N92-27733

# A SIX DEGREE-OF-FREEDOM LORENTZ FORCE VIBRATION ISOLATOR WITH NONLINEAR CONTROLLER

INTERNATIONAL SYMPOSIUM ON
MAGNETIC SUSPENSION TECHNOLOGY
NASA LANGLEY RESEARCH CENTER

August 19-23, 1991

Ralph C. Fenn

SatCon Technology Corporation
12 Emily Street
Cambridge, MA 02139
(617) 661-0540

The other major contributors to this project were Michael Gerver, physicist, and Bruce Johnson, Dynamic Systems and Controls Division Leader at SatCon. The project was sponsored by NASA Marshall Space Flight Center.

This paper presents the results of a Phase II Small Business Innovation Research program sponsored by NASA Marshall Space Flight Center. Technology is developed for isolating acceleration sensitive "microgravity" experiments from structural vibrations of a spacecraft, such as Space Station. Two hardware articles were constructed, a six degree of freedom Lorentz force isolator, and a one degree of freedom low acceleration testbed capable of tests at typical experiment accelerations.

## PRESENTATION OVERVIEW

- o Microgravity experiment isolation requirements
- o Six degree of freedom suspension specifications
- o SatCon six degree of freedom Lorentz force isolator
  - Prototype space based system
    - Design
    - Hardware
    - Test results
- o SatCon single degree of freedom testbed
  - Low acceleration precision test facility
    - Design
    - Hardware
    - Test results
- o Nonlinear control

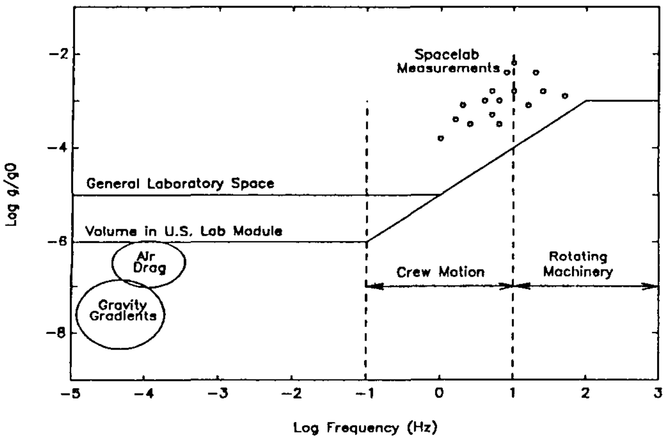
  - Simulations

  - Test results

PRECEDING PAGE BLANK NOT FILMED

The need for isolation of microgravity experiments has been established recently based on Spacelab measurements and modeling of experiment requirements. Low frequency accelerations, caused by air drag and gravity gradients, small and fall below experiment acceleration limits. High frequency vibrations, caused by rotating machinery, require isolation, but simple mechanical isolators are adequate. The difficult vibrations at moderate frequencies, caused by crew motion, require a combination of large stroke and relatively low crossover frequency that is best provided by active suspensions. Isolation above approximately 0.04 Hz is required.

# EXPERIMENT REQUIREMENTS VS THE ENVIRONMENT

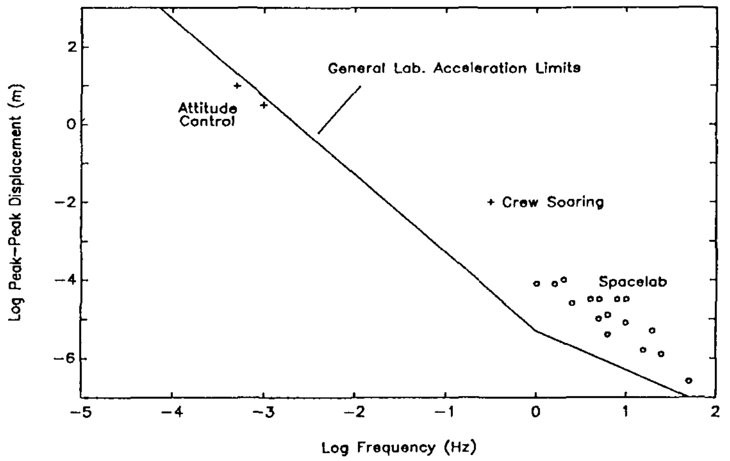


**CHARACTERISTIC FREQUENCY RANGES**

- LOW FREQUENCIES DON'T REQUIRE ISOLATION
- HIGH FREQUENCIES (10-100Hz) REQUIRE ISOLATION BUT EASY MECHANICAL SUSPENSIONS
- MIDDLE FREQUENCIES (0.04-10Hz) HARDEST; CREW MOTION
    - LOW CROSSOVER
    - LARGE STROKE
- INTERSECTION OF ENVIRONMENT AND REQUIREMENT PLOTS AT .04 Hz

The precious plot shows the acceleration environment and limits. Given the 0.04 Hz maximum base following bandwidth from the previous plot, the required suspension stroke can be determined. This figure shows that a peak-to-peak actuator displacement of 2 cm is required for desired isolation.

## VIBRATION AMPLITUDE MEASUREMENTS AND LIMITS



- **SOLID LINE IS THE VIBRATION POSITION AMPLITUDE LIMIT**
- **±1 cm STROKE IS REQUIRED FOR ISOLATION DOWN TO 0.04 Hz**

Both attractive and Lorentz force actuators were considered for this application. Because of the large stroke requirement, the typical mass penalty of Lorentz force actuators did not exist. Many other advantages of Lorentz force actuation are beneficial in this application as listed below.

## THE ADVANTAGES OF LORENTZ FORCE ACTUATORS

### (FORCE $\alpha$ CURRENT TIMES FLUX DENSITY)

- OPEN-LOOP STABILITY (FACILITATES NON-LINEAR CONTROLLERS)
- INHERENT ZERO GRAVITY ISOLATION AT ZERO CURRENT
- CAN ISOLATE TO LOWER FREQUENCIES THAN FERRO-ATTRACTIVE ACTUATORS
- MECHANICAL SIMPLICITY FACILITATING SIX DOF DESIGNS
- EASY INTEGRATION WITH STANDARD ELECTRONICS
- EQUIVALENT MASS PER UNIT FORCE WITH ATTRACTIVE ACTUATORS DUE TO LARGE STROKE
- SATURATION DOES NOT LIMIT FORCE LIKE ATTRACTIVE ACTUATORS

The previous figures showed how the stroke, base following bandwidth, actuator bandwidth and force requirements were formulated, as summarized here.

# ISOLATOR FUNCTIONAL REQUIREMENTS

| | | |
|---|---|---|
| o | STROKE (X, Y, AND Z) | ±1 cm |
| o | MAXIMUM BASE-FOLLOWING FREQUENCY (MAXIMIZE "FREE FLYING") | 4 X $10^{-2}$ Hz |
| o | MINIMUM ACTUATOR BANDWIDTH (COUNTERBALANCE DIRECT FORCES) | $10^{2}$ Hz |
| o | FORCE FOR 500 KG EXPERIMENT | 1 N |

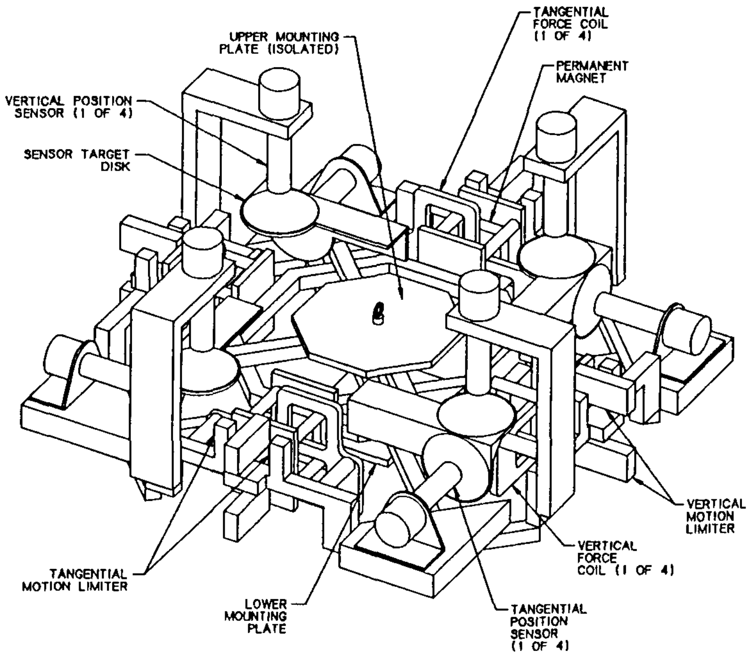
A prototype six degree of freedom (DOF) isolator was constructed that had the characteristics listed below. The width and depth were scaled approximately to typical orbiter locker size. Weight was reduced to some degree by aluminum construction, but further reductions are possible. The prototype force capability was sized for very large 500 kg experiments. This capacity could be reduced, giving a substantial mass savings.

## SIX DOF ISOLATOR DESIGN

| | |
|---|---|
| FORCE | 4 N (EXCEEDS REQUIREMENTS) |
| DIMENSIONS: | |
| STROKE | ±1 CM |
| WIDTH AND DEPTH | 45 CM |
| HEIGHT AT CENTER | 8 CM |
| WEIGHT: | |
| SUSPENDED PLATFORM | 5.0 KG |
| BASE STRUCTURE | 4.5 KG |
| TOTAL | 9.5 KG |
| ISOLATOR POWER: | |
| 1 N Z AXIS | 1 W |
| 1 N X OR Y AXIS (EXPER CG 15 CM UP) | 4 W |
| OPEN-LOOP ACTUATOR BW: | > 100 HZ |

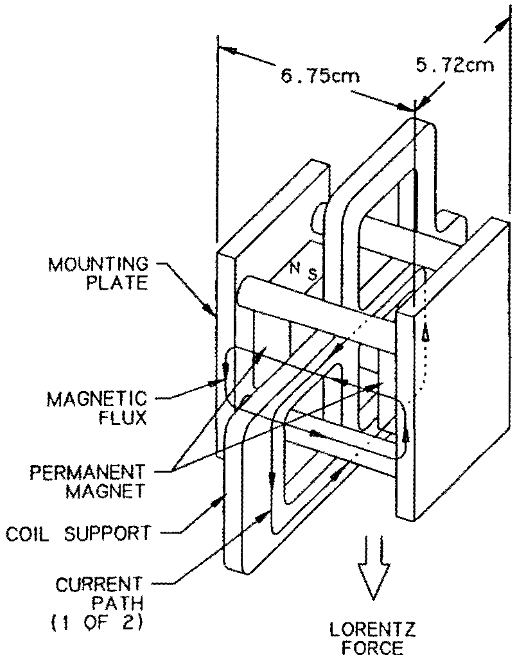
The prototype suspension shown below has four actuators, supplying eight forces, and eight position sensors. Each of the four isolator sides is identical, which provides symmetry and reduces controller complexity. Four Lorentz force actuators in the center of each side produce vertical and tangential forces. Two mounting plates are provided, one for the experiment on top, and the second for Space Station attachment below. Eddy current position sensors measure the vertical and tangential position at each corner.

## SATCON SIX DOF MAGNETIC SUSPENSION



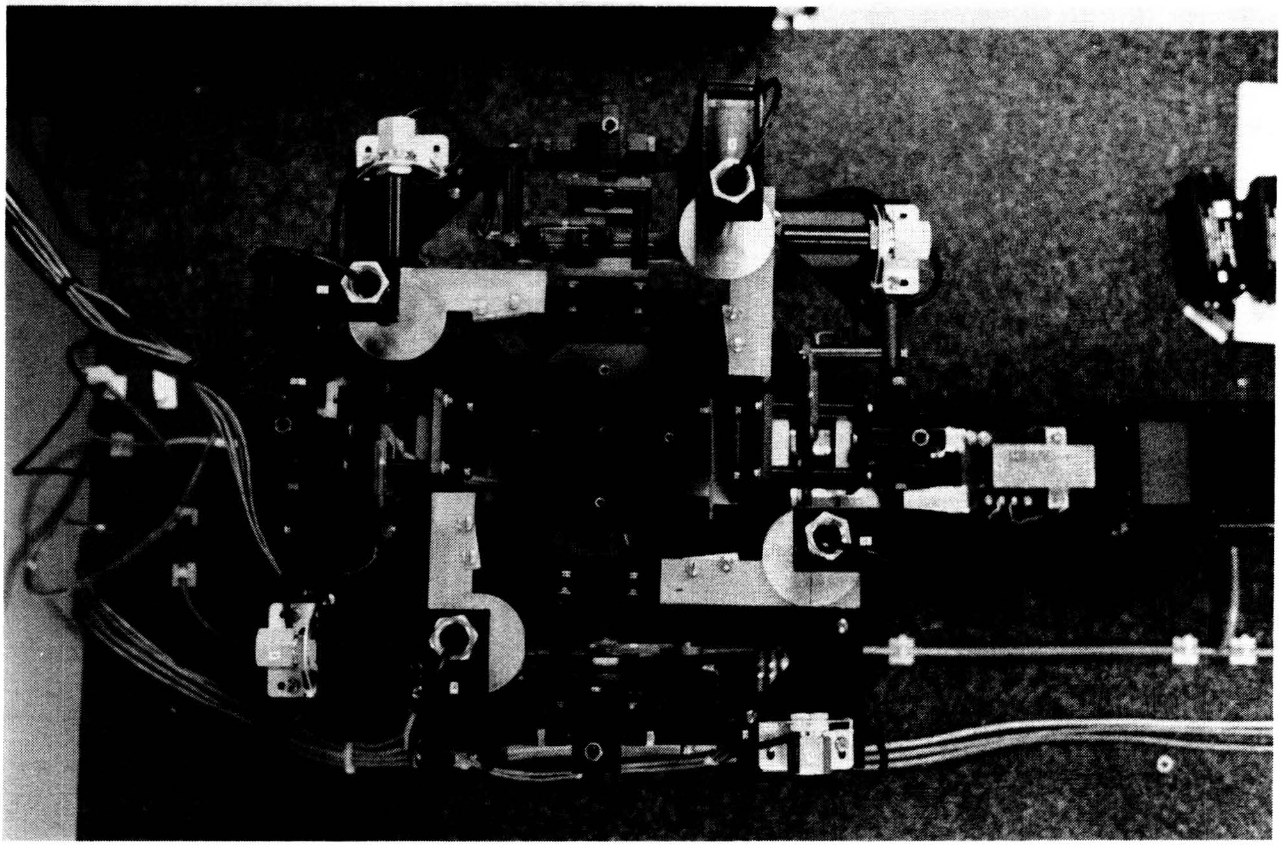
The actuator shown below has two permanent magnets that produce flux in the central air gap, where the coils cross. The flux returns through the four posts at the corners of the mounting plates. "L" shaped coil mounts comprised of separate horizontal and vertical coils are laced through the gap. The return current returns outside the gap. The force constant is 1 Newton per ampere and the coil resistance is 9 ohms. Force capacity depends entirely on the duty cycle because the actuators are heat limited.

## ONE OF THE SIX DOF ISOLATOR ACTUATORS



This top view of the isolator shows the upper mounting plate surrounded by the position sensors and circular targets, and the actuators on the center of each side.

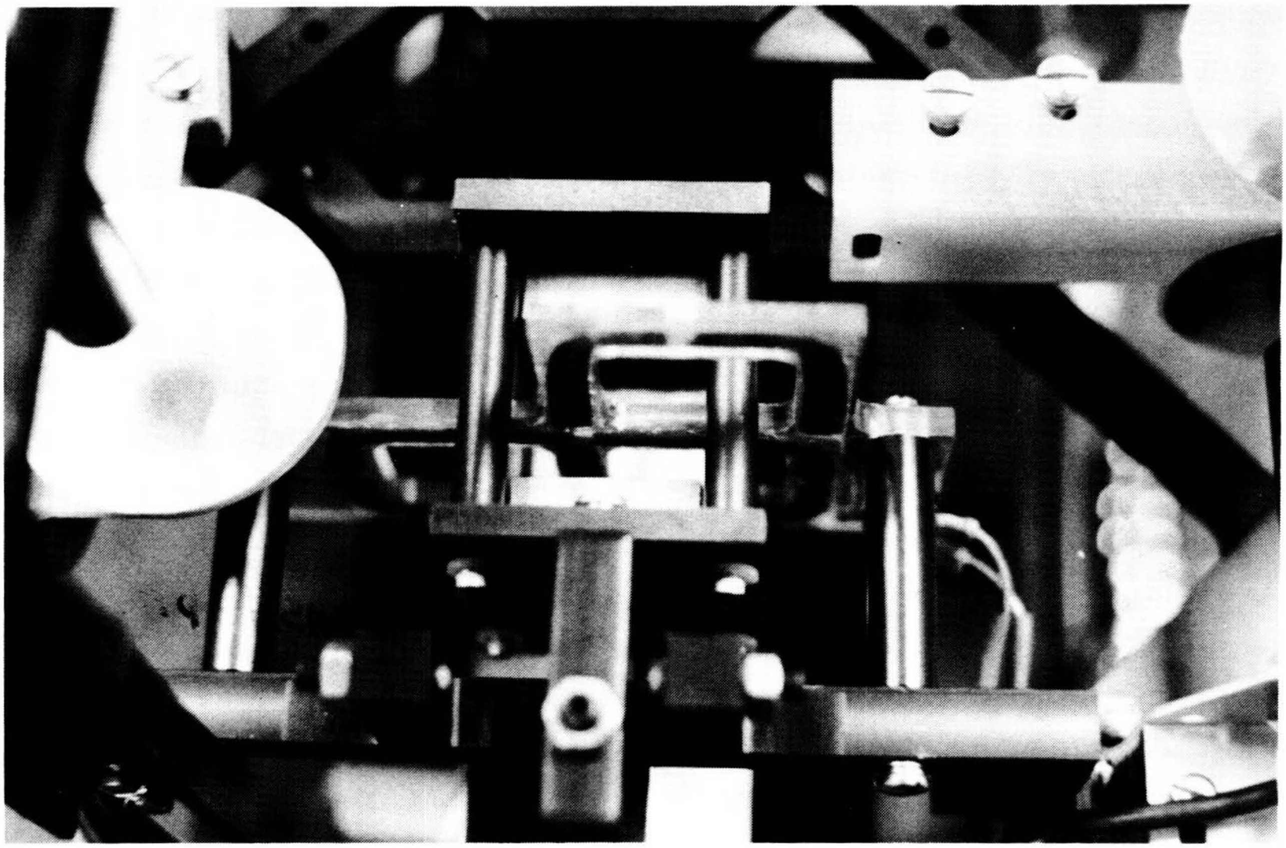
## THE COMPLETED SIX-DOF ISOLATOR



ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

A photograph of one of the actuators is shown below. The crossing point of the coils is visible in the center of the gap, between the permanent magnets. One of the aluminum foil eddy current sensor targets is also shown.

## AN ACTUATOR INSTALLED ON THE SIX-DOF ISOLATOR

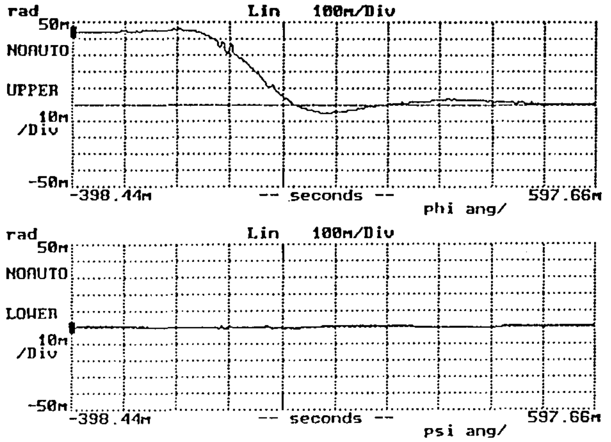


ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

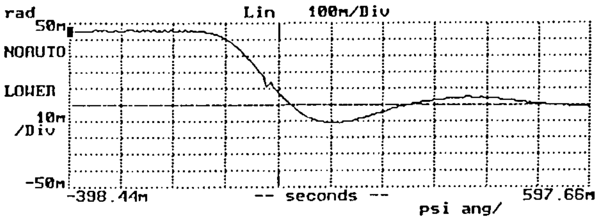
These plots show experimental data for initial condition responses of roll of the suspended platform. A long, soft spring was used to unload the gravity force and give a nominally centered coil position within the gap. The top two plots are concurrent traces of the x axis and y axis roll motions ($\phi$ and $\psi$). The second plot shows that the roll axes are decoupled by the controller. Good damping characteristics are also exhibited.

## INITIAL CONDITION RESPONSE OF ROTATIONAL AXES

(a) phi

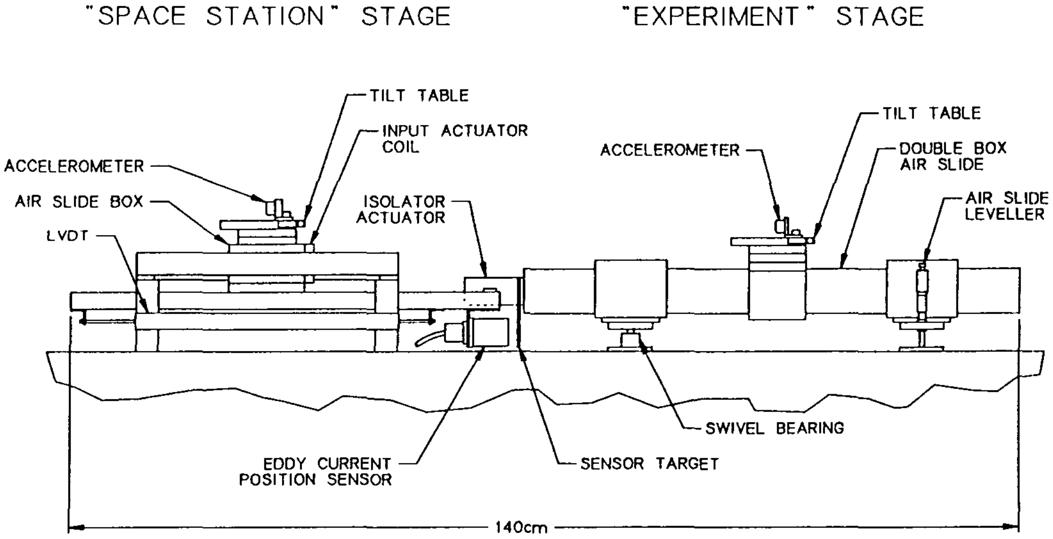


(b) psi



The second article of hardware constructed is a one degree of freedom testbed to simulate on orbit accelerations and test controllers. The figure below shows an integrated Lorentz force motor / air slide on the left, which produces expected Space Station accelerations. On the right is another air slide supported by two air boxes, which simulates the floating experiment mass. The relative position of the "experiment" stage and the "Space Station" stage is controlled to maximize isolation in one DOF while preventing "bottoming out" of the central isolation actuator. This apparatus is useful for testing nonlinear controllers and determining the effect of signal noise levels throughout the control system.

**ONE DEGREE OF FREEDOM TESTBED**



**PRECISION LOW ACCELERATION TEST FACILITY MICROGRAVITY LEVEL ACCELERATIONS**

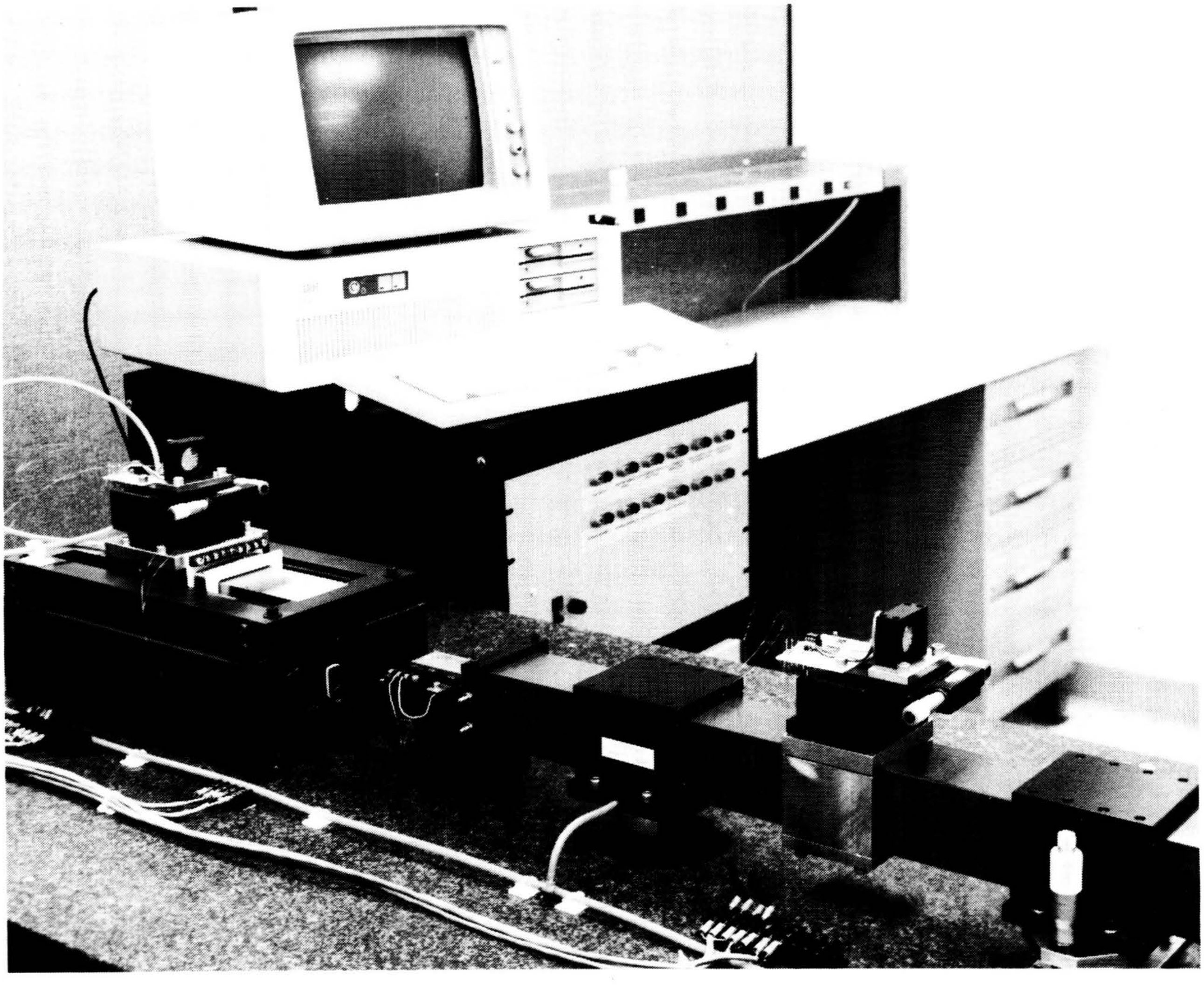
The single digit microgravity background accelerations were produced using noncontacting actuators, sensors and mechanical suspensions where possible. The only connection to the sensitive Space Station stage are several thirty four gage wires carrying the accelerometer power and signals.

## ONE DOF TESTBED

- INPUT STAGE SIMULATES SPACE STATION VIBRATIONS.
- EXPERIMENT STAGE IS ISOLATED BY LINEAR ACTUATOR IN CENTER.
- EACH STAGE HAS POSITION AND ACCELERATION FEEDBACK.
- SIMULATE TYPICAL SPACE ACCELERATIONS AND SIGNAL LEVELS: IMP. FOR NONLINEAR CONTROL TESTS, SENSOR AND ACTUATOR TESTS.
- NONCONTACTING HARDWARE:
  - AIR SLIDES: ACCURATE SPACE STATION ACCELERATION REPLICATION W/O STICTION AND SENSITIVE ISOLATION EVALUATION
  - NONCONTACTING POSITION SENSORS
  - NONCONTACTING INPUT MOTOR AND ISOLATION ACTUATOR
  - AIR LINES ON NONMOVING PART
  - ONLY ACCELEROMETER LEADS CONNECT TO EXPERIMENT
- VERY STIFF STRUCTURE

This figure shows the one DOF testbed mounted on the granite surface plate. The accelerometers mounted on top of each stage are visible. One of the two 0.12 $\mu$m resolution differential micrometers is shown on the right.

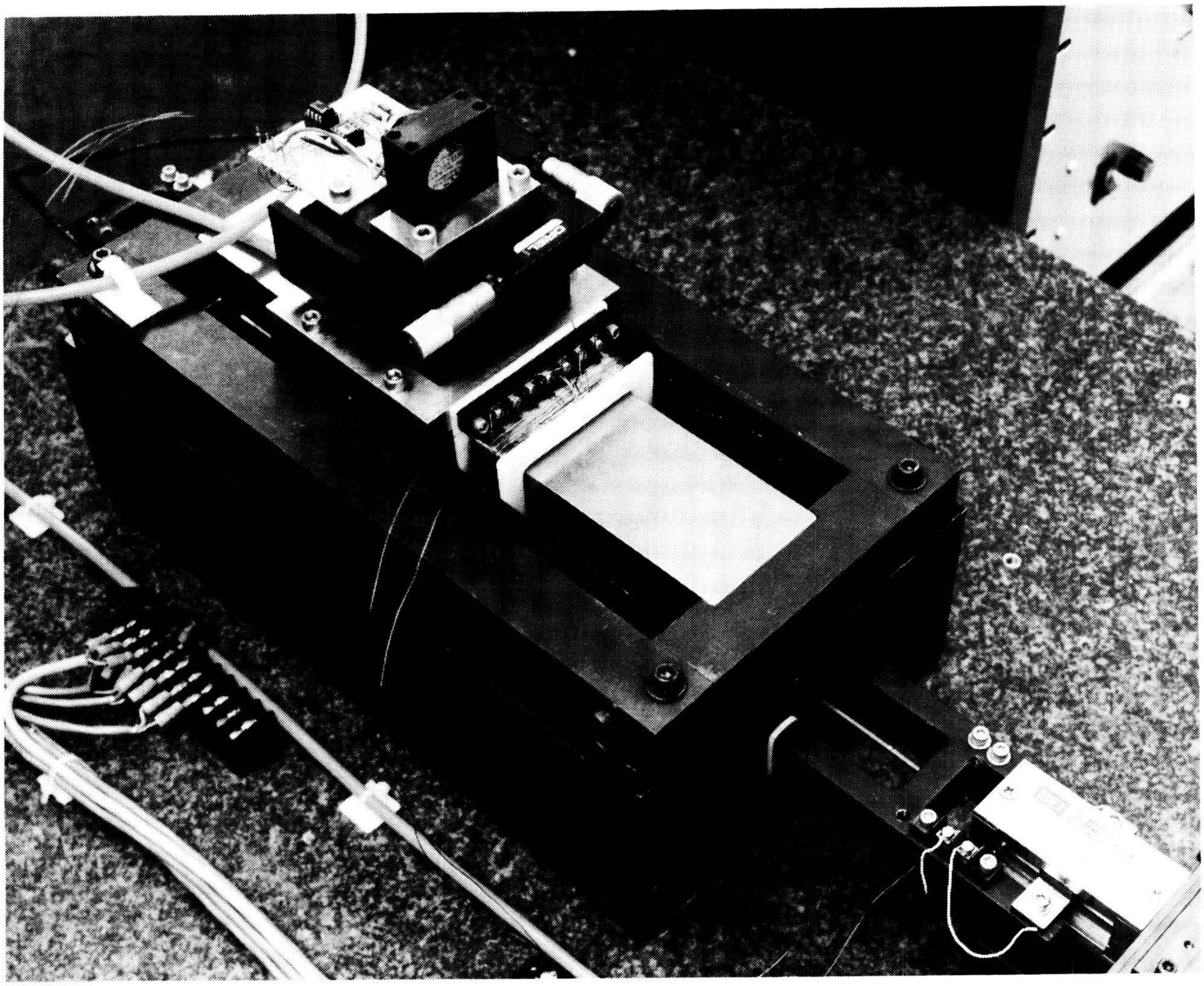
## ONE DOF TESTBED



ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

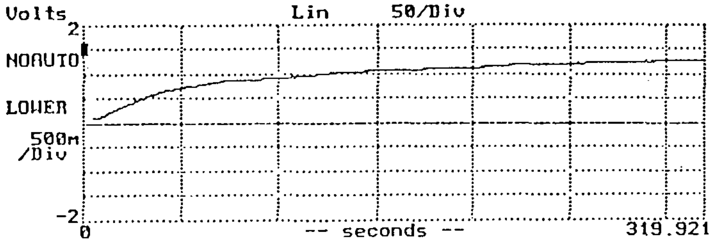
The integrated Lorentz force motor / air slide is shown below. An eight inch long permanent magnet lies on each side of the central air slide. Flux crosses the gap and returns through the airslide and backiron holding the magnets. A coil passes through the gap and encircles the air slide. The Lorentz force on the coil, which is mounted on the air slide, creates the desired Space Station accelerations.

## LORENTZ FORCE INPUT MOTOR AND INSTRUMENTATION

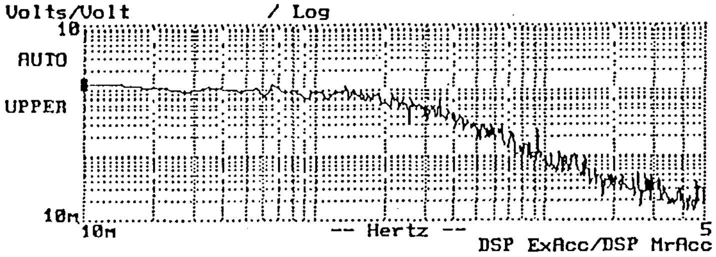


The figures below show experimental data from the one DOF testbed with the desired 0.04 Hz crossover linear controller. The step response shows the desired low friction characteristics that facilitate controller testing using expected on orbit parameters. The frequency response of the system on the lower plot shows crossover to be somewhat higher than the design value of 0.04 Hz. This may be due to unmodeled viscous damping in the air slide.

## STEP RESPONSE OF THE 0.04 Hz BANDWIDTH POSITION CONTROL



## TRANSFER FUNCTION OF 0.04 Hz BANDWIDTH POSITION CONTROL



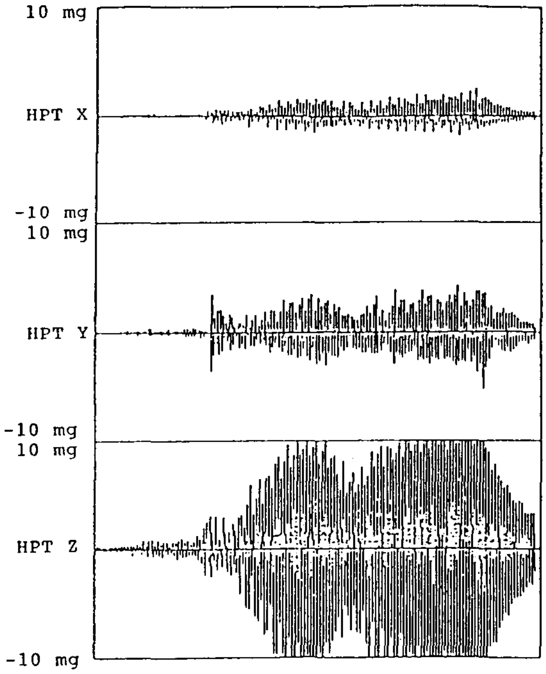
Nonlinear controllers offer many advantages over linear designs. In this application no weight is given to the location of the coil in the gap, as long as the coil does not hit the stops. An ideal controller would not apply forces to the suspended platform carrying the experiment unless the suspension was likely to bottom out. This actuator nonlinearity suggests a nonlinear controller that has a gain that is position dependent. When the suspension is centered, the controller should "turn off" and not apply undesirable forces. The gain should increase when infrequent environmental accelerations are very large so that the experiment must be forced to follow the spacecraft. Such a controller can allow an experiment to free fly at all frequencies, given limits to the position amplitude of the vibrations.

## NONLINEAR CONTROLLER ADVANTAGES

- o ALL ACTUATORS HAVE SATURATION NONLINEARITY
- o A LINEAR CONTROLLER APPLIES EXCESSIVE FORCES
- o A NONLINEAR CONTROLLER CAN FREE FLY AT ALL FREQUENCIES (AT SMALL AMPLITUDES)
- o THE SUSPENSION COULD BE STIFFENED BY GAIN SCHEDULING ANTICIPATING LARGE BASE MOTIONS
- o ADVANCED CONTROLLERS COULD MINIMIZE A COST FUNCTION OF STROKE AND FORCE USING A STOCHASTIC MODEL OF EXPERIMENT SENSITIVITY AND THE ENVIRONMENT

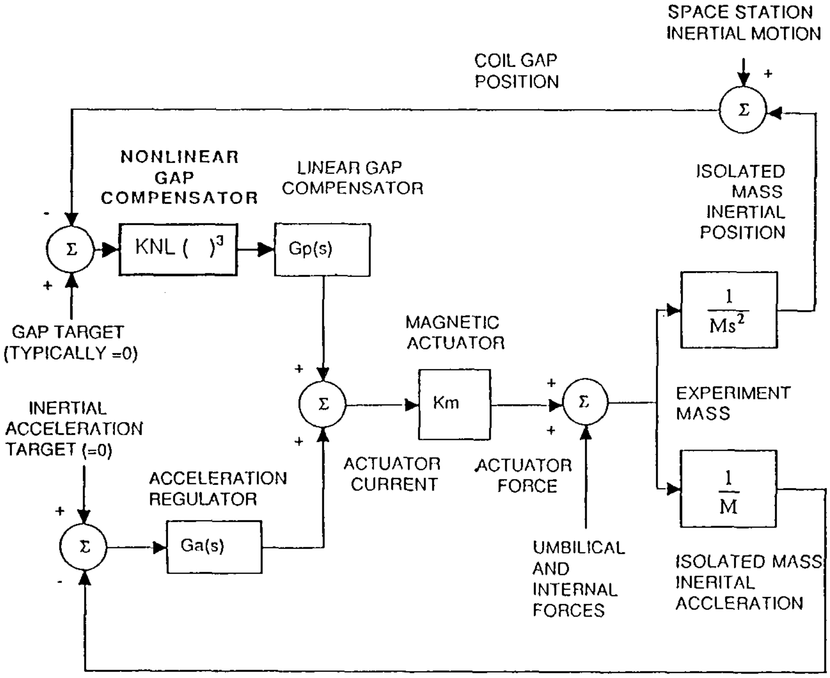
This figure showing D3 mission data illustrates the advantage of a variable gain controller. The vast majority of time has quiescent acceleration levels that are orders of magnitude lower than the peak values. These typical low levels are shown at the left of the plots here. During the great majority of the time that the experiments run, there are no large accelerations requiring isolator action. However, if a linear suspension controller is used, every small but finite motion will produce a proportional and unwanted experiment acceleration. These low level but frequent controller induced accelerations may cause the majority of experiment damage, rather than the much more infrequent large accelerations.

## LARGE VIBRATION DYNAMIC RANGE BUT LOW AVERAGE VALUE



A controller having the desired "dead zone" characteristic without limit cycling behavior is the cubic error controller shown below. The only alteration to a linear position controller is the addition of one operation that cubes the position error before it enters the linear compensator. This cube operation approximates a dead zone but is smoother.

## CONTROL SYSTEM EXAMPLE WITH CUBIC NONLINEARITY



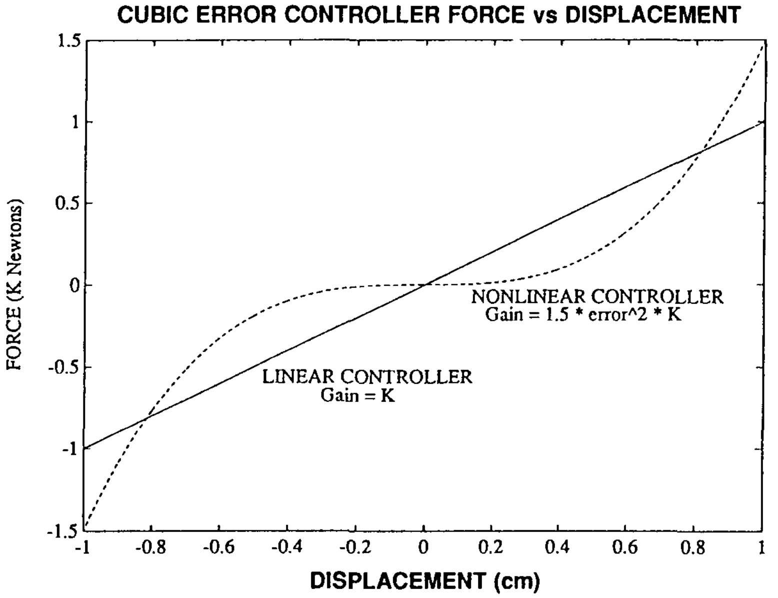
The block diagram on the previous page shows how both position control and acceleration control are used to isolate base vibrations and reject direct forces. The actuator gap position control has a very low bandwidth of 0.04, as developed in the first viewgraphs from environmental accelerations and experiment requirements. The acceleration loop should have a bandwidth of 100 Hz to counterbalance the major directly applied forces. The one degree of freedom testbed has position and acceleration control while the six DOF isolator as constructed has only position feedback, but could be easily modified to add acceleration control. Describing function analysis can be used to model the cubic nonlinearity as 3/4 $(\text{amplitude})^2$. This shows explicitly that the loop gain is reduced dramatically for small excursions. The gain during one DOF cubic controller tests was chosen to provide just slightly more force at maximum stroke than the linear design.

## A CUBIC GAP ERROR NONLINEAR CONTROLLER

- GAP LOOP IS LOW PASS (0.04 HZ) BASE FOLLOWING.
- ACCELERATION LOOP IS BANDPASS REGULATOR (TARGET = 0) REJECTS DIRECT FORCES.
- THE NONLINEAR CONTROLLER REDUCES UNNEEDED FORCES DURING LOW AMPLITUDE MOTIONS.
- THE NONLINEAR GAIN GIVES THE SAME LOOP GAIN AT MAXIMUM DISTURBANCE AMPLITUDE (AND THE SAME BANDWIDTH).
- THE DESCRIBING FUNCTION ALLOWS LINEAR ANALYSIS WHEN THE INPUT FUNDAMENTAL PREDOMINATES.
- THE DESCRIBING FUNCTION OF $(A*SIN(WT))^3$ IS 3/4 $A^2$.
- THE GAP LOOP GAIN BECOMES PROPORTIONAL TO THE $ERROR^2$.
- A STOCHASTIC DESCRIBING FUNCTION FOR $(RANDOM)^3$ IS $3*\sigma^2$. USE FOR GAIN SELECTION FOR STOCHASTIC NONLINEAR CONTROLLER.

The force for small fractions of the maximum displacement is greatly reduced by the nonlinear controller. For the gains shown here, the ability of the two controller designs to absorb large accelerations is nearly identical. The nonlinear controller applies larger forces at large, but infrequent, disturbances than the linear design. In this way, the lack of action at small displacements is compensated for.

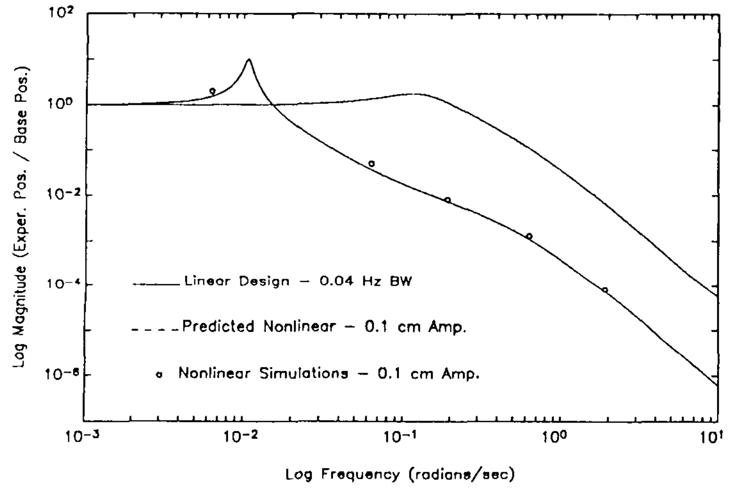
# CUBIC ERROR CONTROLLER FORCE vs DISPLACEMENT



NO FORCE IS APPLIED FOR SMALL DISPLACEMENTS

The continuous plots here show the predicted linear response and the predicted nonlinear response using describing functions. Nonlinear simulation data points are also plotted. It shows that the describing function discussed above approximates very closely the nonlinear response of the system. The plot shows the desirable behavior of reduced base following bandwidth for small position disturbances. Low bandwidth gives better isolation and less experiment damage.

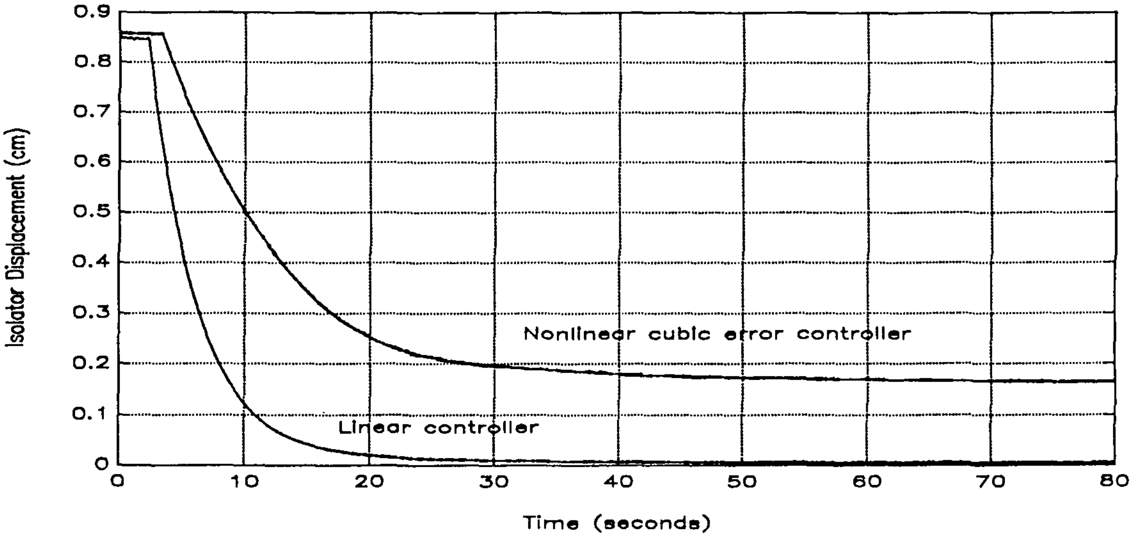
# CONTROL SYSTEM EXAMPLE WITH NONLINEAR SIMULATION DATA



1) COMPARES EXPERIMENT ACCELERATIONS FOR 10% FULL-SCALE BASE MOTION
2) CUBIC NONLINEARITY IS AN ADJUSTABLE GAIN - DOWN BY A FACTOR OF 90
3) ISOLATION FREQUENCY REDUCED BY A FACTOR OF 17
4) NONLINEAR CONTROLLER PRODUCES LOWER EXPERIMENT ACCELERATIONS IF BASE RMS VIBRATION IS MUCH SMALLER THAN PEAK VALUES

This time plot shows how the nonlinear controller essentially "turns off" when the coils are within 15% of the centered position. Because this application has no penalty for small steady state position errors, this behavior is preferable because of the lower forces applied to the experiment by the controller.

**CUBIC ERROR AND LINEAR INITIAL CONDITION RESPONSES**



**MEASURED DATA FROM SINGLE-DEGREE-OF-FREEDOM TESTBED**

The paper shows that microgravity isolation will be required on Space Station, and that current technology can satisfy this need. Lorentz force actuation with nonlinear controls is a good match to the requirements of this application.

## SUMMARY

- MICROGRAVITY ISOLATORS ARE REQUIRED.
- 0.04 HZ ISOLATION AND ±1 CM STROKE ARE REQUIRED.
- BOTH BASE ISOLATION AND DIRECT FORCE REJECTION ARE DESIRABLE.
- LORENTZ FORCE ACTUATORS ARE WELL SUITED FOR THIS APPLICATION.
- A NEW TWO DEGREE OF FREEDOM ACTUATOR WAS DESIGNED.
- A SIX DEGREE OF FREEDOM SUSPENSION WAS DESIGNED, CONSTRUCTED AND TESTED.
- NONLINEAR POSITION CONTROLLERS CAN REDUCE EXPERIMENT ACCELERATIONS.
- A ONE DOF MICROGRAVITY ACCELERATION TESTBED WAS BUILT.
  - INVESTIGATE ACCELERATION DISTURBANCES PRODUCED BY CONNECTIONS TO THE EXPERIMENT:
    - POWER
    - SIGNAL
    - COOLING