structure and not the suspension (i.e very soft suspension.) It is therefore desirable to minimize the effective mass, stiffness, damping and friction contributions from the suspension to the overall system.

Develop and demonstrate suspension systems for CSI ground testing

- Vibratory
- Rigid body
- Articulating

Technical Approach

The technical approach in this research is to evolve from simple devices into combinations of devices which will be suitable for general suspension requirements. Leading candidates for suspension devices are zero-spring-rate mechanisms (ZSRMs.) Various ZSRMs have been studied (1-4)* for stiffness reduction or vibration isolation. Their use, however, is restricted to vibratory motion. The CSI suspension problem concerns itself with vibratory as well as nonlinear types of motion. Air bearings are possible candidates for use with ZSRMs.

Spherical and translational air bearings offer almost friction-free surfaces. These devices could be incorporated into structures with large translational and rotational motions. However, their mass coupling with that of the structure becomes a concern. Although it is desirable to use passive systems, active system use becomes inescapable for structures which have both vibratory and large rigid body motion. Development of active suspension should, when possible, be built upon passive devices. Mass coupling, friction, and increased stiffness due to nonlinearity require active systems to reduce or eliminate their effects.

* Gold, R.R.; Reed, W.H.: "Preliminary Evaluation of Suspension Systems for 60-Meter Mast Flight System," prepared for the NASA Langley Research Center, Report No. C2602-008, February 1987.

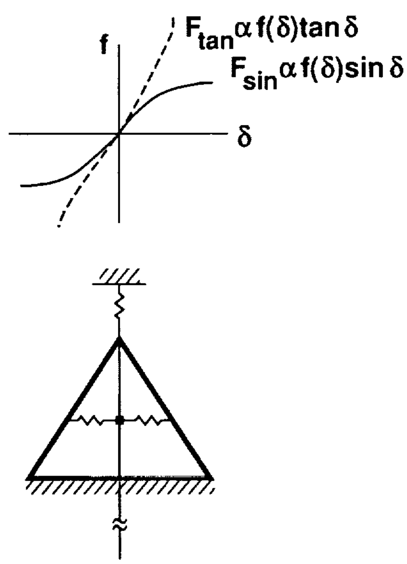
Simple ⇒ Complex

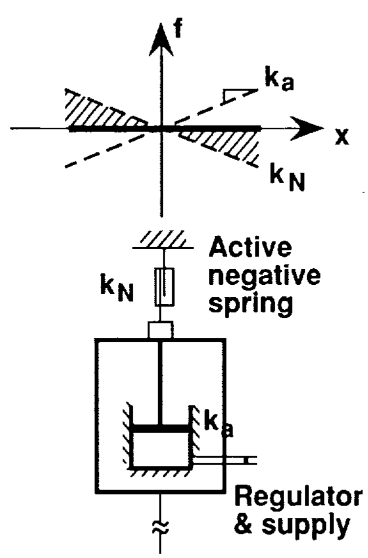
Passive ⇒ Active

Suspension Device Overview

Two leading suspension devices screened by NASA Langley's Dynamic Scale Modeling Technology research were a mechanical ZSRM and a pneumatic ZSRM. There are several implementations of the mechanical ZSRMs. All consist of a main spring which supports the weight of a test article and members in compression which behave as negative springs. The device can support a wide load range by changing the main spring or main spring prestretch. Compressive side members provide force components which act in a sense opposite to the main spring force. The load in the side members, $f(\delta)$, is dependent upon deflection from some initial position. These devices differ from one another by how the vertical component of the compressive forces varies with deflection. Force-deflection curves for two types of devices are illustrated below. On one curve the force varies with the tangent of deflection. Because the tangent curve is increasing as compared with the increasing/ decreasing nature of the sine curve the tangent type device is less nonlinear than the sine type.

The pneumatic ZSRM has a passive pneumatic main spring which is a piston/ cylinder arrangement. The load carrying capacity can be varied by changing the pressure in the cylinder. This device is inherently linear as illustrated in the force-deflection curve below. A DC servomotor provides a negative spring rate via active control based on the vertical position of the piston. The effective spring rate of the active motor is also linear. Combining the passive pneumatic spring rate and that of the DC servomotor produces a zero spring rate. The active system is remotely tuned to vary load capacity and spring rate.





- **Wide load range**
- **Several implementations**
- **F_{tan} less nonlinear than F_{sin}**

- **Remotely tuned**
  - **Stiffness**
  - **Load**
- **Wide load range**
- **Noncontacting**

Assessment of Existing Hardware

Three suspension devices were considered for application to CSI ground testing. A sine type ZSRM was developed at NASA Langley. This device has an effective stiffness which varies with the sine of deflection. The pneumatic Zero-g and the Mechanical lever ZSRM were developed under the Dynamic Scale Modeling Technology (DSMT) research at NASA Langley. DSMT requirements for the two devices were that the suspension frequency be 0.10-0.25 Hz, each device carry 50-500 lbs (290 lbs nominal), frictional force remain less than 0.1 lbf and the devices be remotely controlled for load balancing and tuning.

The table below assesses the three devices for criteria necessary for structures undergoing vibratory as well rigid body motion. All three devices were within the DSMT frequency range. However, because low stiffness structures are considered for some anticipated NASA missions the stiffness of the devices was compared. Because of air piston leaks the pneumatic device was not suitable for vacuum chamber usage. Cart suspension will be necessary of large rigid-body motion. All devices were suitable for cart suspension, however, the mechanical lever ZSRM is more compact. The mechanical lever ZSRM is assessed to be more suitable for all suspension configurations and environments.

Criterion	Pneumatic zero-G	Mechanical lever ZSRM (tangent type)	Sine type
Linearity	+	+	○
Remote tuning	+	Planned	Unplanned
Payload (lbs)	24 - 284	120 - 330	2 - 20
Stiffness (lbs/in.)	0 - 5.000	0.47	0.2700
Damping %	2.3	3.30	2.7000
Breakaway friction, lbf	0.002	0.01	0.0003
Vacuum chamber usage	-	+	+
Suitability for cart suspension	+	+	+

Mechanical lever ZSRM ⇒ all suspension configurations and environments

+ = desirable ○ = limited - = undesirable	D. Keinholz J. Gooding CSA Engineering	Marc Cronet, LMSC Ed Crawley, MIT David Keinholz, CSA	V. Cooley NASA/ Langley

Sine-type Zero-Spring-Rate Mechanism

The figure below illustrates a sine-type ZSRM. The compressive force, $f(\delta)$, is provided by two beams in bending. Sandwiched spring steel compressive side members reduce the friction of the device. A tension spring supports the suspended weight.

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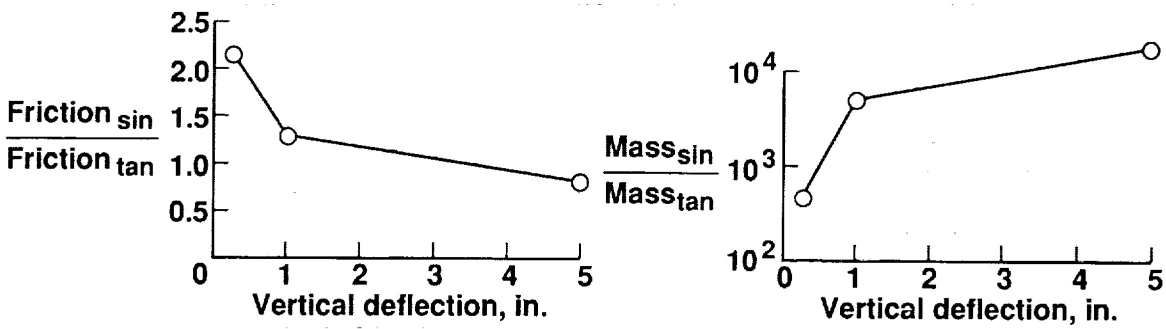
Zero-Spring-Rate Mechanism Optimization

Two mechanical ZSRMs were considered in an optimization study which had objectives of minimizing friction and coupled mass. One ZSRM had a force proportional to the sine of the vertical deflection of its side members. Similarly, the other had force proportional to the tangent of deflection. In both designs members are loaded in compression, so a buckling constraint was applied to the optimization analysis. The results of the analysis show that for small deflections the tangent type device has less friction than the sine type. Only for large deflections ($\approx$ 3.0 in) does the sine type device design become slightly advantageous. The two devices have substantial differences in the mass coupling characteristics. The sine type device would require a thousand times more mass than the tangent type to satisfy the same linearity constraint. Because the sine type device is inherently more nonlinear it requires much larger dimensions to have the linearity characteristic.

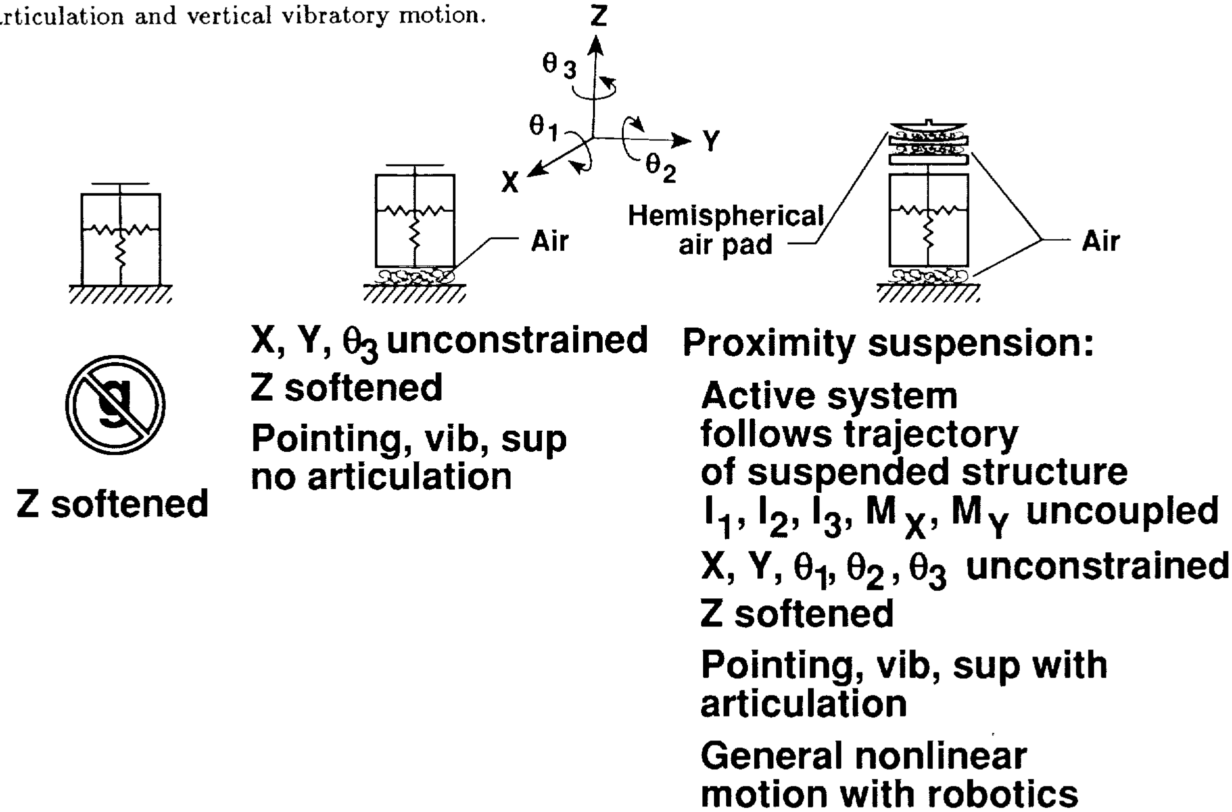


- **Minimum effective mass**
- **Constraints on: linearity**
  bending stress f.s.
  buckling f.s.
- **Assumed solid rectangular x-sections**
- **Flexible suspension modes not examined**

Evolution of Suspension Devices

Existing zero-spring-rate-mechanisms are one degree of freedom devices which support the weight of a test article with a low vertical stiffness. If possible, more complex suspension systems should evolve from simpler ones. A device combining some type of cart and a ZSRM would seem to be the next appropriate stage in suspension device evolution. The type of cart under consideration is an air bearing. Air bearings provide a translational load carrying capability with very low friction. A ZSRM/air bearing combination allows a structure to have unconstrained horizontal degrees of freedom necessary for large horizontal rigid body motion and vertical vibratory motion. Because this device is attached to the supported structure its mass couples horizontally with the structure. A device such as this is suitable for structures undergoing slewing (i.e pointing control). However, because of the horizontal mass coupling this is not suitable for lightweight articulating structures.

The next progression for suspension systems is to augment the ZSRM/air bearing with active control. To eliminate the mass coupling problem the proximity suspension device illustrated below could be used. The proximity device consists of the ZSRM/air bearing combination mentioned above, an air table atop this device, and a concave hemispherical air bearing atop the air table. A convex hemisphere, constructed of lightweight material, will be attached to the test article. The hemispherical air bearing is added to unconstrain the roll and pitch degrees of freedom. The air table that the hemispherical bearing rests on will make it possible to use open-loop active control. When structures and/or the appendages move in ground testing the trajectory of their rigid body motion is known a priori. However, the subsequent vibratory motion is not known. Active control (i.e. DC motor and pulleys) will be provided so that the suspension device synchronously follows the same trajectory of the rigid-body motion attachment point. The air table allows the structure to have horizontal vibratory motion in proximity to the rigid-body motion attachment point. The active system and air table decouple all the horizontal mass except for that of the hemispherical air bearing. This device is suitable for all suspension requirements of large horizontal rigid body motion and/or articulation and vertical vibratory motion.



Suspending Articulating Systems:
Underneath versus Overhead

Much of this paper has focused on suspension devices; however, it is also necessary to consider suspension configurations for articulating systems. The basic consideration is whether structures will be supported overhead or underneath. The charts below illustrate the advantages and disadvantages of each. Overhead supension is usually done with cables. These are broadly used, their overall vertical stiffness can be reduced with ZSRMs and they offer simplicity for ground testing of structures undergoing only vibratory motion. Cable suspension produces pendular and axial stiffness. The necessary controls and hardware will be complex for rapid slewing or articulation.

Suspending articulating structures underneath can be done with the air bearing/ZSRM concepts mentioned earlier. With underneath suspension overhead height is not a factor (i.e. to reduce pendular and axial stiffness.) The air bearing/ZSRM combination is a passive means for suspending articulating structures; however, the mass of the suspension hardware couples horizontally with the structure. The proximity suspension device mentioned earlier could eliminate the horizontal mass coupling.

Overhead

Advantages

- Broad use
- Soft systems/ vibratory motion ⟶ cable/ZSRM
- Simple

Underneath

Advantages

- Overhead height not a factor (i.e. vacuum chamber)
- All DOF's unconstrained with proximity suspension
- Vibratory and large rigid body motion (i.e. slewing, telescope)
- Simple open-loop control for proximity suspension
- Safety

SUSPENDING ARTICULATING SYSTEMS
Underneath versus overhead

Overhead

Disadvantages

- Constrained DOF's due to pendular and cable axial stiffness
- Control complexity for rapid slewing/articulation
- String modes
- 82 ft overhead height for pend freq < 0.1 HZ
- Added weight to test configuration
- Tensioned cables may behave as tuned mass dampers

Underneath

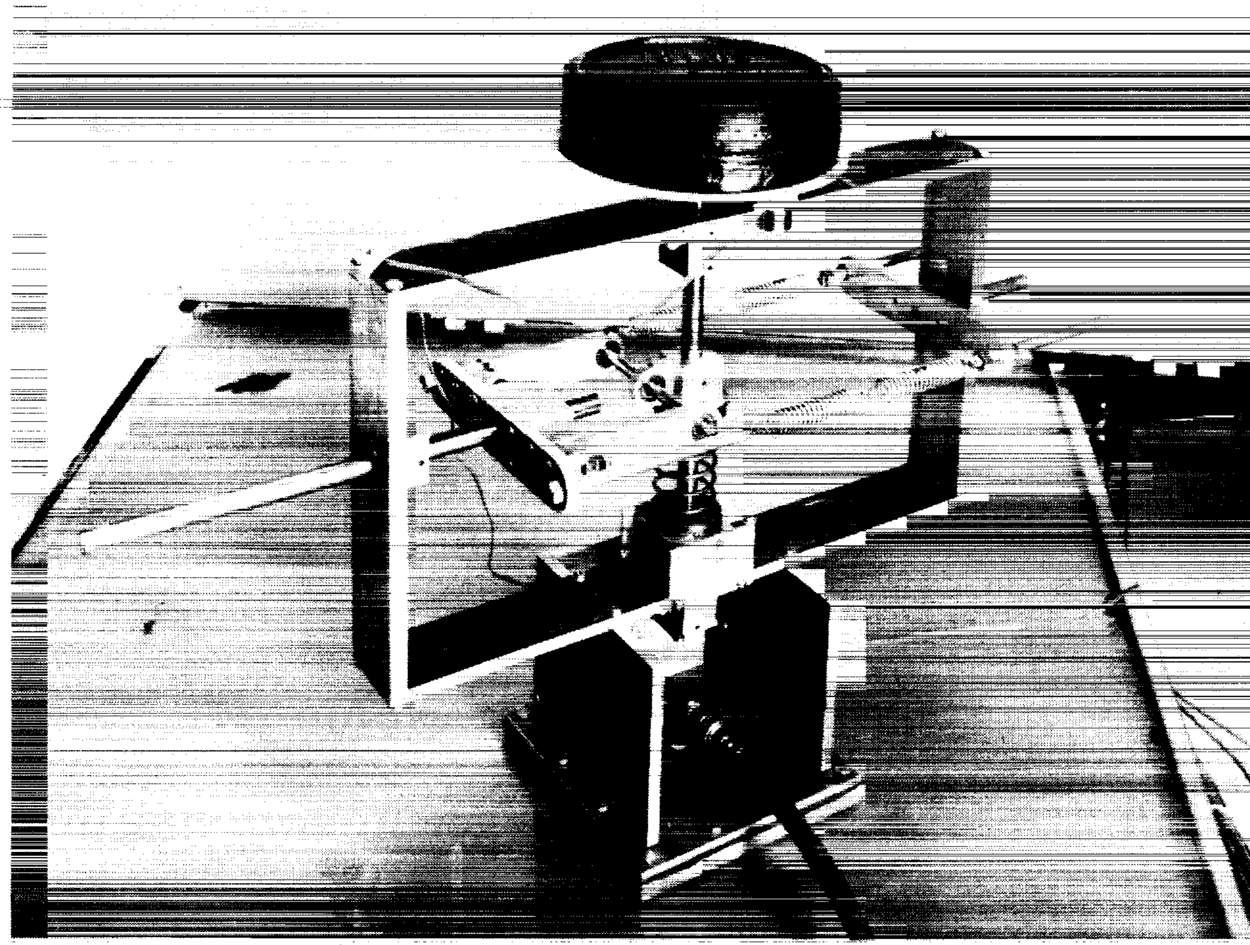
Disadvantages

- Mass coupling in vertical direction (all other eliminated by active control)
- Inverted pendulum stability

Bottom suspension more suitable for structures with large rigid body motion and/or articulating motion

Zero-Spring-Rate Mechanism/Air Suspension Cart

The figure below illustrates a zero-spring-rate mechanism atop an air bearing. This device is for suspending structures undergoing large horizontal rigid body motion concurrently with vertical vibratory motion. A compressive spring supports the weight of the lumped mass.



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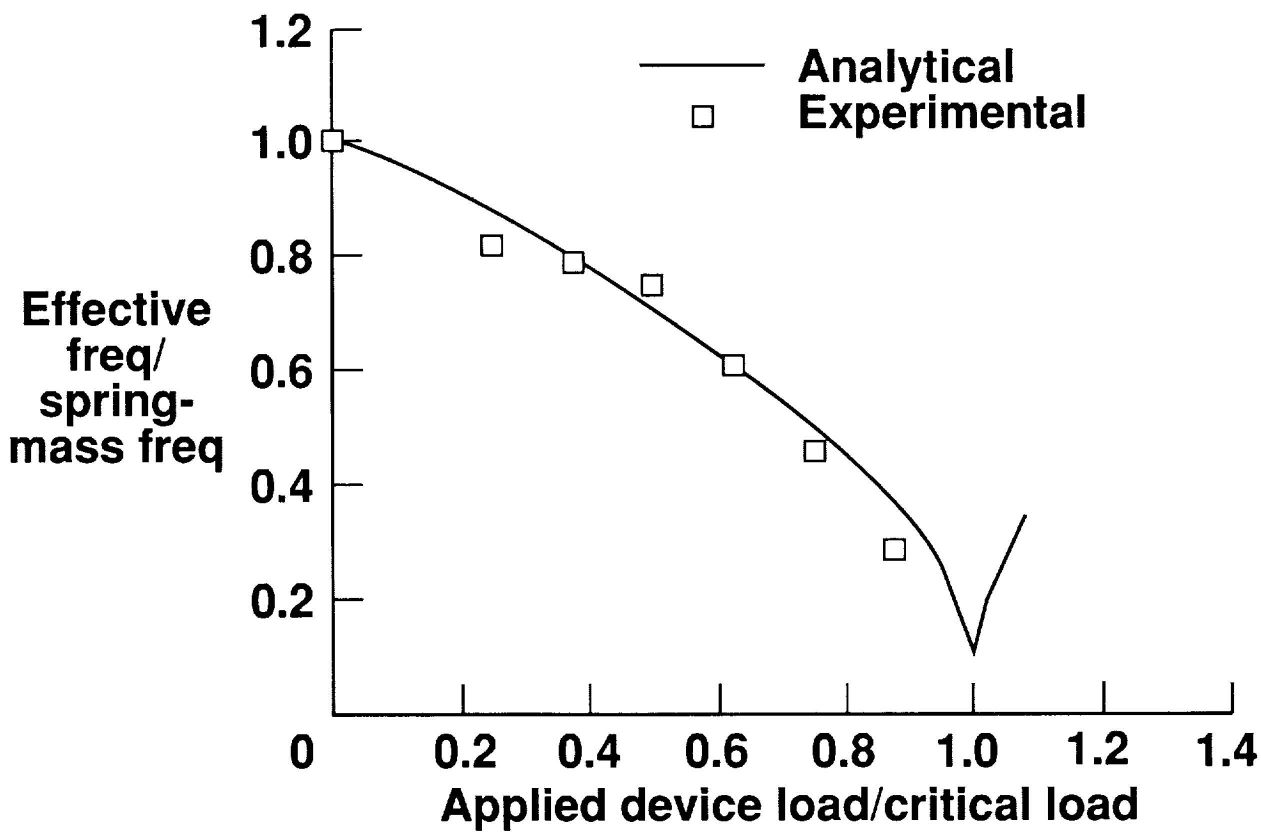
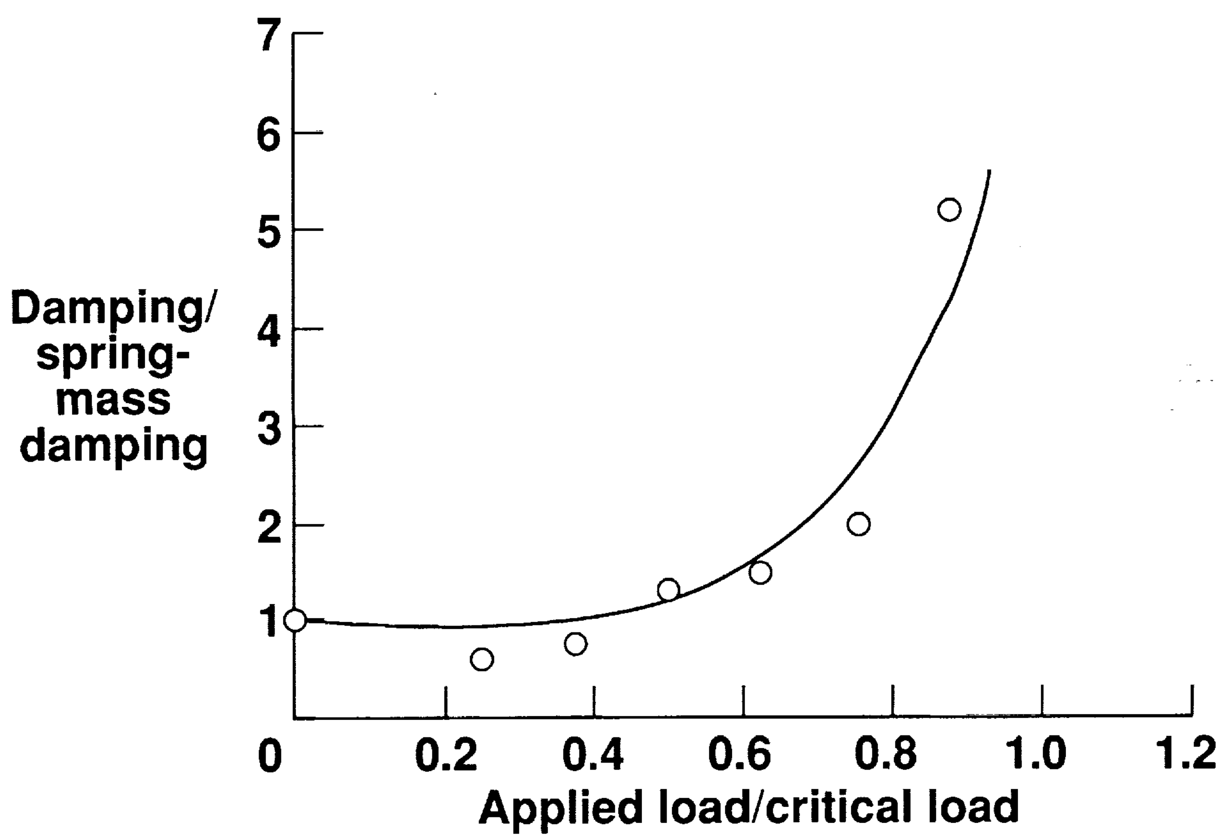
Frequency Variation with Applied Load

The experimental and analytical frequency variation with applied load of the ZSRM used as part of the ZSRM/Air Suspension Cart has been characterized in the figure below. The applied load is normalized with the compressive load (critical load) which would result in a spring rate of zero for linear deflections. Effective frequency is normalized with the frequency of a system containing only the main spring and the lumped mass. As load increases the frequency decreases, which is the essence of the zero- spring-rate device. The minimum frequency occurs at the critical load. However, the frequency is nonzero because the system is nonlinear. For linear systems the effective frequency is independent of initial conditions. The effective frequency of a nonlinear system is dependent upon initial deflection and velocity. The minimum experimental frequency was due to friction in the device.



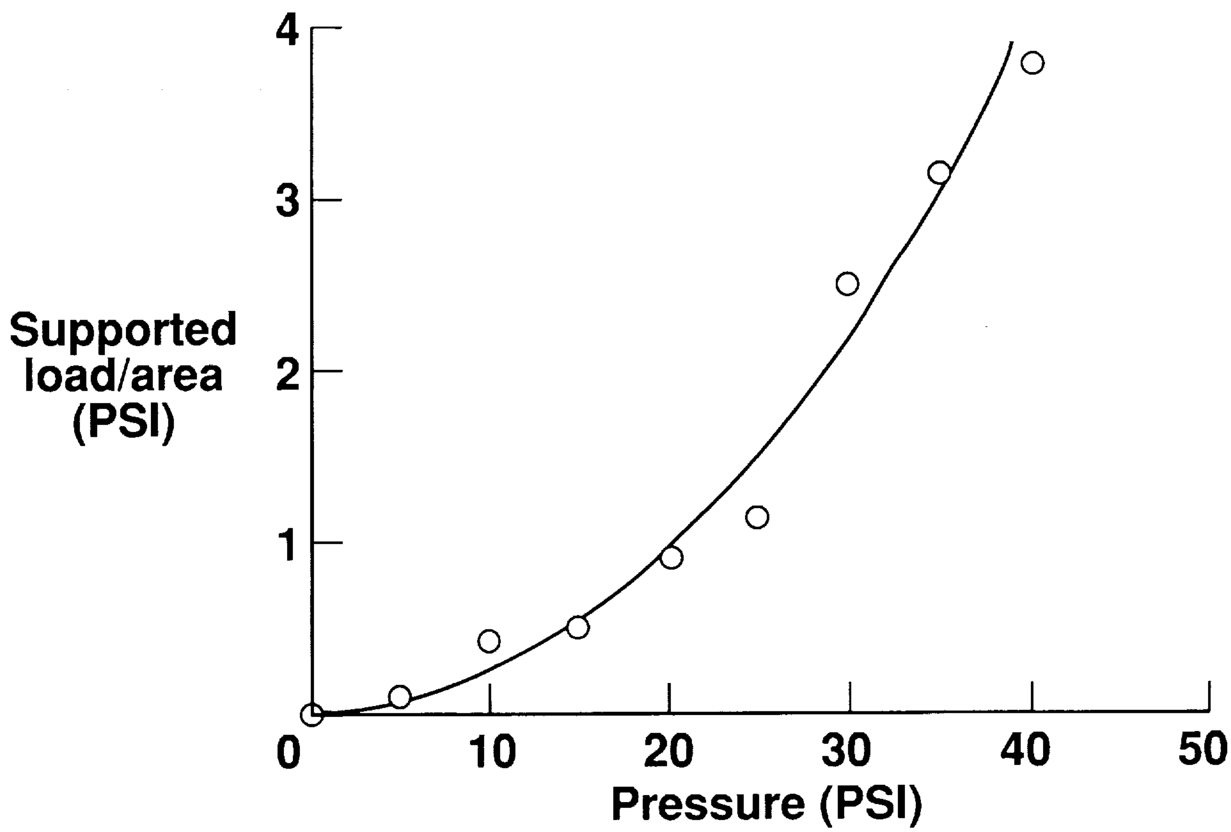
Damping Variation with Applied Load

The experimental damping variation with applied load of the ZSRM used as part of the ZSRM/Air Suspension Cart has been characterized in the figure below. The applied load is normalized with the compressive load (critical load) which would result in a spring rate of zero for linear deflections. Damping is normalized with the damping of a system containing only the main spring and the lumped mass. As load increases the damping increases. The friction in the device is proportional to the horizontal component of the applied load but is not constant when the device is in operation. During the cycle of motion the frictional force is highest when the side members are in the horizontal position and lowest when the deflection is peaked. As illustrated in the previous figure the use of the device can be limited by friction.



Supported Load Variation with Line Pressures

The load carrying capability of the air bearing used as part of the ZSRM/Air Suspension Cart has been characterized in the figure below. The air bearing has an area of 64.0 sq. in. Because the air bearing is capable of supporting a load of approximately 250.0 lbs. with less than 50 psi of supplied pressure it is feasible for suspending heavy structures in most ground test facilities. For most structures it is envisioned that at least two ZSRM/Air Suspension Carts will be used.



Concluding Remarks: Future Work

The problem of suspending flexible structures undergoing large rigid body motion as well as vibratory motion will require new suspension techiques and hardware. It has been shown that existing suspension hardware can be evolved to solve some of the future suspension demands. Passive systems should, if possible, be augmented with active control to eliminate their shortcomings (i.e. mass coupling and increase stiffness due to nonlinearity.) Proximity suspension can be used for structures undergoing large horizontal rigid body motion and/or articulation with vertical and horizontal vibratory motion. By combining air bearings, spherical air bearings and zero-spring-rate mechanisms a structure can be supported while its degrees of freedom remain unconstrained. Much work needs to be done in testing and validation of these concepts.

Future work will consist of a zero-spring-rate mechanism/air suspension cart slewing experiment. A flexible beam will be hinged at one end. On the other end will be an attached zero-spring-rate mechanism/ air suspension cart. This passive device serves as a prelude to a proximity suspension device. The beam will be slewed through large angles. During the slewing motion the structure will be excited so that it will have large rigid body motion as well as vibratory motion. The experiment will validate the use of air bearings and zero-spring-rate mechanisms for flexible structures undergoing large rotations.

- Proximity suspension: promising method for structures with vibratory as well as large rigid body and/or articulating motion
- Active/ZSRM/air suspension supports test article while leaving all DOFs unconstrained
- Passive $\Rightarrow$ Active

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