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SYSTEM DYNAMIC SIMULATION OF PRECISION SEGMENTED REFLECTOR

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INTRODUCTION

To develop enabling technologies needed for future advanced astrophysics missions, two NASA centers, the Jet Propulsion Laboratory (JPL) and the Langley Research Center (LaRC), are undertaking a joint effort on a Precision Segmented Reflector (PSR) Project. The missions to which PSR is intended to support include the Submillimeter Explorer (SMME) and Submillimeter Infrared Line Survey (SMILS), both planned for the mid-1990's, and the Large Deployable Reflector (LDR) for the early 2000's. All of these mission will employ large (up to 20 meters in diameter) telescopes. The essential requirement for the telescopes is that the reflective surface of the primary mirror must be made extremely precise to allow no more than a few microns of errors and, additionally, this high surface precision must be maintained when the telescope is subjected to on-orbit mechanical and thermal disturbances. Based on the mass, size, and stability considerations, reflector surface formed by segmented, probably actively or passively controlled, composite panels are regarded as most suitable for future space-based astronomical telescope applications.

In addition to the design and fabrication of composite panels with a surface error of less than 3 microns RMS, PSR also develops related reflector structures, materials, control, and sensing technologies. Furthermore, a Technology Demonstration has been proposed to illustrate hardware integration, study interaction of technologies, and evaluate system performance. As part of the planning effort for PSR Technology Demonstration, a system model which couples the reflector, consisting of panels, support truss and actuators, and the optical bench was assembled for dynamic simulations. Random vibration analyses using seismic data obtained from actual measurements at the test site designated for PSR Technology Demonstration are described in this paper.

BACKGROUND

- **The Precision Segment Reflector (PSR) Program was initiated in early 1988 as an element of NASA's Civilian Space Technology Initiative (CSTI).**
- **A joint LaRC/JPL effort.**
- **To develop enabling technologies needed for future astrophysics missions**
  - **Large Deployable Reflector (LDR)**
  - **Submillimeter Explorer (SMME), Submillimeter Infrared Line Survey (SMILS)**
- **Four major elements are included in the PSR technology development**
  - **Lightweight composite panels**
  - **Lightweight support structures**
  - **Panel figure control**
  - **System technology demonstration**

STRUCTURAL CONFIGURATION

The current baseline LDR telescope system, illustrated in the sketch shown in Figure 1, has a 20-meter filled aperture reflector with the reflective surface form by five rings of 84 hexagon-shaped, lightweight, composite panels[1]. The backup structure employed to support these panels is a tetrahedral, space-erectable truss constructed with thin-walled composite struts. In order to conduct astronomical observations in the sub-millimeter/far-infrared wavelength range of 30 to 50 microns, the LDR is required to have a surface precision that allows no more than a few microns (root-mean-square) errors.

As a precursor technology development effort for the LDR-class space optical systems, the Precision Segmented Reflector (PSR) Program was initiated in 1988 as one of the major elements of NASA's Civil Space Technology Initiative (CSTI). The PSR (Figure 2) has a parabolic reflective surface that is formed by 19 hexagonal composite panels and with a focal length of 2.4 meters. The nominal size of each PSR hexagonal composite panel is 0.9 meters, measured from vertex to vertex. When fully assembled, all PSR panels except the central one will be actively controlled by voice-coil actuators. There will be three actuators for each panel to accomplish controlled motions for three degrees of freedom, one piston and two tilts.

In the PSR structures area, the major accomplishment has been the successful development of the PSR Testbed (TB) truss structure [2]. This space-erectable truss structure, consisting of 45 aluminum nodes, 300 aluminum joints and 150 graphite-epoxy composite struts, was designed, analyzed, fabricated, and assembled at LaRC. Photogrammetry survey performed on the as-assembled PSR TB truss structure indicated that the RMS error of positioning accuracy for the 27 upper surface nodes is about 70 microns and is substantially better than the 100 microns goal. Structural tests including static deflection and modal survey were also conducted and correlated with analytical predictions [3].

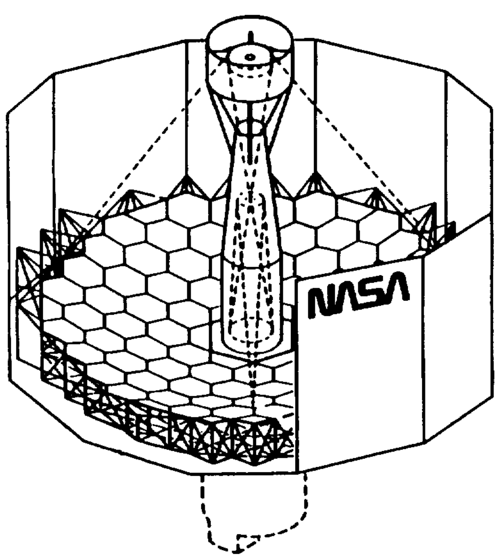


Fig.1 Large Deployable Reflector (LDR)

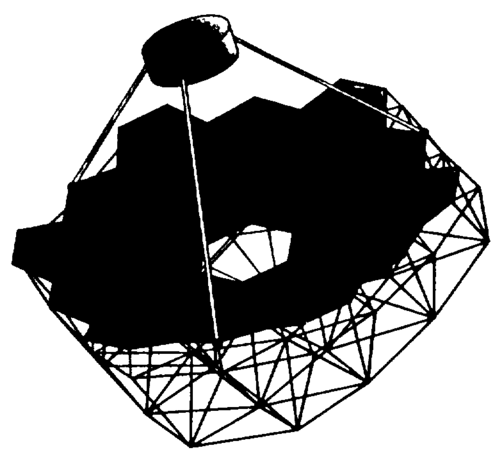


Fig.2 Precision Segmented Reflector (PSR)

ARTICULATED PANEL MODULE (APM)

Another significant accomplishment related to the PSR structural effort is the development of the Articulated Panel Module (APM) design concept for attaching panels to the support truss. The APM is a modular design specifically developed to provide well-defined, "soft-support" interface between the PSR composite panels and the TB truss structure (Figure 3). It also provides physical support to the control actuators and serves as the optical bench for the edge sensors employed for aligning neighboring panels.

Specific PSR/APM design requirements for the 0.9 m panel are described in Reference 4. The allowable panel movements and panel offset are applied to define the geometries of the APM components. The flexure sizes, as well as the dimensions of the lateral constraint struts, are derived from the specifications of the desired natural frequency range. The current APM configuration has been designed so that the natural frequencies of the piston mode and the tilt modes are less than 0.2 Hz and the natural frequencies of the rotational and the lateral modes are somewhat near 50 Hz. In addition, the non-rigid spatial deformation of the front panel facesheet above the interface node is not allowed to exceed 20 nm. over a 6.6 cm. distance with a temperature difference of 2°C. This thermal deformation requirement led us to choose INVAR as the panel interface fitting material.

Various design considerations and solutions had to be addressed in the design of a prototype APM that would accommodate all the functional requirements and the design criteria. The first design consideration was to establish low thermal expansion coefficients in the overall APM components for an expected 200 K space operational environment. This CTE consideration was solved by using low CTE materials through the entire APM. The proposed materials are graphite/epoxy, titanium and INVAR-36. The consideration of design simplicity was met through the proper design configuration. There are only three panel interface points in the current APM design. The lateral constraint struts were placed inside the subframe tubes in order to reduce the packaging complexity. The lightweight consideration was fulfilled by choosing lightweight materials. That is why graphite/epoxy was used for the lateral constraint struts and the subframe tubes, moreover, titanium was proposed for all the fittings and flexures. Fittings are applied in order to facilitate the APM assembly. Flexures are used in the APM for both precise and predictable considerations. A description of the APM development, including details on its structural and functional requirements and design approaches, is presented in Reference 5.

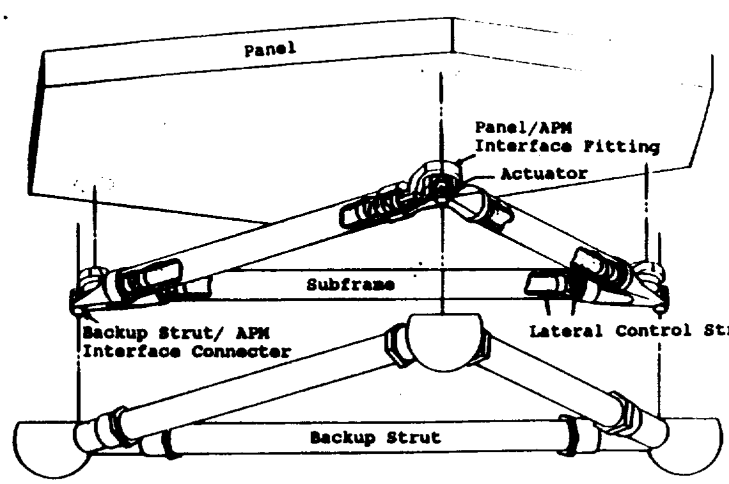


Fig.3 APM,Panel,and Backup Struts

PSR TECHNOLOGY DEMONSTRATION MODEL

The PSR TD is a test and demonstration effort with the following specific objectives: (1) demonstrate the integration of panels, backup structure, APM and figure sensing hardware components developed within the PSR program; (2) validation of individual PSR component technologies in a complete telescope reflector system environment; (3) development of ground test methods for large precision space structures; and (4) generation of experimental data for comparison with results predicted by an optical performance simulation model. Figure 4 is one of the baseline test configuration proposed for the PSR TD. Only one of the nineteen composite panels will be actively controlled in the PSR TD tests. The actively controlled panel can be located on either the first (inner) or the second (outer) ring of the reflective surface, however, the final locations for actively controlled panels have not been selected.

The structural model of the PSR TD system includes the panels, the APM and the backup support truss. However, the optical bench is not included in the PSR TD system model. This is because of that the structural design of the optical bench has not been completed and its stiffness is considered to be relatively rigid compared to the TD structural system. The panels incorporated in the PSR TD program are a hexagonal shape and of a 2-inch thick aluminum core and 0.04-inch thick composite facesheets. The corresponding lowest natural frequency of the panel itself is about 200 Hz[6]. Two PSR TD structural models were assembled in the present study. The first model (System I) is based on the assumption that the actively-controlled panel is attached to the first ring of the backup support struts, as shown in Figure 5.a. The System II model assumes that the actively-controlled panel is attached at the second ring of the backup struts, as shown in Figure 5.b. The boundary conditions of both systems are assumed to be rigidly mounted to the ground at the three inner nodes of the lower surface of the backup truss.

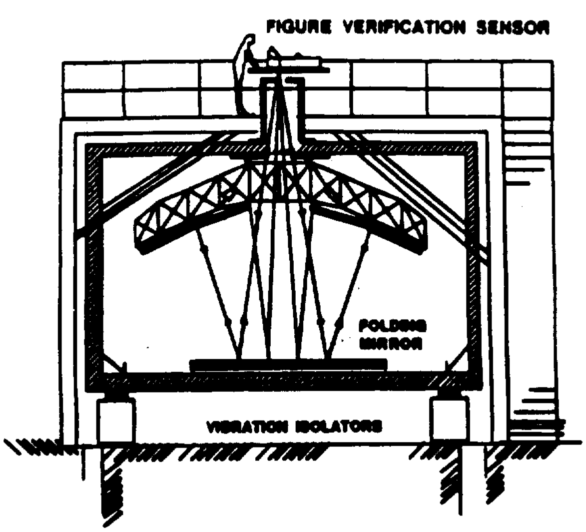
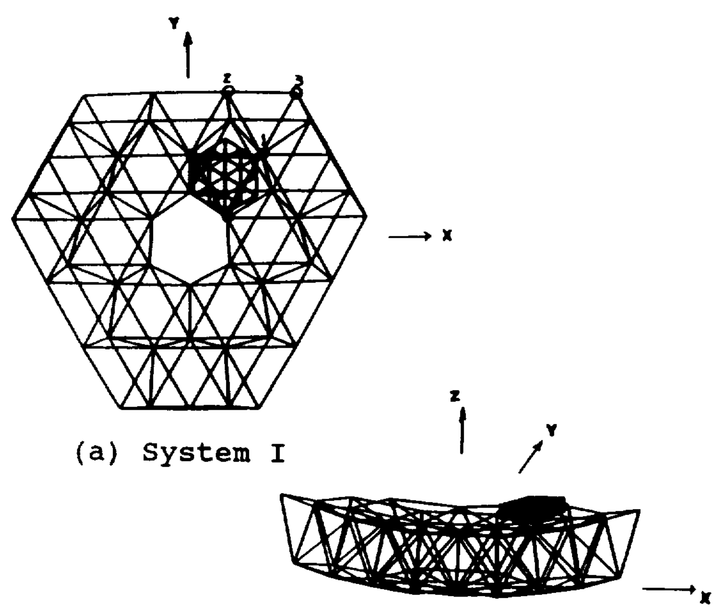


Fig.4 PSR TD Configuration



(a) System I

(b) System II

Fig.5 PSR TD System Models

DYNAMIC CHARACTERISTICS OF PSR TD SYSTEMS

The natural frequencies of these two system models are listed in Table 1, with the corresponding mode shapes briefly described. It should be noted that the natural frequencies of the APM alone are very close to those of the PSR system models. No couplings are observed for the piston mode, tilt modes and rotational mode between the APM and the backup struts. However, slight couplings are noted for the lateral modes. This is may also be due to the effects of an in-plane offset as discussed in Ref. 5.

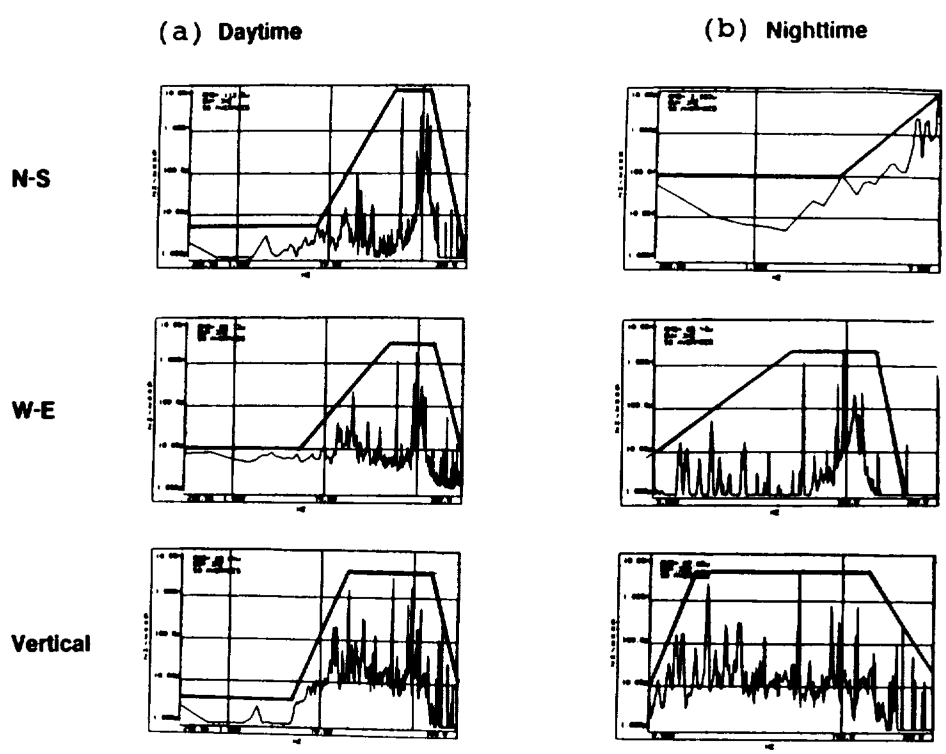
Table 1 Dynamic Characteristics of PSR System Models

MODE NO.	NATURAL FREQUENCY (Hz)		MODE SHAPE
	SYSTEM I	SYSTEM II	
1-6	0.000	0.000	Rigid Body Modes
7	0.087	0.087	Panel Piston Mode
8	0.105	0.105	Panel Tilt Mode
9	0.106	0.106	Panel Tilt Mode
10	25.15	25.32	Bending Mode of Backup Struts
11	25.29	25.75	Bending Mode of Backup Struts
12	29.43	29.43	Panel Core Mode
13	43.53	44.31	Translation Mode in X-direction
14	53.05	47.32	Translation Mode in Y-direction
15	54.12	53.06	
16	55.62	55.47	Panel Rotational Mode
17	57.46	57.55	
18	67.44	67.09	
19	68.35	68.90	
20	95.79	96.84	

CHARACTERIZATION OF THE TEST ENVIRONMENT

The PSR TB structural tests are to be performed in the Magnet Room of High Bay 1 located in the Spacecraft Assembly Facility (SAF) at JPL. A survey was conducted to characterize acoustic and seismic environments of this proposed test site [7]. In this survey, acoustic and seismic data were accumulated over a time period of one week. For ground motion measurements, three Wilcox Research Model 731 accelerometers, one unit along each of the north-south, east-west, and vertical axes, were used. The 1dB frequency responses of these seismic accelerometers were measured from 0.1 to 300 Hz. Three set of data, for day time, night time, and day time with equipment off, were collected by these accelerometers. The collected data was presented in three forms: (1) G^2/Hz vs. Hz; (2) G vs. Hz; and (3) peak displacement vs. Hz. A 1024 point Fast Fourier Transform was taken with a 1024-channel analyzer to convert the raw data into frequency domain from the time domain. The resulted acceleration power spectrum densities of the measured seismic disturbances are applied in the random response analyses of the PSR Technology Demonstration system model. Two extreme cases are examined in this work: (1) daytime disturbances (Fig. 6.a), and (2) nighttime disturbances (Fig. 6.b). The coordinate system shown in Figure 6 is defined as follows: X-Axis is for the recorded north-south data, Y-Axis is for the east-west direction and Z-Axis is for the vertical direction. For conservative purposes, the envelopes shown in these disturbances are applied in the random analyses. It is noted that the magnitudes of the daytime disturbances in the low frequency range are much higher than those of the nighttime disturbances. However, the magnitudes of the daytime disturbance in the high frequency range are very close to those of the nighttime disturbances.

Fig.6 **SAF DISTURBANCES**



ANALYTICAL APPROACH

Random analysis approach used in this work is based on a data reduction procedure that is applied to the results of a frequency response analysis. The frequency response function H(f) is obtained by applying a variable frequency sinusoidal acceleration, A_o, to the PSR system models and calculating the acceleration response at the specified points. Dividing the calculated acceleration by the input A_o, H(f) can be expressed as function of the excitation frequency, f. Then the root-mean-square (RMS) responses (â) at the specified points can be calculated numerically from the equation

$$\bar{a} = \left[\sum_i S(f_i) \, |H(f_i)|^2 \, \Delta f_i \right]^{1/2}$$

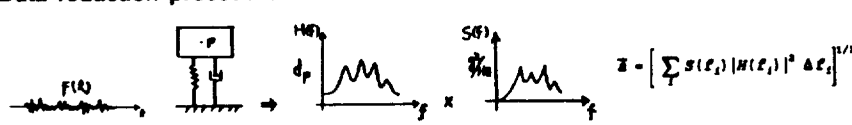
where $S(f_i)$ is the acceleration power spectral density function at the discrete frequency f_i.

The random response analyses are implemented by using the NASTRAN modal frequency response solution scheme (Sol. 30) coupled with the results from the normal mode analyses (Sol. 3). The peak random responses of the PSR system are calculated by using the RMS values of frequency responses induces by random disturbances over a frequency range form 0.01 Hz to 200 Hz. An uncorrelated approach is applied in this work in order to be able to examine the peak responses of the PSR system due to each individual external disturbance in a different excitation axis. The final peak responses of the system subjected to the disturbances of all three axes are then calculated by using the root sum square (RSS) of the RMS peak responses in three axes. Two sets of relative displacements are calculated in the analyses. The first one is the relative displacement between the grid point of the front panel facesheet, located above the truss node, and the backup truss node. The second set is the relative displacement between the backup truss node and the ground support points. An 0.5% modal damping was applied to the frequency response analyses.

RANDOM RESPONSE ANALYSES

- **Modal frequency response associated with results from normal mode analyses**

- **Data reduction procedure**



- **Implemented by using MSC/NASTRAN**

- **Uncorrelated approach**

- **Frequency range: 0.01Hz to 200 Hz**
  Modal damping: 0.5%

- **Probability of exceeding the specific displacement**

RESULTS AND DISCUSSION

The results of the 1-σ peak displacements are summarized is Table 2 for both the PSR System I and System II models subjected to these seismic disturbances. It is noted that the movements of the panel occurred in nighttime are much smaller than those occurred in daytime. However, the difference in the nighttime and the daytime movements of the nodes is not as large as that in the panel. This is because the movements of the panel are predominant in the lower frequency (about 0.1 Hz) range (Figure 7) and the movements of the nodes are predominant at a higher frequency (about 25 Hz) governed by the truss modes (Figure 8). It is also noted that the lateral movements of the panel are larger in the PSR System II than those in the PSR System I. However, the vertical movements of the panel are almost identical in both PSR systems. This is because the vertical movements of the panel are dominated by the piston modes and the natural frequencies of the piston mode in both PSR systems are identical. Another observation is that the lateral movements of the panel are more location-dependent than the vertical movements of the panel. However, the opposite results are observed in the movement of the strut nodes.

For the proposed PSR Technology Demonstration configuration (System I), the lateral peak movements (1-σ) are about 2.9 μm for the daytime disturbance case and 0.36 μm for the nighttime case. The vertical peak movements are 13μm and 2μm for the daytime case and the nighttime case, respectively. The 1-σ peak responses of the PSR System II are 4.5 μm for the lateral movement and 13 μm for the vertical movement in the daytime case. These peak responses are well below the expected figure control range of $\pm$1mm and the 100 μm gaps between the panels. This implies that the isolation table is not a necessity in the TD optical bench design.

The peak responses of a hard mount case had also been studied by increasing the flexure size of the lateral constraint struts such that the natural frequency of the piston mode is 1.6 Hz and the natural frequency of the tilt modes is 2.0 Hz. Results of analyses based on the nighttime SAF environmental data indicate that the 1-σ lateral movement of the panel is 0.14 μm and the 1-σ vertical movement of the panel is 0.08 μm. The comparison indicates that the peak vertical movement can be reduced dramatically (from 2.0 μm to 0.08 μm) by using the hard mount APM design.

Table 2 1-σ RMS **Displacement Responses (μ m) of the PSR systems**

Location	Component	Daytime Disturbances		Nighttime Disturbances	
		System 1	System 2	System 1	System 2
Relative Displacements Between Front Panel Facesheet and Strut Nodes					
Corner 1	x	1.34	2.18	0.202	0.377
	y	1.72	3.14	0.293	0.479
	z	12.89	12.85	1.851	1.794
Corner 2	x	1.12	1.89	0.172	0.284
	y	2.58	4.05	0.336	0.573
	z	12.53	12.46	1.911	1.846
Corner 3	x	1.50	2.29	0.221	0.336
	y	2.54	3.92	0.331	0.551
	z	11.96	11.83	1.819	1.751
Relative Displacements Between Strut Nodes and Ground					
Node 1	x	0.026	0.031	0.019	0.022
	y	0.018	0.019	0.013	0.015
	z	0.012	0.038	0.010	0.032
Node 2	x	0.029	0.034	0.020	0.024
	y	0.018	0.019	0.013	0.015
	z	0.022	0.044	0.020	0.039
Node 3	x	0.032	0.037	0.023	0.027
	y	0.023	0.027	0.017	0.022
	z	0.053	0.065	0.046	0.055

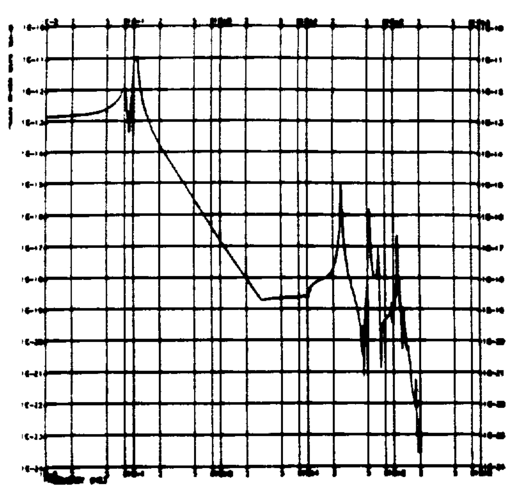


Fig.7 Response of Panel Facesheet

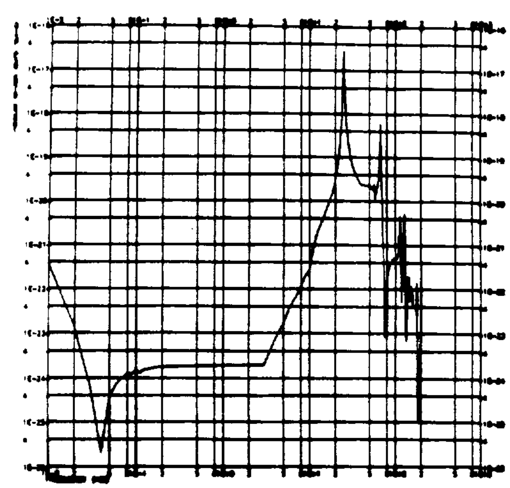


Fig.8 Response of Strut Node

CONCLUSION

Technologies, including those related to large space structures, developed by the PSR program play a vital role in enabling future astronomical missions that require large precise telescopes. To verify these enabling technologies, ground tests must be performed and the planning of the tests mandates a need for a thorough assessment of the test environment and responses of the test structure to the environment. This need has been partially satisfied by random vibration analyses of the PSR structure using seismic inputs derived from measurements of ground motions of the test site. Results of the analyses indicated that the maximum daytime movements of the precise panel supported by the PSR structural system, including the APM, will be less than 13 microns in the vertical direction and 3 microns in the lateral directions. These movements are well within the acceptable limits and the need for elaborate vibration isolation devices does not exist. The next step in planning the PSR TD tests is to design an optical-bench structure which will not amplify or adversely alter the seismic disturbances imposed on the test structure. The PSR TD optical bench will be extremely stiff such that frequencies of its vibratory modes are well above the frequency range occupied by PSR structural system. A fundamental frequency above 50 Hz is considered to be desirable for the PSR TD optical bench. Design of such an optical bench is currently in progress.

SUMMARY

- **PSR Technology Demonstration system model has been established**
  - **Panel**
  - **Articulated Panel Module (APM)**
  - **Backup truss**
- **Seismic disturbances of the PSR TD test site were measured. The resulted acceleration power spectrum densities of these disturbances were applied in the random response analyses of the PSR TD system model.**
- **Analytical results indicated that the movements of the precise panels supported by the PSR structural system were within the acceptable limits.**
- **Elaborate vibration isolation devices are not necessary.**
- **Future Work**
  - **Optical bench**
  - **Suspension system**

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