Evaluation of Damping Concepts for Precision Mounting Platforms[1]

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ABSTRACT

Conceptual analysis of a damped precision mounting platform with improved thermal and dynamic stability is presented. The use of metal matrix composite materials combined with viscoelastic damping materials results in uniquely stable, lightweight structures. Achievable goals for improved performance of an existing spacecraft precision mounting platform are established. Eight concepts are evaluated and ranked on damping, strength, thermal distortion, instrument mounting, and cost of fabrication. Three designs are selected for detailed quantitative analysis. Results for all three designs indicate performance goals can be met or exceeded. Thermal distortions and dynamic jitter response are both reduced by a factor of 5.

INTRODUCTION

Improved thermal and dynamic stability of spacecraft precision structures is an evolving requirement generated by the need for increased accuracy and size in the presence of more severe orbital disturbances. Remote sensing spacecraft are projected to require larger and more stable precision mounting platforms (PMPs) to support the next generation of sensors, while larger dynamic excitations caused by high instrument scanning masses and larger spacecraft guidance actuators make the platforms more susceptible to jitter. The combination of metal matrix composite (MMC) materials and passive damping using viscoelastic materials (VEM) provide uniquely stable lightweight structures suitable to the needs of future spacecraft. MMC materials are utilized to provide high stiffness, high thermal conductivity, low thermal expansion, and high specific strength. VEMs are engineered to provide high damping at desired modulus, frequency, and temperature ranges and can be used to obtain high composite loss factors on precision platforms.

A USAF Wright Research Development Center program, Damping and Metal Matrix for Precision Structures (DAMMPS), is being performed by GE Astro Space Division to develop and demonstrate a stable spacecraft PMP utilizing damping and metal matrix materials. The approach is to design, fabricate and test a Demonstration Structural

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Article (DSA) using the design requirements of an existing platform to assure interdisciplinary design constraints are represented. The selected platform is from an existing GE-ASD spacecraft shown in Figure 1. The program utilizes the design requirements of this platform to set goals for the DSA representative of those required for the next generation of improved sensors.

The alignment critical sensors of the satellite are mounted on the PMP, located at the forward end of the spacecraft. The current design is a dip brazed aluminum egg crate structure which is kinematically mounted to the main body of the spacecraft through three struts with ball fittings at either end and a shear attachment with a ball fitting at one end. The kinematic mounting arrangement minimizes distortions due to thermal growth or distortion of the main body of the spacecraft.

The DSA design requirements and goals have been set to provide major improvements in performance including an enlarged sensor-mounting area. The DSA platform is shown in Figure 2 and the performance requirements and goals are compared in Table 1. The enlarged platform extends both axially and laterally while configured to stay within limits imposed by launch stowage of the solar array. Package locations are based on field-of-view studies. The DSA requirements are similar to the current design except for the minimum resonant frequency which has been lowered, based on control system considerations. The goals were selected based on previous experience with damped panel designs(1) and are felt to be achievable. Major performance improvements will be accomplished if these goals are met.

DESIGN CONCEPTS

The first step in the design process is the identification of concepts which should satisfy the design requirements, and goals. At this point the design goals can be regarded in general terms which fall into five categories, namely damping, stiffness and strength, thermal control and thermal distortion, support and component mounting interfaces, and ease of fabrication and cost.

Concepts which were intended to rank well in all five categories were considered as design candidates, and those in which damping is an integral part of the design were of primary interest since this is expected to provide the best damping at minimum weight. The eight concepts presented here are shown in Figure 4, and each concept is given a brief description below.

The VEM is sandwiched between two honeycomb panels in the dual honeycomb design. Each honeycomb panel consists of an aluminum core and MMC facesheets. Instruments can be mounted to inserts potted in the honeycomb panels.

The external stiffener concept has been used successfully in the past(1) to provide stiffness and damping in equipment panels on a defense communications satellite. The base panel is constructed of aluminum honeycomb core with MMC facesheets. Strips of VEM and aluminum honeycomb core with MMC facesheets are bonded to the base panel to provide damping and added stiffness. The interior stiffener concept is a similar design with the stiffeners mounted inside the base platform. The advantage over the external stiffener design is the improved instrument mounting area.

The dual eggcrate concept evolved from the present, undamped platform design. The eggcrate core is dip brazed, then facesheets with lightening holes are dip brazed to the core. Two panels would be fabricated with eggcrate cores and MMC facesheets. These would then be bonded to the VEM layer to form the platform.

An isogrid concept is currently being used for mounting instruments on another of GE ASD's earth sensing satellites. The isogrids would be machined from MMC castings. Two isogrids would be machined and bonded to the VEM layer in the center of the platform. Instruments mount into holes at the web intersections.

The adhesive used to bond the MMC facesheets to the aluminum honeycomb core for the lower panel provides the required damping in this concept. The upper panel would be mounted to the spacecraft structure. The upper and lower panels share a common inner facesheet.

The dual honeycomb/intercostal platform is constructed of two honeycomb panels (aluminum core with MMC facesheets) connected by intercostal beams with an intermediate VEM layer. The modified intercostal concept is an offspring of the original intercostal concept. This concept cuts the number of parts by almost half. The VEM is bonded to the top and bottom flanges of the intercostals, and the honeycomb is in turn bonded to the VEM.

CONCEPT SELECTION

The five concept ranking categories in descending order of importance are ease of fabrication and cost, damping, thermal distortion, strength and stiffness, and instrument mounting. Each category is assigned a weight factor from 1 to 5 based upon relative importance. The design concepts are assigned a rank from 1 to 5 in each category. The rank in each category is multiplied by the weight factor and summed to a total. The three designs with the highest total score are selected for quantitative trade studies.

The concept ranking matrix is shown in Table 2. The highest ranked concept is the dual honeycomb concept, which received high rankings in all categories. The external stiffener concept is ranked second. It received high rankings in all categories but mounting, and the mounting category was assigned the least overall importance. The third highest ranked concept is the modified dual honeycomb/intercostal concept, which ranked higher than the original intercostal concept because of lower fabrication cost. The adhesive damped concept received the lowest ranking because of development cost, damping and strength considerations.

PLATFORM SIZING ANALYSIS

The three concepts emerging from the concept evaluation studies are the dual honeycomb, external stiffener, and modified dual honeycomb/intercostal (henceforth referred to simply as "intercostal") designs. Initial component sizes were determined based upon the 15.5 Hz minimum frequency requirement and damping goal of greater than 10 percent in all modes below 100 Hz subject to minimizing platform weight. The thicknesses of the MMC facesheets and VEM layers were limited due to manufacturing constraints. The MMC is available in thicknesses from 0.015 to 0.15 inches. The VEM can be formulated in thicknesses from 0.05 inch to 1.0 inch. The honeycomb thickness may range between 0.25 inch and 3.5 inches.

MSC/NASTRAN Finite element models (FEMs) were constructed to evaluate the stiffness and damping characteristics of the designs. The three concept FEMs are shown in Figure 3. The FEMs are composed of solid elements (HEXA) representing the VEM layers and plate elements (QUAD4) modeling the honeycomb layers. The intercostal FEM has additional plate elements representing the geometry of the intercostals themselves. An additional model of the original eggcrate structure with the same platform area, but with no damping material was constructed for comparison with the other designs.

A normal modes analysis was performed on each FEM to determine frequency and damping values for all modes less than 100 Hz. Damping was calculated using the modal strain energy method(2), thus

$$\eta_i = \varepsilon_v \times \eta \tag{1}$$

were η_i is the composite loss factor, ε_v is percentage of strain energy within the VEM, and η_v is the material loss factor for the VEM. A material loss factor of 1.0 was assumed for sizing since the specific VEM was unspecified at this point and the modulus of the VEM was one of the variables subject to optimization.

The element sizing analysis is similar for all three designs and only the dual honeycomb sizing will be discussed here. The design parameters which were varied are the thicknesses of the outer facesheets, honeycomb core, and VEM, and the shear modulus of the VEM. The inner facesheet thickness was fixed at 0.015 inch because it is primarily a bonding layer, and contributes little to platform stiffness because it is close to the platform neutral axis.

An initial sensitivity study was performed to determine which parameters were effective in increasing frequency and damping. Each design variable was modified one at a time and the frequency and damping effects on each mode below 100 Hz were plotted against the change in platform weight. Results presented here are for the fundamental mode only. Different and even opposite trends occurred for the higher modes.

Results for the dual honeycomb concept, shown in Figure 5, indicate increasing honeycomb core thickness and facesheet thickness raise the fundamental frequency while also raising platform weight. Decreasing the VEM thickness increases the fundamental frequency and lowers the platform weight, both of which are desirable results. Unfortunately, decreasing the VEM thickness also decreases damping in the fundamental mode. Damping is increased by reducing core thickness or increasing facesheet thickness. Damping is also affected by the VEM shear modulus. Decreasing the shear modulus increases damping but reduces frequency.

The sensitivities provided insight for the 19 design iterations that were required to meet the frequency requirement and damping goal. A total of 29 and 31 sizing iterations were performed for the external stiffener and intercostal designs respectively. Progress toward the final design can be charted by defining a penalty function as follows:

$$
PF = \begin{cases}
W_p \times [1 + 0.2 \times \Sigma (10. - \eta_i) + (15.5 - f_1)]; & \eta_i < 10.\ ; f_1 < 15.5 \\
W_p \times [1 + (15.5 - f_1)]; & \eta_i > 10.\ ; f_1 < 15.5 \\
W_p \times [1 + 0.2 \times \Sigma (10. - \eta_i)]; & \eta_i < 10.\ ; f_1 > 15.5 \\
W_p & \eta_i > 10.\ ; f_1 > 15.5
\end{cases} \qquad (2)
$$

where W_P is the platform weight, and f_1 is the fundamental frequency. This function is shown for all three designs in Figure 6. While the penalty function is somewhat arbitrary, it does reflect the relative ease in achieving the design objectives, and it reduces to only the platform weight when the design goals are satisfied. The plot illustrates that the dual honeycomb design converged to a lighter configuration in fewer iterations. The dual honeycomb penalty function shows a large spike at iteration 7. This was one in a series of runs with increased modulus and stresses the importance of a low modulus VEM. As the VEM modulus was raised, the damping fell off rapidly.

The modal characteristics and weights of all three designs in the final configuration are given in Table 3. The dual honeycomb platform is 4.0 inches thick with 0.045 inch outer facesheets and 0.050 inch thick VEM. The external stiffener has a 1.0 inch thick base panel. The exterior stiffener has a 0.050 inch outer facesheet, 5.5 inches of high density honeycomb core, and a 0.125 inch VEM layer. The intercostal design has 0.030 inch outer facesheets, 2.5 inch honeycomb core, 0.125 inch VEM layers, and 1.75 inch intercostals. Only the dual honeycomb met the 10 percent damping goal for all modes. The external stiffener had one mode and the intercostal had two modes with damping values slightly less than 10 percent. Additional iterations would have increased damping in the three modes. However, the damping values were deemed sufficiently close to the goal as not to warrant further iterations during the trade study phase of the program. The design selected for detailed design, fabrication, and test will be thoroughly optimized, and meet all damping goals.

VEM AND MMC MATERIAL SELECTION

The platform sizing analysis provided insight as to the range of VEM shear modulus which results in optimum damping. Optimum damping in all three concepts was provided by a VEM shear modulus between 50 Psi and 1200 Psi. Some latitude in the damping material modulus can be gained by examining the shear stiffness, GA/t, where G is the storage modulus of the VEM, t is material thickness, and A is the area in shear. Therefore, for a given damping material, lower stiffness can be achieved by increasing the material thickness or reducing the area in shear. However, increasing the VEM thickness increases weight and reduces through thickness thermal conductivity. Reducing the area of VEM in shear increases the stress in the material and also reduces the through thickness thermal conductivity. Then, the most desirable manner of decreasing the shear stiffness is the selection of a low modulus VEM.

Table 4 shows the shear modulus and other VEM requirements. A high material loss factor is critical to achieving the damping goal of greater the 10 percent in each mode less than 100 Hz. Outgassing criteria must be adhered to for every space qualified material. Many damping materials have high material loss factors, but also have high outgassing properties. This is undesirable in space because material lost from the VEM not only degrades platform performance, but may condense on the sensors or solar array panels causing serious degradation in satellite performance.

The material tentatively selected is one of the GE-ASD SMRD formulations, designated B37T2B. The SMRD damping material has a proven track record in space applications and the material properties can be tailored to meet stiffness requirements. This material was subjected to detailed testing as part of the DAMMPS program. The VEM properties were measured with CSA Engineering's DCS tester. The machine uses the direct complex stiffness (DCS) technique, in which a shearing force is applied across the specimen and the resulting displacement is measured and used to compute the complex modulus. The test results are shown in Figure 7. Also shown are modified Oberst beam results for comparison. The test results are in good agreement considering the accuracy of the beam test method. The material satisfies the VEM requirements for all three designs.

The metal matrix selection issues are modulus, strength, hysteresis, thermal conductivity, coefficient of thermal expansion, cost. Materials with high stiffness-to-weight and strength-to-weight ratios are desirable for light weight designs. Hysteresis should be low to minimize alignment error. The material of choice should have high thermal conductivity and low coefficient of thermal expansion to minimize thermal distortions. Low cost materials are always sought to reduce overall program costs.

The properties of the three leading candidate materials are compared with those of aluminum in Table 5. P120/Al has the highest modulus and thermal conductivity and the lowest coefficient of thermal expansion. The modulus is three times higher than aluminum with comparable density. The thermal conductivity of P120/Al is higher than that of aluminum with a coefficient of thermal expansion which is 8 times lower. The cost of P120/Al is somewhat higher than SiCp/Al and B/Al because it is relatively new. The P120/Al material has been tentatively selected because of the outstanding properties and in spite of the increased cost.

JITTER ANALYSIS

This analysis is helpful in relating the modal characteristics of the designs to physical quantities so they may be compared on a more direct basis. The rotational response of an instrument mounted on the platform to a disturbance input is the jitter which an instrument will experience during operation on orbit. Uncontrolled jitter adversely affects instrument performance. Damping can be used to control jitter by limiting the magnitude of the instrument response and by decreasing the settling time. The settling time of the instrument response is the time taken to reach an acceptable level of jitter at which instrument performance will not be adversely affected.

The dynamic torque imposed by the primary sensor, the SSS, is the major disturbance. The sensor imposes torque pulses on the platform when the moving element reverses direction as shown in Figure 8. The Fourier analysis of the pulse train depicted in the figure shows rich harmonic content through 100 Hz. Other disturbances which must also be considered are the solar array torque, reaction wheel unbalance, and the torques resulting from the rotating dish of the SSM/I instrument.

The jitter evaluation was performed using the same FEMs developed for the modal and stress analyses. An MSC NASTRAN modal transient response analysis formed the basis for the evaluation. The worst case jitter results (including all disturbances simultaneously) are shown in Figure 9. The eggcrate model without the benefit of viscoelastic damping has the highest jitter response. The responses of the three damped designs are relatively small in comparison. The intercostal design has the smallest response, and this is probably due to the excellent damping in the first three vibrational modes.

To further investigate the effect of damping on platform stability, the response to a generic slew maneuver was determined. Figure 10 displays the superior settling time of the damped designs. It is a comparison of the slew maneuver response of the undamped eggcrate model to that of the dual honeycomb design. The results are a classic illustration of the effect of damping on settling time. The damped designs stabilized 20 times faster than the eggcrate.

THERMAL DISTORTION ANALYSIS

The thermal distortion analysis provides a basis of comparison for the thermal performance for each of the designs. In order to make a relative assessment of the designs, it will be assumed that the same thermal control system is applied to each design. With the same heater inputs, each design will have a different thermal gradient normal to the plane of the panel. Therefore, designs with lower thermal resistance will have lower thermal gradients and lower thermal distortions. The equivalent thermal gradient across the platform can be calculated from

$$\Delta T = (\Sigma\ 1/k_i)\ /\ (\Sigma\ 1/k_j)\ \Delta T' \tag{3}$$

where

ΔT = equivalent thermal gradient

$\Delta T'$ = reference thermal gradient

k_i = normal conductivity of the ith platform element

k_j = normal conductivity of the jth reference platform element

Then selecting the 3.96 inch thick dual honeycomb concept as the reference with the design thermal gradient of 3 C, the equivalent gradient across the 1.05 inch thick external stiffener platform is 0.76 C. Similarly, a 8 C thermal gradient is applied across the 6.88 inch thick intercostal.

The relative distortion of each design is shown in Figure 11. As indicated by the equivalent thermal gradients, the intercostal distortions are significantly higher, followed by the dual honeycomb and external stiffener thermal distortions.

SUMMARY AND CONCLUDING REMARKS

The concept analysis results at this point in the program are compared with the goals in Table 5. The weight reduction goal was exceeded in all three designs. The damping goal was satisfied in the dual honeycomb design, but damping in the other two designs fell slightly short of the goal. This does not appear to have affected the dynamic response of the platforms since all three designs far exceed the jitter reduction goal. The dual honeycomb and external stiffener designs exceeded the thermal distortion reduction goal, but the thermal distortion reduction of the intercostal design fell short of the goal. All three designs are viable candidates for the final design.

Preliminary conceptual design results have been presented for the on-going DAMMPS program. In the subsequent program phases, a detailed design will be developed for one of the three selected concepts. The design will be fabricated, and finally, ground tests will be performed to verify performance predictions. This work has established the feasibility of combining MMC and VEM materials to dramatically improve the dynamic stability of satellite sensor platforms.

ACKNOWLEDGMENT

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Table 1 DSA Requirements and Goals

DESIGN REQUIREMENTS

CONDITION/REQUIREMENT	PRESENT PLATFORM	DSA
INSTRUMENT MOUNTING		
• SURFACE AREA	$7.7\ FT^2$	$10.9\ FT^2$
• INSTRUMENT TOTAL WEIGHT	150 LBS	300 LBS
PRELAUNCH/LAUNCH CONDITIONS		
• LIFT-OFF TRANSIENT-AXIAL/LATERAL	1.5 ± 1.8G/± 2.2G	SAME
• STAGING TRANSIENT - AXIAL LATERAL	9.9 ± 5G/± 2.8G	SAME
• QUAL PLATFORM VIBRATION - ANY SINGLE AXIS	± 15G	SAME
• ACOUSTIC NOISE	144 dB	SAME
• PLATFORM MOUNTED COMPONENT VIBRATION	$0.13G^2/Hz$	SAME
• TEMPERATURE EXTREMES	-5° TO 35°C	SAME
• MINIMUM RESONANT FREQUENCY	27 Hz	16 Hz
ORBITAL CONDITIONS		
• THERMAL GRADIENT - FACE/FACE	3°C	SAME
• OPERATING TEMPERATURE	5 ± 1 1/2°C	15 ± 1 1/2°C
ORBITAL POINTING ERRORS		
• ALIGNMENT	10 ARC SEC	SAME
• JITTER	30 ARC SEC IN ONE SEC	SAME
• THERMAL DISTORTION AT COMPONENT	4 ARC SEC	SAME
• PLATFORM STRUCTURAL WEIGHT	45 LBS	90 LBS

DESIGN GOALS

- REDUCE PLATFORM STUCTURAL WEIGHT BY 20 PERCENT
- PROVIDE DAMPING (2C/Cc) OF 10 PERCENT IN ALL MODES < 100 HZ
- REDUCE JITTER BY A FACTOR OF 2
- REDUCE PROBABILITY OF EXCEEDING REQUIRED JITTER BY 50 PERCENT
- REDUCE PLATFORM MOUNTED COMPONENT QUAL VIBRATION REQUIREMENT BY 6 dB
- REDUCE THERMAL DISTORTION BY A FACTOR OF 5

Table 2 DSA Concept Ranking Matrix

Performance Category	Damping	Strength/ Stiffness	Thermal Distortion	Sensor Mounting	Fabrication and Cost	Weighted Total *
Weight Factor	4	2	3	1	5	
Concept						
Dual Honeycomb	5	4	4	5	5	70
Ext. Stiffener	4	5	5	2	5	68
Int. Stiffener	2	5	4	5	4	55
Dual Eggcrate	5	4	5	4	2	57
Dual Isogrid	5	4	5	3	2	56
Adhesive Damp.	3	2	4	5	2	43
Intercostal 1	4	5	3	5	3	55
Intercostal 2	4	5	3	5	4	60

* Scale of 1 to 5 with indicated weighting factors

Table 3 Frequency, Damping, and Weight comparison

Mode	Dual Honeycomb		External Stiffener		Intercostal	
	Freq. (Hz)	Damping (prcnt)	Freq. (Hz)	Damping (prcnt)	Freq. (Hz)	Damping (prcnt)
1	16.8	10.4	15.7	10.9	15.8	22.0
2	25.2	13.7	23.2	11.9	18.8	17.1
3	40.0	15.6	47.0	17.7	27.2	22.2
4	48.3	10.7	50.0	10.5	43.2	11.5
5	56.0	14.4	63.0	8.4	50.4	12.3
6	62.9	11.4	76.0	10.1	52.3	13.3
7	66.5	13.1	91.9	12.8	55.9	9.1
8	69.1	12.0	94.7	11.8	67.8	17.7
9	80.3	12.7			71.3	16.6
10	86.3	10.1			78.0	13.9
11	88.0	12.1			80.4	13.5
12	94.8	10.2			91.4	9.6
13					96.9	10.1
Platform Weight	26 lbs		34 lbs		33 lbs	

Table 4 VEM Requirements

TEMPERATURE RANGE (F)	40 - 75
FREQUENCY RANGE (HZ)	15-2000
SHEAR MODULUS (PSI)	50-1200
LOSS FACTOR	> 1.0
STRENGTH (PSI)	> 50
OUTGASSING - TML (%)	< 1.0
OUTGASSING - CVCM (%)	< 0.1
THICKNESS (INCH)	.010 - 1.0

Table 5 MMC Requirements

Material	Volume Fraction	Laminate Geometry	Elastic Modulus	Yield Strength	CTE	Thermal Conduct.
	Percent		Msi	Ksi	10^6/F	BTU/H Ft F
SiCp/Al	40	Isotrop.	21	60	8.1	75
P120/Al(6061)	50	(0/90)NS	31.7	12	1.7	120
B/Al	50	(0/90)NS	25	12	5.6	42
Aluminum	-	-	10	35	13	85

Table 6 Analysis Summary

CATEGORY	GOAL	DUAL HC	EXTERNAL STIFF	INTERCOSTAL
WEIGHT REDUCTION (%)	20	30	21	22
>10 % DAMPING <100 HZ	ALL	12/12	7/8	11/13
THERM DIST REDUCTION	5	5.5	13	3.6
JITTER REDUCTION	2	5.1	4.8	5.3

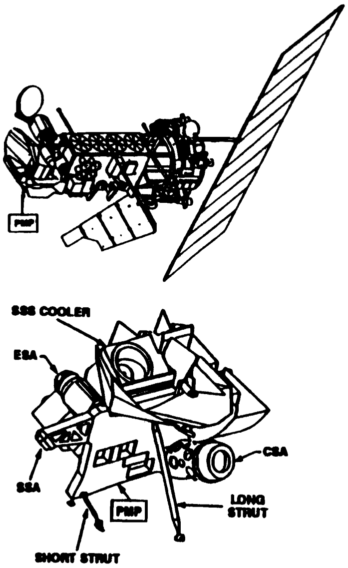


Figure 1 Remote Sensing Spacecraft and Existing Platform

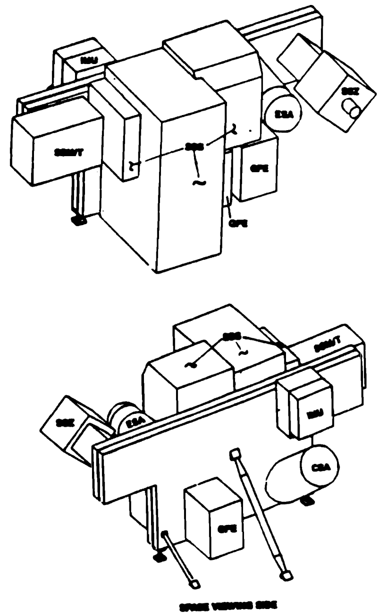


Figure 2 DSA Platform with Increased Mounting Area

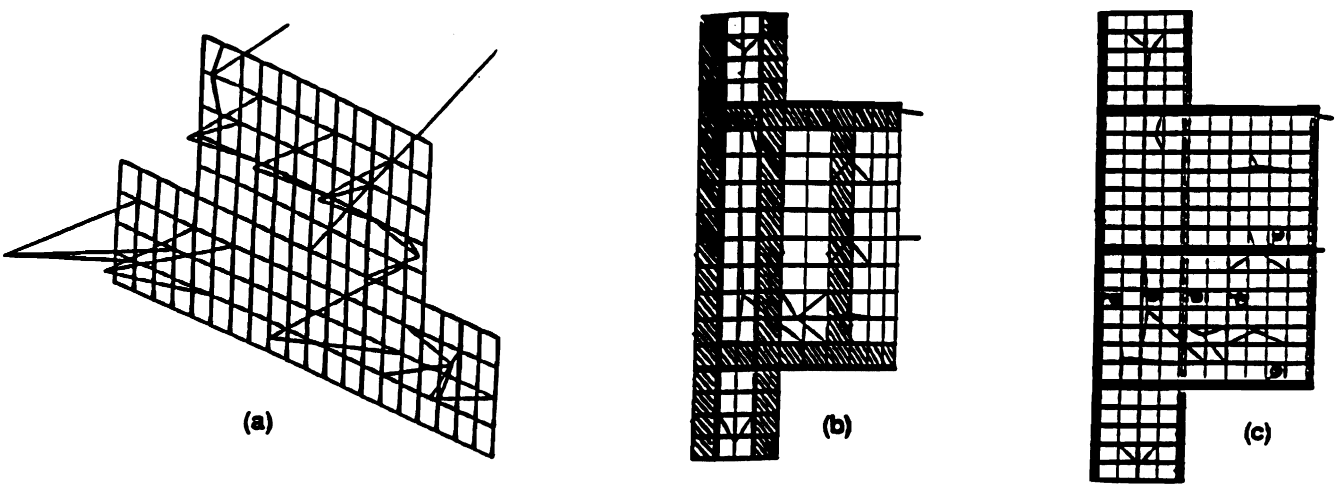


Figure 3 Concept FEMS: (a) Dual Honeycomb, (b) External Stiffener, (c) Intercostal

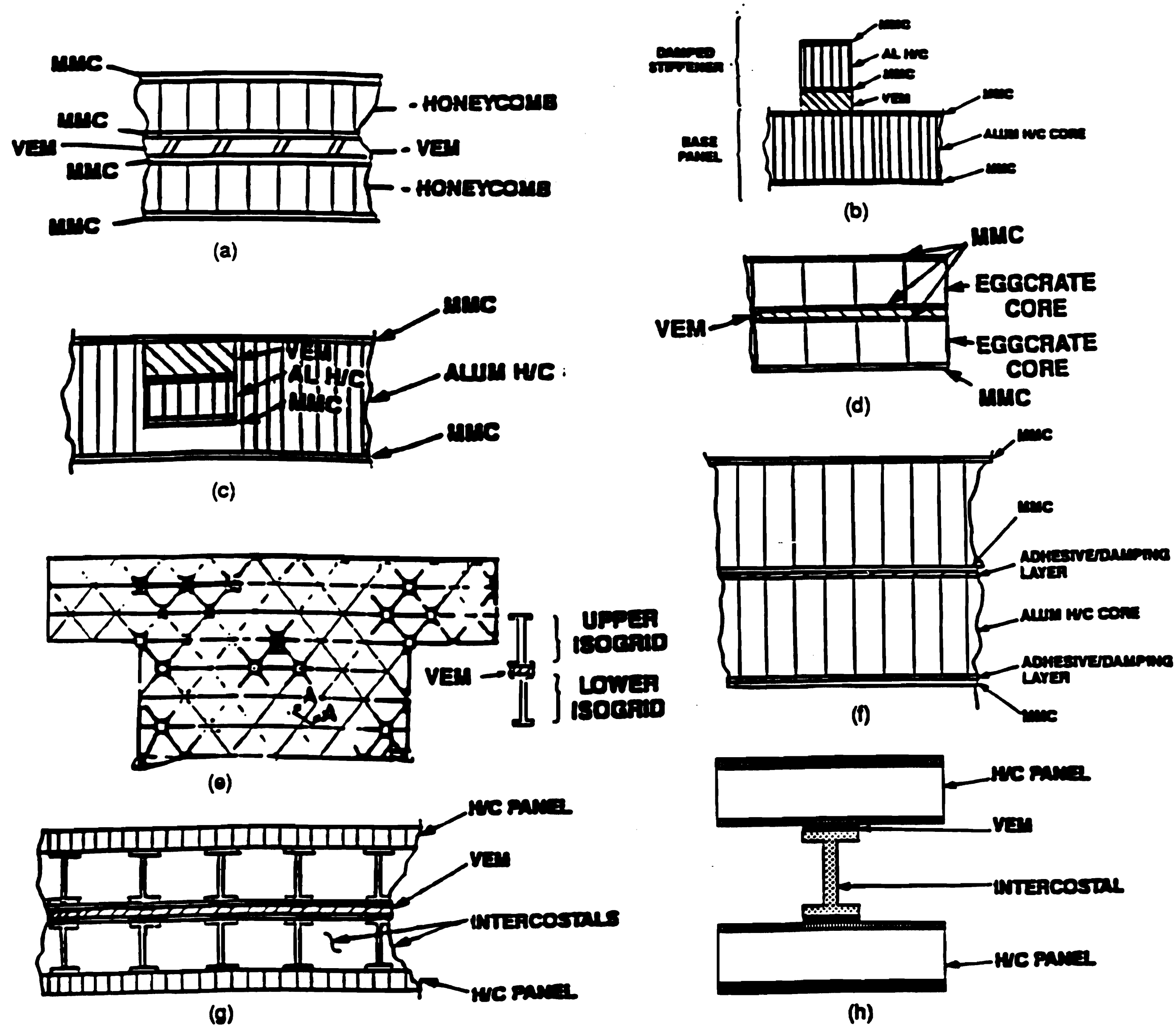
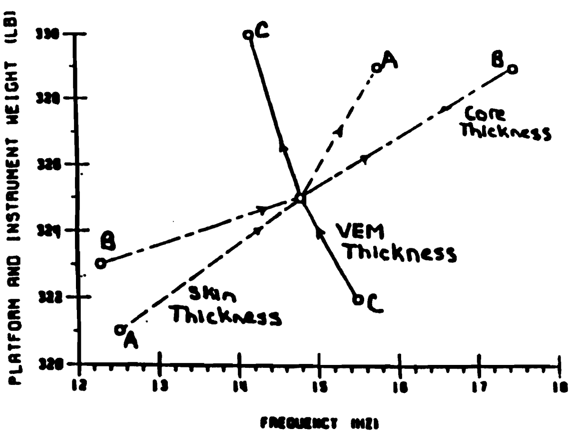
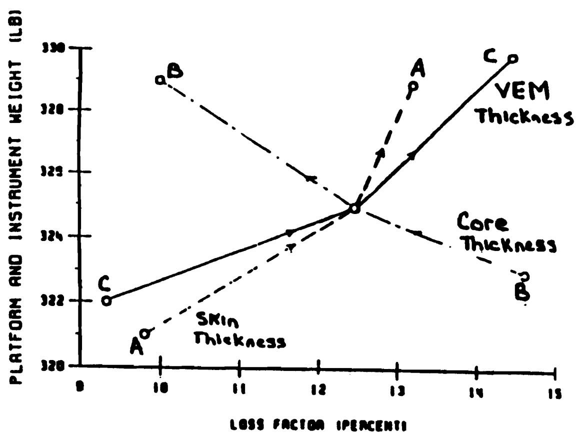


Figure 4 Eight DSA Concepts: (a) Dual Honeycomb, (b) External Stiffener, (c) Interior Stiffener, (d) Dual Eggcrate, (e) Dual Isogrid, (f) Adhesive Damping, (g) Dual Honeycomb/Intercostal, and (h) Modified Intercostal



Fundamental Frequency Sensitivity



Fundamental Modal Damping Sensitivity

Figure 5 Frequency and Damping Sensitivity of the Dual Honeycomb Fundamental Mode

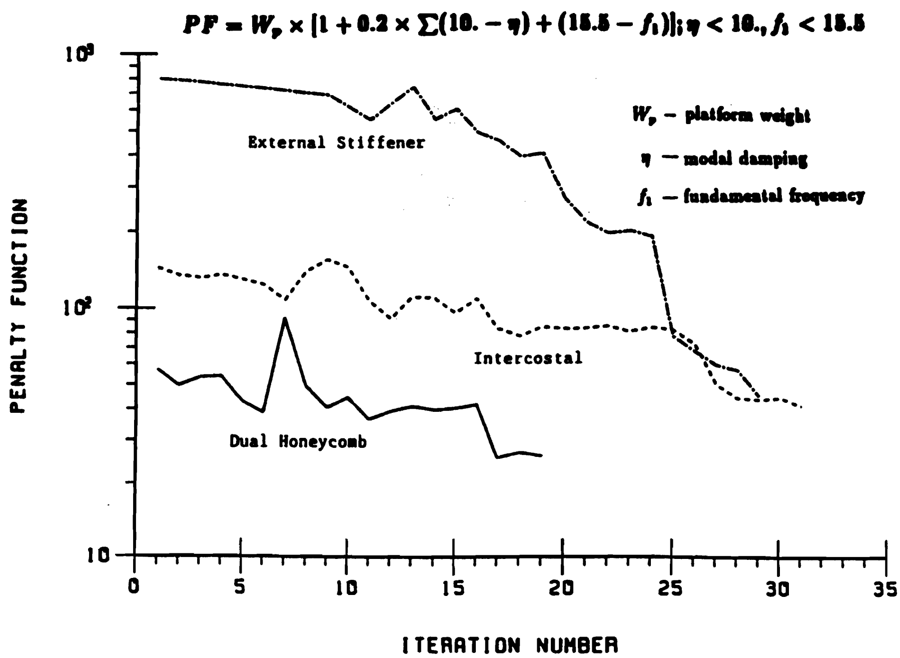


Figure 6 Penalty Function and Design Iteration History

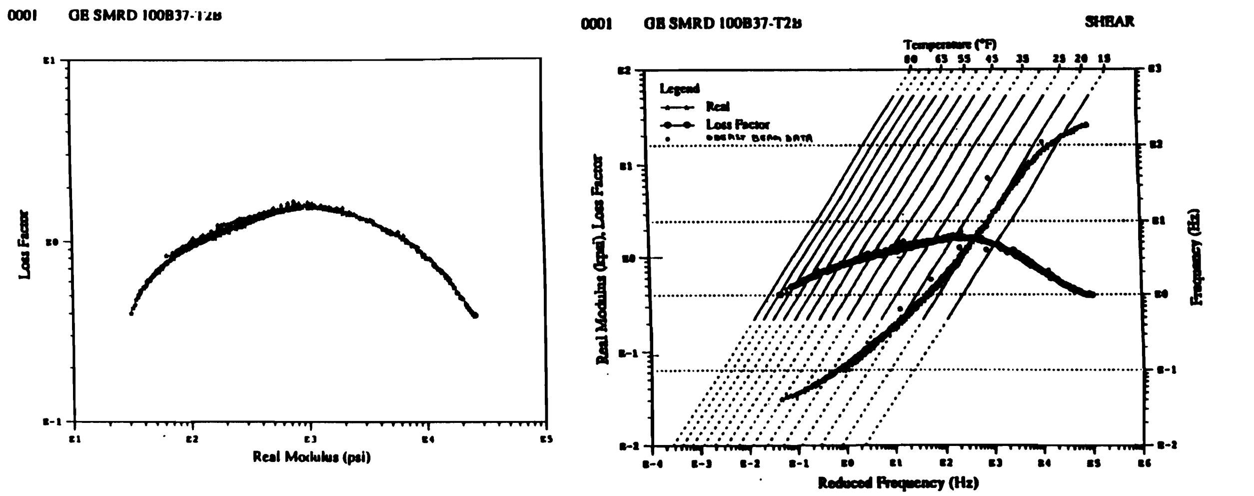


Figure 7 Storage Modulus and Loss Factor Data for SMRD B37T2B

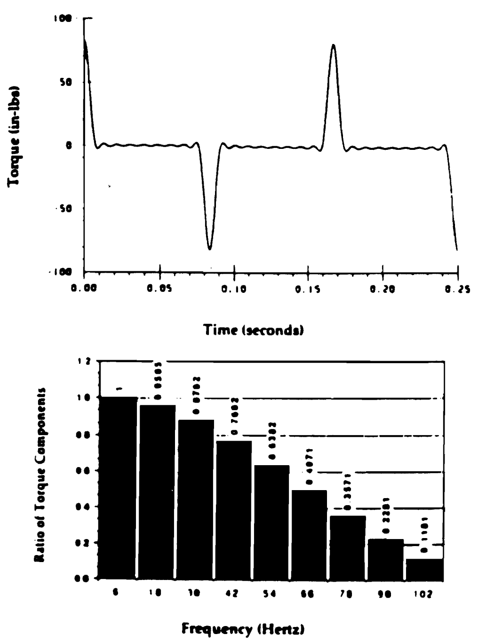


Figure 8 Input Torque Pulse Train and Fourier Components

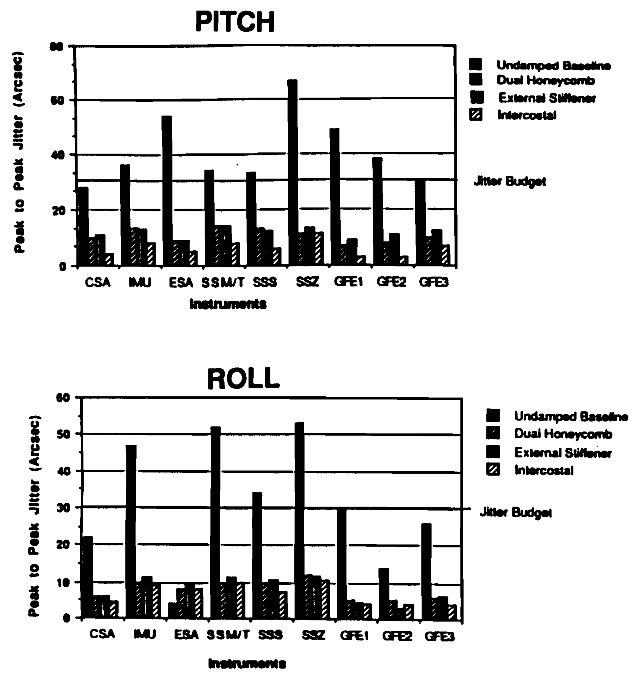
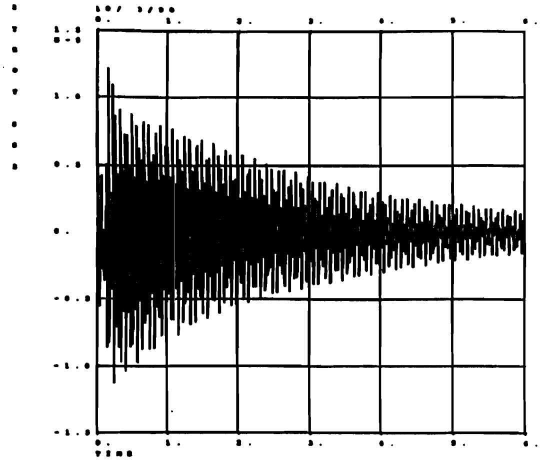


Figure 9 Worst Case Jitter Results Comparison



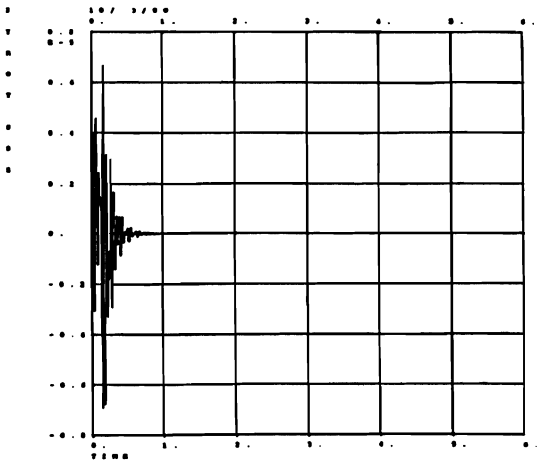


Figure 10 Settling Time Comparison - Undamped Eggcrate vs Damped Dual Honeycomb

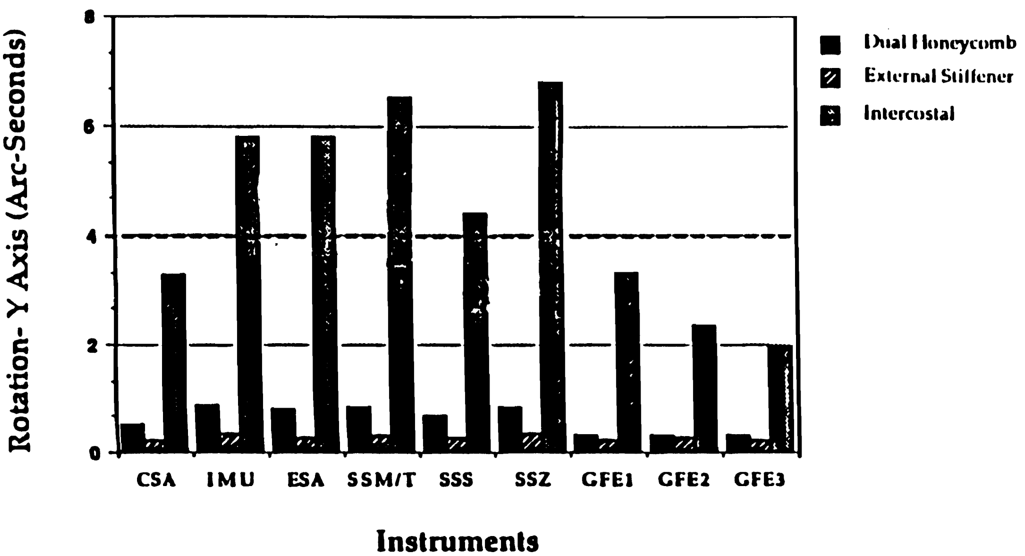


Figure 11 Thermal Distortion Comparison