International Space Station Thermally Induced Solar Array Base Loads

by

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ABSTRACT

As the International Space Station orbits around the earth, it goes through sunlight and the shadow of the earth. This causes temperature variations in the station as a function of time and position. The solar arrays are very sensitive to temperature variations and generate vibratory motion which can lead to accelerations in the racks where even very small accelerations are a concern. One method of computing the rack accelerations is to first determine the solar array base loads and then use transfer functions to obtain the rack accelerations. Finite element codes that allow thermal loads are meant for structures where support loads are generated from over restraint. These codes are not meant for structures, such as solar arrays, where support loads are due to inertia forces generated by thermal loading.

The purpose of this paper is to show a simple method of obtaining solar array base forces when there is free thermal expansion. In such a case, the boundary forces are primarily from inertia forces and drag forces are simply negligible. The inertia forces are a product of mass and acceleration. The acceleration is estimated from thermal displacements accurately computed by MSC/NASTRAN. The mode superposition approach using MSC/NASTRAN is used to include any drag effect of damping and the influence of vibratory modes. The net result is an efficient process that gives reasonable results.

INTRODUCTION

The International Space Station is an international joint venture with countries across the globe participating. It is a giant station which will operate in space, and mankind will use it for research, commercial production and voyages to outer space. When completed, it will be about 300 feet long. There are eight large United States built solar arrays to convert heat energy to electricity. Each array weighs about 2400 lbs and is 1000 inches long and 300 inches wide. Figure-1 shows a lower (incomplete) configuration.

The station will be used to conduct experiments, and there are specially built racks where accelerations no greater than micro-g's are desired. But as the station orbits around the earth, there is heating and cooling that generates vibrations. Since the solar arrays have large surface areas and very low frequencies, they are most susceptible to vibration arising from these changing thermal gradients.

It should be noted that the only load path from a solar array to the rest of the station is through its base which is treated as a single point. So, if the loads at the base of the solar array are known, then transfer functions can be used to compute the rack accelerations.

Based on engineering judgment, it can be said that a solar array fixed at its base and subjected to transient thermal loads is a case of free thermal expansion and the forces and moments at the base will be due to inertia forces. As the solar array expands and contracts, points on the array experience motion in the form of displacements, velocities and accelerations. Since the solar array is an assemblage of mass points, any acceleration of the mass points will generate forces called inertia forces. Since the coefficient of thermal expansion is very small, temperature fluctuations experienced by the solar array, displayed in Figure 2, can generate very small forces. The coefficient of thermal expansion, α, is typically on the order of 10^{-6} inch/inch. For a solar array of length 1000 inches and maximum temperature variation of about 200°F, maximum deflections on the order of 10^{-1} inch can occur. If the temperature variation occurs in about 240 seconds, the acceleration will be on the order of 10^{-5} inch/sec^{2}. For a solar array weighing 2400 lbs, the base force due to inertia forces will be on the order of 10^{-5} lbs.

Even though these forces are small, the presence of eight solar arrays and the need to have rack acceleration levels as low as 10^{-6} g, make it necessary to generate solar array base time histories that can be used to estimate rack accelerations. Therefore, there is a need for a method to reasonably estimate the solar array base force/moment time histories.

The customary method for computing forces generated by thermal loads (temperatures) is to create an equivalent force problem. The equivalent grid forces are generated based on the element (end) forces when the element is fixed at the boundary and a temperature load is applied. Though the method gives the correct formulation for over-constrained problems, for free thermal expansion problems the formulation is incorrect.

The subject of this paper is to present a simple yet reasonable method that will give base forces and moments of the order expected.

The mode superposition method is used to include the possible effect of drag forces and vibration modes. The drag forces are included through the use of viscous damping while the vibration modes are included through the modeshapes.

The flowchart of the process is shown in Figure 3. The heat transfer coefficients were obtained using TRASYS[1]. The temperature distribution was obtained using SINDA[2]. The modal solution was performed using MSC/NASTRAN[3]. Mapping of the SINDA computed temperatures on to the MSC/NASTRAN model was done using post-processors. The non-linear geometric stiffening of the arrays was considered to obtain the stiffness matrix. Selection of modes was done using a special Direct Matrix Abstraction Program (DMAP) as described by Bedrossian[4].

METHODOLOGY

The methodology used to compute the PV Array base loads is shown in Figure 3 and consists of seven steps:

Step-1: Compute heat transfer coefficients using TRASYS.

Step-2: Compute temperature distribution using SINDA.

Step-3: Map the temperature data on to the finite element model.

Step-4: Compute the grid displacements from thermal loads using MSC/NASTRAN Solution 101 with the PV Array fixed at base.

Step-5: Compute the accelerations at selected grid points from the displacements in Step-4. Distribute the PV Array mass to the selected grid points. Multiply the masses with the accelerations to compute the external (inertia) forces.

Step-6: Using MSC/NASTRAN Solution 106 compute the stiffness matrix of the PV Array fixed at the base with geometric stiffening and use it to compute the frequencies and modeshapes.

Step-7: Using the frequencies and modeshapes of Step-6 and the force vectors of Step-5, compute the PV Array base loads by the mode-superposition method of MSC/NASTRAN Solution 112.

THEORY

(a) ***Obtaining Displacements***

The thermal expansion of a line element is given by

$$\delta = L\alpha(\Delta T) \qquad (1)$$

where

L = length of element

α = coefficient of thermal expansion (linear)

ΔT = temperature change

The equivalent end forces on a beam (equal and opposite in direction) to generate the same deflection would be

$$F = \alpha EA(\Delta T) \tag{2}$$

where

E = modulus of elasticity

A = cross-section area

For plate elements the forces at the ends can be obtained in a similar manner. By summing the element end forces at a grid, a static load vector can be generated. This force vector can be used in the equations of motion. The equations of motion of the solar array (or any finite element model) are given in Meirovitch[5] as

$$[m]\{\ddot{u}\} + [c]\{\dot{u}\} + [k]\{u\} = \{f(t)\} \tag{3}$$

$[m]$, $[c]$ and $[k]$ are the mass, stiffness and damping matrices respectively. $\{u\}$, $\{\dot{u}\}$ and $\{\ddot{u}\}$ represent the generalized displacements, velocities and accelerations at the physical degrees of freedom and $\{f(t)\}$ represents the generalized forces at the physical degrees of freedom. MSC/NASTRAN solution 101 can compute the thermal displacements which can be used to compute inertia forces.

(b) ***Obtaining Inertia forces***

The displacement, δ, and velocity, $\dot{\delta}$, of a particle (mass point) assuming constant acceleration is given by

$$\delta = \dot{\delta}_0 t + \tfrac{1}{2}\ddot{\delta}t^2 \tag{4}$$

$$\dot{\delta} = \dot{\delta}_0 + \ddot{\delta}t \tag{5}$$

where

$\dot{\delta}_0$ = initial velocity

$\ddot{\delta}$ = acceleration

t = time

From (4) one can write

$$\ddot{\delta} = \frac{2\left(\delta - \dot{\delta}_0 t\right)}{t^2} \tag{6}$$

Therefore, the inertia force on the particle is given by

$$f(t) = \frac{2m\left(\delta - \dot{\delta}_0 t\right)}{t^2} \tag{7}$$

(c) ***Obtaining Boundary Forces***

The eigenvectors of an undamped free (no force) system can be used to generate an eigenvector matrix [Φ]. For linear systems,

$$\begin{aligned} \{u\} &= [\Phi]\{\eta\} \\ \{\dot{u}\} &= [\Phi]\{\dot{\eta}\} \\ \{\ddot{u}\} &= [\Phi]\{\ddot{\eta}\} \end{aligned} \tag{8}$$

Then, by replacing $\{u\}$, $\{\dot{u}\}$ and $\{\ddot{u}\}$ in (3) by the right hand sides of (8) and pre-multiplying both sides by $[\Phi]^T$ as in Cook[6] gives,

$$[\mathrm{M}]\{\ddot{\eta}\} + [\mathrm{C}]\{\dot{\eta}\} + [\mathrm{K}]\{\eta\} = \{\mathrm{F}(t)\} \tag{9}$$

where $[\mathrm{M}]$, $[\mathrm{C}]$ and $[\mathrm{K}]$ are the system modal mass, stiffness and damping matrices. $\{\eta\}$ is the generalized (modal) displacement vector and $\{\mathrm{F(t)}\}$ is the modal load vector.

$$\begin{aligned} [M] &= [\Phi]^T [m][\Phi] \\ [K] &= [\Phi]^T [k][\Phi] \\ [C] &= [\Phi]^T [c][\Phi] \\ \{F(t)\} &= [\Phi]^T \{f(t)\} \end{aligned} \tag{10}$$

Equations in (9) can be solved to obtain the displacements and the base force.

SOFTWARE USED

The following software were used in the analysis:

- MSC/NASTRAN (Version 68.2) finite element program developed by the MacNeal-Schwendler Corporation.

- THERMAL : a FORTRAN code for generating load vectors

- TRASYS: A computer code to compute thermal coefficients

- SINDA: A thermal code to compute temperature distribution

UNITS USED

The following units were used:

- unit of mass is lbs
- unit of length is inches
- unit of time is secs.
- unit of temperature is degrees Fahrenheit

For consistency in units, mass units were internally converted to lb-sec-sec/in by MSC/NASTRAN.

ASSUMPTIONS, APPROXIMATIONS AND SIMPLIFICATIONS

Several assumptions, simplifications and approximations were made in this analysis as is common in most structural analysis.

(1) All vibration modes were assumed to have 1% viscous (modal) damping as is customary in such analysis.

(2) From the temperature variations as a function of time in Figures 4 and 5, it is clear that high frequency modes will not have any contribution. Therefore, only vibration modes below 10.0 Hz were used in the computation of PV Array base loads.

(3) For simplicity the mass of the PV Array was lumped at selected grids. This would introduce some uncertainty. It was assumed that:

Mast weighs:	800 Lbs
Canister weighs:	200 Lbs
Blanket Weighs:	400 Lbs each
Bottom Cover weighs:	400 Lbs
Top Cover weighs:	200 Lbs

(4) It was assumed that the initial velocity when temperature begins to change (i.e. $\dot{\delta}_0$ in equation (7)) is zero. If the temperature had peaked (maximum or minimum) at the initial condition, then this assumption would give smaller inertia forces. If the temperature had not peaked at the initial condition, then this assumption would give larger inertia forces.

(5) For simplicity, the temperature distribution in an element was simplified (linearized) so that it can be represented as varying linearly. This justified computation of inertia force vectors only at a few time points.

(6) For simplicity, the weight of the solar array was lumped at only at a few grids. This justified computation of inertia forces only at a few grids as only lower order vibration modes were assumed to participate.

CASE STUDY

Two cases were considered. Case-1 is that of no shadow. Case-2 is that for a moving shadow (possibly generated by the EPS radiator). The temperature variation in each case of a typical mast grid (Node 8351) and a typical array grid (node 511) are shown in Figures 4 and 5. The temperature distribution for Case-1 is from Reference 3 while that for Case-2 is from Reference 4.

It is obvious from Figures 4 and 5 that the maximum temperature change occurs during day-night transition. Therefore, the maximum PV Array base loads are expected to occur during the transition periods.

Also of interest is the daily variation of the PV Array base load (for Case-1).

RESULTS, CONCLUSIONS AND IMPORTANT REMARKS

The peak loads are shown in Table 1. Note, that the unit of force is lb and that for moments is in-lb. For the short duration excitation (sudden change of temperature), a computation time step of .025 second was used. For the long duration excitation (daily change of temperature), a computation time step of 1.0 second was used. The loads are in the basic coordinate system.

The forces are very small. This is because acceleration from free thermal expansion is very small giving very small inertia forces. The moments are somewhat higher because of the large moment arms associated with the inertia forces. The response is the superposition of the individual contribution due to each mode. Again, a mode will participate only if the loading is such as to excite it. If the loading (temperature distribution) is perfectly symmetric about the PV Array axis, the F_y force and M_x and M_z moments at the base of the solar array will be zero. Non-zero F_y for the case of 'no-shadow sudden' indicates unsymmetric temperature distribution. The in-plane (unsymmetric) vibration modes have low frequencies and get excited making F_y larger than F_x. This also explains why M_z is large for this case.

The beta angle defining the orientation of the solar angle was 0° for the case of no shadow and 65° for the case of shadow. Though the magnitude of the loads is expected to change with beta angle, still the loads would be very small.

The analysis performed here has scope for improvement. The actual initial velocity in place of zero can be used when the initial velocity is known, as in the case of long term (daily) change of temperature. Also, the actual temperature distribution, in place of the assumed temperature distribution, can be used to generate the load vectors. These two improvements would make a difference in the PV Array base loads for long term (daily) change of temperature.

Ideally, the displacement, velocity and acceleration from equations (4), (5) and (6) should match those from equations (8). Therefore, some iterative technique can be developed to satisfy this requirement. This could be part of further studies in this area.

ACKNOWLEDGMENT

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TABLE -1
PEAK BASE LOADS

Component	No-Shadow Sudden	No-Shadow Daily	Shadow Sudden
Fx (lb)	1.9E-6	6.3E-7	1.7E-6
Fy (lb)	1.5E-4	5.9E-5	5.4E-6
Fz (lb)	1.3E-5	3.2E-5	4.8E-5
Mx (in-lb)	1.4E-1	5.9E-2	5.3E-3
My (in-lb)	1.9E-3	5.5E-4	6.4E-4
Mz (in-lb)	1.8E-3	6.6E-4	1.2E-4

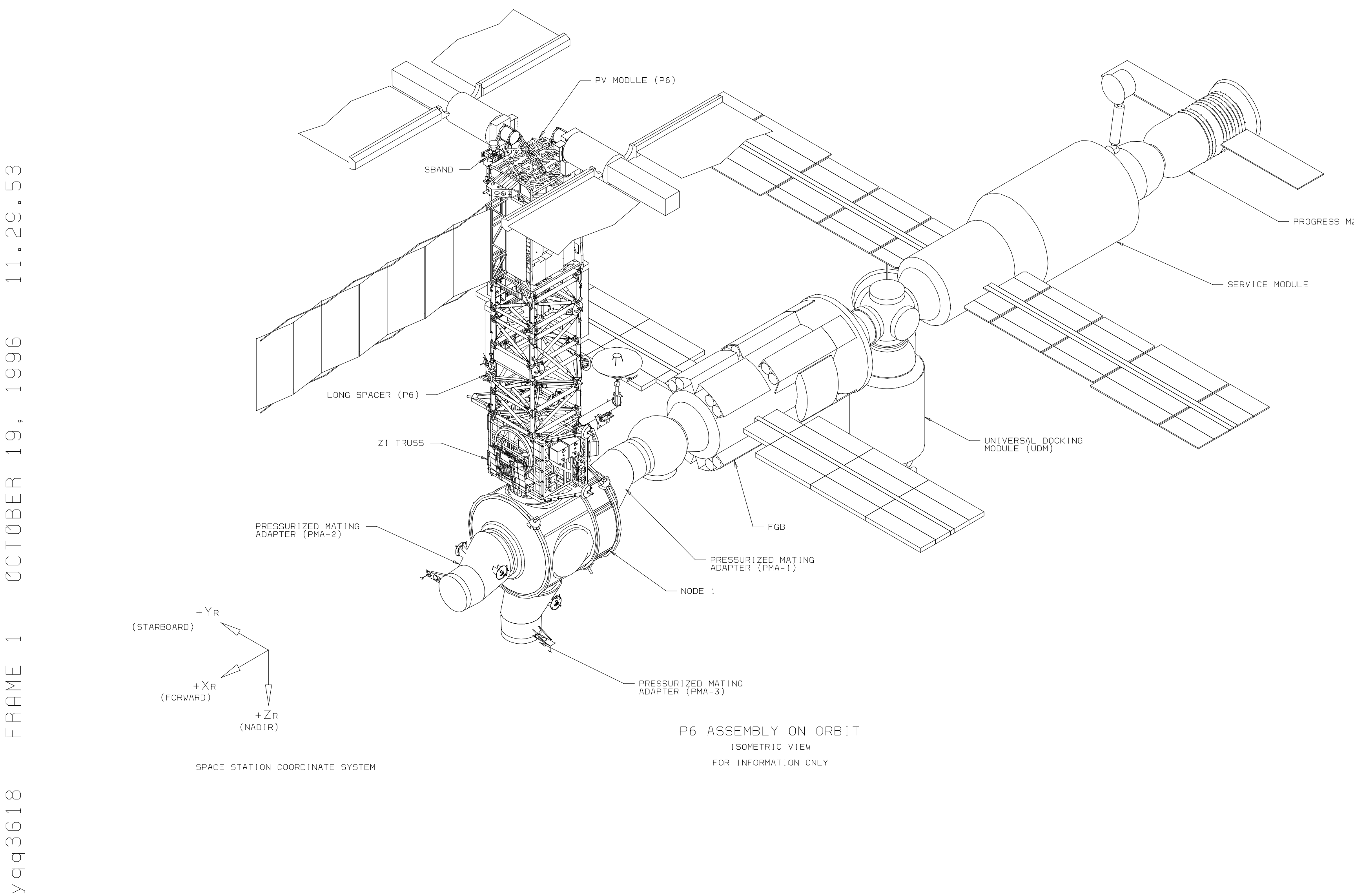

FIGURE 1: INTERNATIONAL SPACE STATION

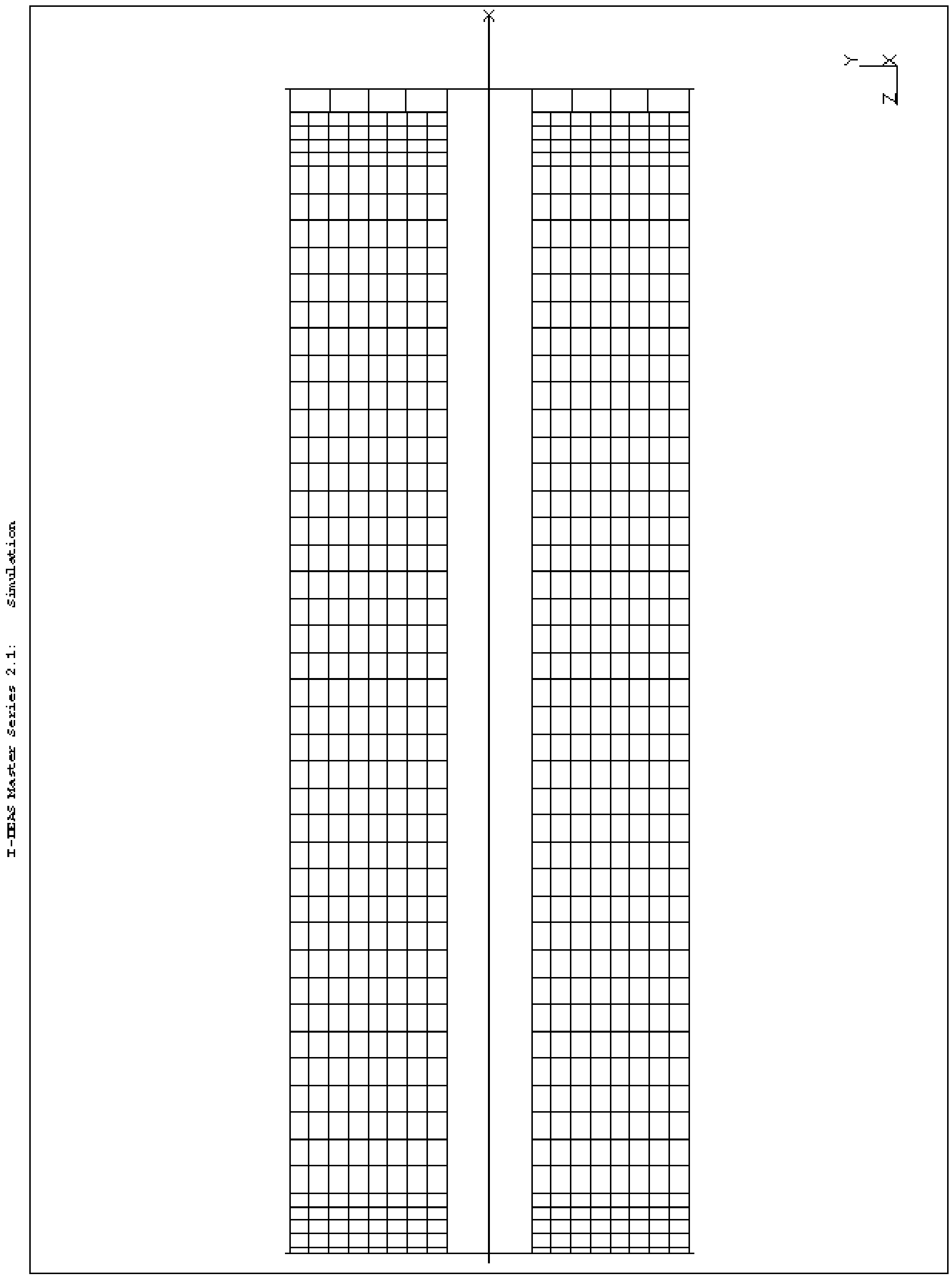

FIGURE-2: DEPLOYED SOLAR ARRAY

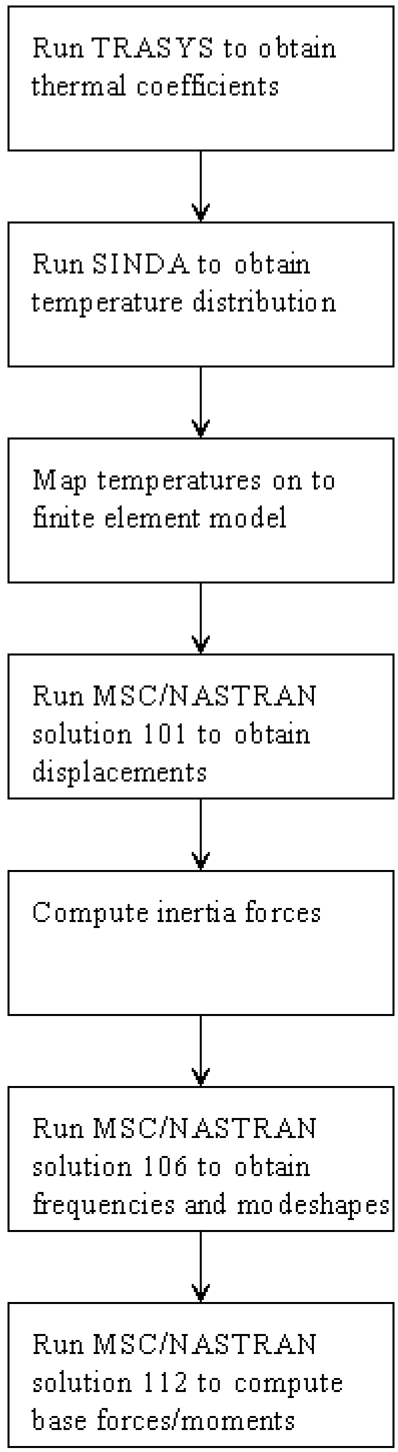

FIGURE-3: PROCESS FLOWCHART

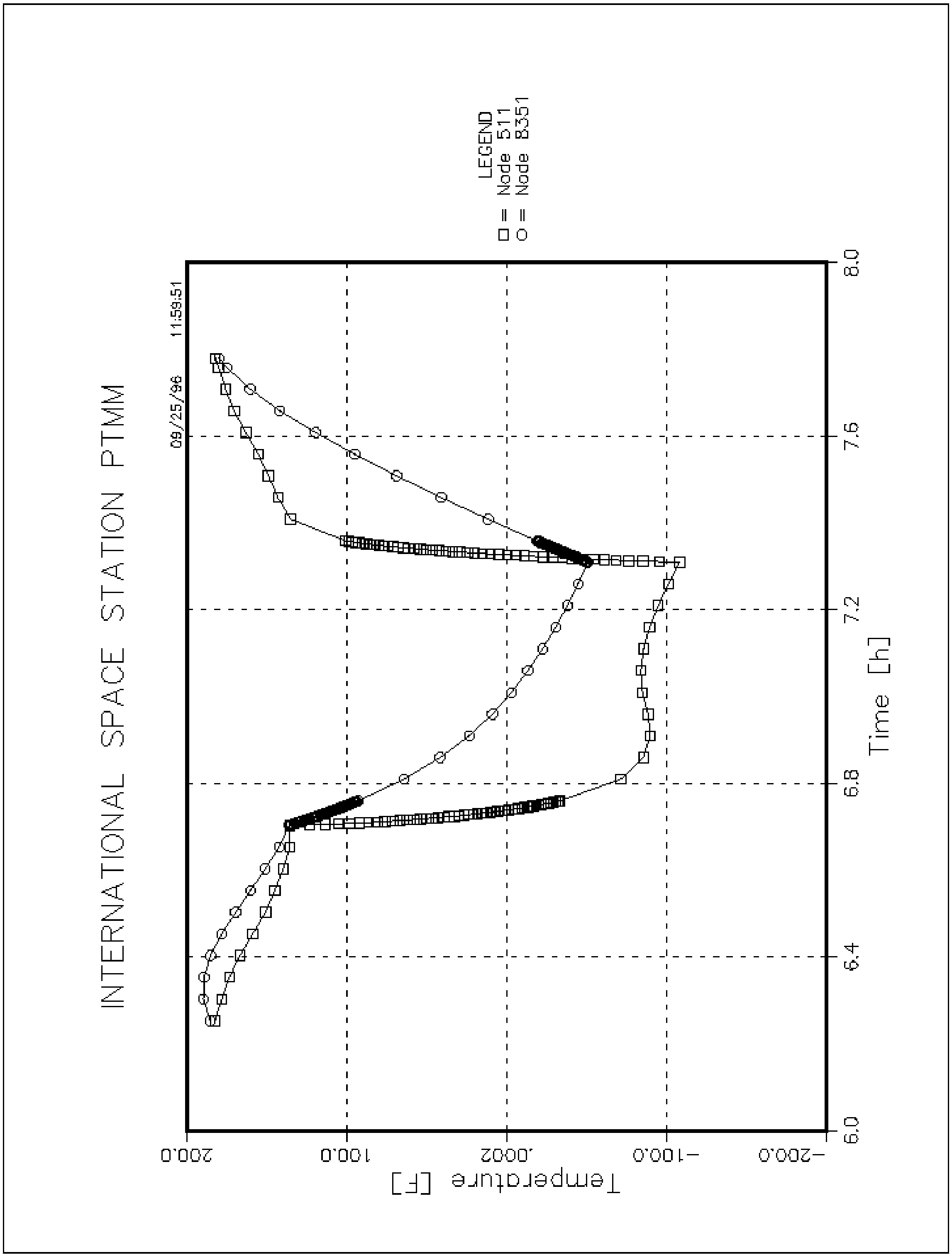

FIGURE-4: NO SHADOW TEMPERATURE LOADS (TYPICAL)

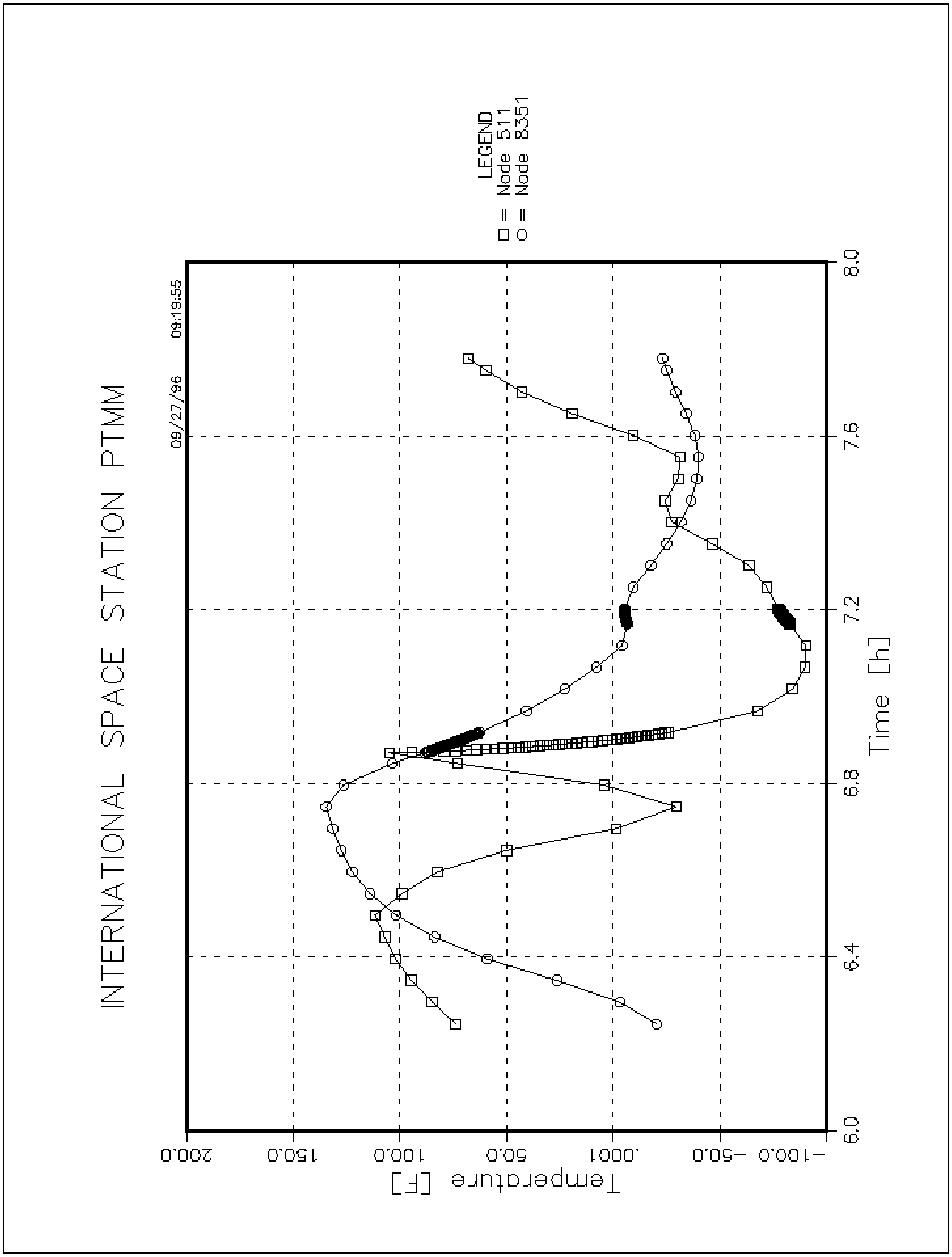

FIGURE-5: SHADOW TEMPERATURE LOADS (TYPICAL)