SPS STRUCTURES AND CONTROL: A PERSPECTIVE

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Current concepts for a Solar Power Satellite (SPS) are inherently large systems. In the relatively benign external load environment of space; however, the characteristics and design requirements for the structure and control systems are quite different from a terrestrial system. To provide a perspective on these systems, and to provide some background for the more comprehensive papers which follow, a rather simplistic but indicative analysis on a representative configuration has been developed. It should be emphasized that this approach addresses a particular concept only as a mechanism for providing insight.

The first figure illustrates the representative configuration masses and dimensions in convenient approximate magnitudes. The largest magnitude external influences are illustrated in the second figure. There are, of course, many smaller external disturbances which must be considered in the design of a real system as well as control forces, forces between conductors, inertial and gravity loading and the most significant internal loading, isometric stress for stiffness. The lightest weight structure can be achieved through the use of the most efficient structural elements (axially loaded members). A cable or membrane represents the most efficient structural elements, however these elements are limited to tension. To take compression, a column or truss must be designed to be stable from buckling. For lightly loaded and long columns, the most efficient approach is to build a tier of smaller efficient elements as illustrated in Figure 3. Note that as the structure is tiered the mass characteristics approach a proportionality to material density and load and an inverse proportionality to Young's Modulus (E). In general, the structural mass can be reduced by configurations which use fewer but larger compression members. A significant point is that in spite of the large scale of SPS structures, the lightly loaded columns can be designed by minimum gauge material considerations.

The prime design consideration for the SPS structure and control systems is dynamic stability. The classical approach for achieving a dynamically stable system is to employ a frequency separation as illustrated by the frequency hierarchy in Figure 4. The greatest magnitude disturbance is the gravity gradient torque which cycles only twice a day. A simple attitude control law approach, as illustrated in Figure 5, gives a control correction frequency which is proportional to the square root of the disturbance torque derived by the allowable angular momentum impulse deadband. The system dynamic frequencies, as governed by the structural stiffness and overal system mass, are dependent primarily on geometry as illustrated in Figure 6. The largest component of this SPS mass is the solar cell blankets which, to first order, behave as membranes with a frequency dependence as illustrated in Figure 6.

Classical frequency separation is possible for the isolated major system components of the example configuration as illustrated in Figure 7. If the array and the antenna were isolated for this example configuration, the structure control interaction would be minimal. Since these components are connected by the rotary joint, the dynamics and control characterization requires a more in-depth analysis. The significance of structure control interaction and the significance of stiffness to the minimization of dynamic energy is illustrated in Figure 8 by the dimensionless plot of energy against time for a step function input to a simple beam. There do not appear to be any insoluble problems associated with the dynamics and control of an SPS but it is an area requiring more in-depth

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analysis and experiments.

The thermal environment for an SPS is dominated by solar radiation and waste heat rejection by the antenna, in the example configuration. Thermal distortion can significantly reduce the buckling stability for a compression column as illustrated in Figure 9. This can be avoided by structural configuration design, appropriate thermal control, use of a low coefficient of thermal expansion (CTE) material or a combination of these. The daily solar cycle of the antenna could also lead to unacceptable thermal distortion if similar techniques were not employed. The significant parameters to the distortion of an antenna is illustrated in Figure 10. An in-depth assessment of the achievable flatness for the reference system antenna was studied by General Dynamics, Convair. As given in Figure 11, the results of this study indicate that the desired flatness of 2 arc minutes could be achieved by state-of-the-art manufacturing tolerance, within maneuvering distortions and within thermal distortion if a low CTE material is used. An existing graphite/epoxy (GY-70/X-30 pseudoisotropic) was used to provide a realistic assessment of material properties and variations in properties. The transient thermal environment associated with biannual occulations can induce dynamic distortions of the overall system depending on the detailed thermal response characteristics and configuration. The dynamic response of the example configuration can be held to a minimum if the structural material is a low CTE material.

The prime findings of the SPS studies to date in the areas of structures and controls are listed in Figure 12. Although the SPS has a significant need for engineering and development work by analysis and experiment in the structures, controls and materials areas, there do not appear to be any insurmountable problems in these areas. There is a definite need for technology development in these areas, however. An in-depth assessment of the control system design and associated system performance is still needed. The significant interrelationships between control sensors, actuators and structural response are not well understood. The limitations of structural and dynamic modeling and their significance to control and system performance require assessment. First order analysis indicate that a 7% scale system (.4% full scale energy) in low earth orbit can provide a reasonable similitude for verification testing of the structure and control systems.

There is also a need to develop an understanding of the long term behavior of materials and coatings in the SPS operating environment. The behavior of materials under the particulate, UV radiation and plasma exposure with low level stress and thermal cycling needs quantification. The significance of construction and assembly to structural design, material selection and control requirements cannot be underemphasized. Overall, the SPS system is an intriguing challenge to the control, structures and materials specialists.

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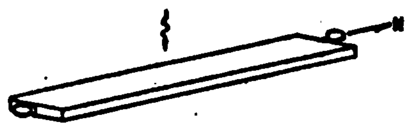


	DIMENSIONS, KM	MASS, MILLIONS OF KG.
SOLAR ARRAY STRUCTURE	5 x 20 x .4 SAFE	70 3.5
ANTENNA (EACH) STRUCTURE	1 DIA. x .1 DEPTH SAFE	15 .6
TOTAL	~ 100 KM² AREA	~ 100

FIGURE 1 - EXAMPLE SPS CONFIGURATION

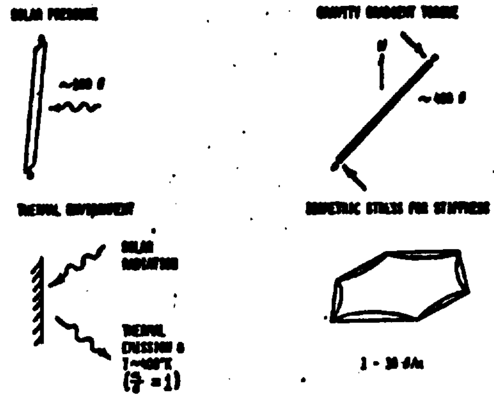


FIGURE 2 - LOADS AND ENVIRONMENT

	MINIMUM GAUGE (t) LIMITED	CRIPPLING LIMITED
CYLINDRICAL ELEMENT	$\sim \rho\left[Lt\right]^{1/2}\left[\frac{P}{E}\right]^{1/2}$	$\sim \rho L\left[\frac{t}{D}\ \frac{P}{E}\right]^{1/2}$
TRIANGULAR TRUSS OF CYLINDRICAL ELEMENTS	$\sim \rho\left[Lt\frac{P}{E}\right]^{1/2}$	$\sim \rho\left[\frac{t}{D}\right]^{1/2}\left[\frac{PL}{E}\right]^{2/3}$

- EFFICIENT SPACE STRUCTURES CAN BE MADE WITH LIGHTLY LOADED (P), LONG LENGTH (L), BUCKLING LIMITED COLUMNS WHICH ARE TICKED FROM SMALL GAUGE (t) BUCKLING LIMITED ELEMENTS
- STRUCTURAL MATERIAL REQUIREMENTS ARE:
  - LOW DENSITY, ρ
  - HIGH YOUNG'S MODULUS, E
  - SMALL GUAGE, t

FIGURE 3 - STRUCTURAL MASS/LENGTH CHARACTERISTICS

[illegible] (e.g. SOLAR BLANKETS) 〉 STRUCTURE/SYSTEM (e.g. ARRAY) 〉 CONTROL SYSTEM 〉 DISTURBANCE FREQUENCY

- MAJOR DISTURBANCE FREQUENCIES ≤ GRAVITY GRADIENT
- GRAVITY GRADIENT FREQUENCY = [illegible]

FIGURE 4 - FREQUENCY HIERARCHY FOR CLASSICAL DYNAMIC STABILITY

ASSUMPTIONS

- SINGLE DEGREE OF FREEDOM ROTATION [illegible]
- RIGID BODY
- CONSTANT DISTURBANCE TORQUE IMBALANCE, M_D
- SQUARE WAVE CONTROL TORQUE, M_C

CONTROL FREQUENCY, $f_c \approx \left(1 - \frac{M_D}{M_C}\right)\sqrt{\frac{M_C}{2 I_{yy} \Delta\theta}}$

GRAVITY GRADIENT DISTURBANCE

	ARRAY	ANTENNA
$\Delta\theta$	$\sim 1^\circ$	$\sim 5^\circ$
$\frac{M_D}{2 I_{yy}}$	$\sim \frac{3\omega_o^2}{4}$	$\frac{3\omega_o^2}{16}$
f_c	$\sim 2.5 \cdot 10^{-4}$ HZ	$\sim 1.5 \cdot 10^{-4}$ HZ

FIGURE 5 - CONTROL FREQUENCIES (FREEMAN PHYSICS APPROACH)

ARRAY $f_s \sim$ (ASPECT AREA) (ASPECT RATIO) $(\frac{E}{\rho})^{1/2}$ (STRUCTURE MASS / TOTAL MASS)$^{1/2}$ (STRUCTURE CONFIGURATION FACTOR)$^{1/2}$

ANTENNA $f_s \sim$ (ASPECT AREA) $(\frac{E}{\rho})^{1/2}$ (STRUCTURE MASS / TOTAL MASS)$^{1/2}$ (STRUCTURE CONFIGURATION FACTOR)$^{1/2}$

SOLAR BLANKETS (UNDAMPED) $f_s \sim$ [illegible]

FOR EXAMPLE CONFIGURATION

ARRAY	ANTENNA	BLANKETS
[illegible]	[illegible]	[illegible]

FIGURE 6 - SYSTEM (STRUCTURAL) FREQUENCIES

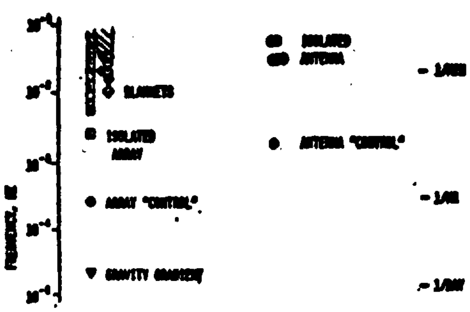


FIGURE 7 - "FREQUENCIES" FOR EXAMPLE SPS SYSTEM.

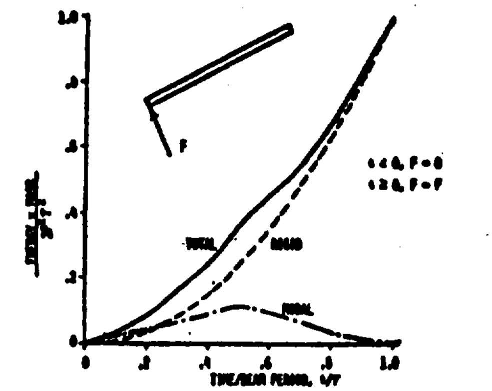
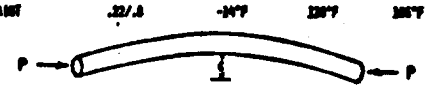


FIGURE 8 - ENERGY IN A BEAM FROM STEP FUNCTION FORCE

THIN WALLED ALUMINUM CYLINDER

- NORMAL TO SUN
- SURROUNDED BY DEEP SPACE
- $D/t \sim 1000$

SURFACE	α_s/ε	T_{max}	T_{min}	ΔT
BARE AL	.22/.04	[illegible]	[illegible]	[illegible]
BLACK PAINT	.9/.9	[illegible]	7°F	[illegible]
ANODIZED	.4/.8	[illegible]	-40°F	[illegible]
WHITE PAINT	.22/.8	[illegible]	[illegible]	[illegible]



EULER BUCKLING CRITICAL LOAD REDUCTION	P'_{cr}/P_{cr}	δ/R	L/D
	.42	.4	100
	.2	1.6	200

FIGURE 9 - SOLAR RADIATION INFLUENCE ON COLUMN STABILITY

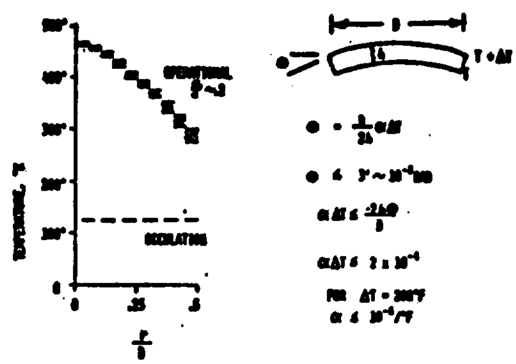


FIGURE 10 - EXAMPLE ANTENNA THERMAL ENVIRONMENT

- MANUFACTURING TOLERANCES CAN BE MET WITH STATE-OF-THE-ART TOOLING AND ASSEMBLY TOLERANCES
- ACTUAL SLOPE ERRORS ARE INSIGNIFICANT EXCEPT FOR POSSIBLE OSCILLATIONS AFTER OCCULTATION
- THERMAL DISTORTIONS ARE SMALL FOR STATE-OF-THE-ART GRAPHITE MATERIAL PROPERTIES

	SLOPE ACCURACY ARC MIN.	PERCENT LOSS
MANUFACTURING TOLERANCE	1.5	.5
MANEUVERING ACCELERATIONS	1.1	.5
THERMAL DISTORTIONS	.7	.2

FIGURE 11 - REFERENCE ANTENNA ACHIEVABLE FLATNESS ASSESSMENT (GENERAL DYNAMICS, CONVAIR CONTRACT NAS 9-15423)

- BENIGN LOAD ENVIRONMENT
- STRUCTURAL MASS FRACTION LOW (~ [illegible])
- STRUCTURE & CONTROL SYSTEMS ARE INTIMATELY COUPLED IN PROVIDING DYNAMIC STABILITY
- PRIME STRUCTURAL DESIGN REQUIREMENT IS STIFFNESS
- FRESHMAN PHYSICS CALCULATIONS INDICATE FREQUENCY SEPARATION POSSIBLE FOR ISOLATED MAJOR COMPONENTS
- TERRESTIAL VERIFICATION OF STRUCTURE & CONTROL NOT POSSIBLE - UNPRECEDENTED RELIANCE ON NUMERICAL SIMULATION
- THERMAL DISTORTION CAN BE SIGNIFICANT UNLESS LOW CTE MATERIAL USED OR APPROPRIATE DESIGN STRATEGY EMPLOYED
- ANTENNA FLATNESS APPEARS TO BE ACHIEVABLE
- CONSTRUCTUION AND ASSEMBLY ARE MAJOR CONSIDERATIONS TO STRUCTURE, CONTROL AND MATERIALS
- TECHNOLOGY DEVELOPMENT NEEDED IN:
  - CONTROLS
  - MATERIALS
  - STRUCTURES

FIGURE 12 - SPS SATELLITE STRUCTURE/CONTROL CONSIDERATIONS