Interaction Between Gravity Compensation Suspension System and Deployable Structure

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Gravity compensation suspension systems are essential to support space structures during tests on Earth, but also impose constraints on the structures that have the effect of changing their behavior. A computational and experimental study of the interaction of a rigid panel solar array model with a manually adjustable suspension system during quasi-static deployment tests in the 1-g environment of the laboratory is presented. A methodology is established for modeling this interaction, for predicting the effects of suspension system adjustments, and for optimization of the suspension system through these adjustments. Some improvements can be achieved by manual adjustments, but further optimization requires an active system.

Nomenclature

\( d \) = vector of generalized displacements
\( f \) = \( z \) component of force
\( K \) = stiffness matrix
\( m \) = nodal couple
\( p \) = vector of generalized forces
\( s \) = vector of suspension forces
\( w \) = \( z \) component of deflection
\( \alpha \) = deployment angle
\( \delta \) = vector of suspension adjustments
\( \theta \) = nodal rotation

Subscripts

\( A \) = array
\( C \) = combined
\( M \) = measured
\( P \) = predicted
\( R \) = required
\( S \) = suspension

Superscript

\( ^{/c_{187}} \) = full (i.e., uncondensed)

Introduction

The 0-g environment of space makes it possible to design large space structures of low mass. The dimensions of such structural systems impose problems during transport into orbit, however, because the payload volume of launchers is limited. Therefore, a variety of deployable structures are used that can be packaged into a small volume and, once in space, can be deployed into their operating configuration.

Prior to flight, ground validation tests of such structures are carried out to ensure reliable and accurate performance in space. However, the 1-g environment and the associated self-weight loading on the structure have to be counteracted with an artificial support system. The problem is that this system imposes constraints on the structure, and, thus, perturbs its static, dynamic, and deployment behavior.

Gravity compensation systems play a key role in replicating as closely as possible the 0-g conditions of space. Concepts used for the testing of space structures include physical methods such as drop towers and parabolic flight maneuvers, buoyancy techniques, air bearings/tables, and simple mechanical suspension systems featuring cables and pulleys, often in combination with counterweights, zero-springrate mechanisms, and pneumatic/electric devices. Improvement of the mechanical methods lead to the development of actively controlled single-point suspension systems.

To support the large-scale deployment motion of modern space structures, passive and, more recently, actively controlled multipoint suspension systems are used. However, the inherent flexibility of deployable structures is the source of complex interactions between structure and suspension system that requires careful examination. To obtain reliable predictions from ground tests for the deployment behavior in space, these interactions have to be understood.

The particular deployable structure that is investigated in this paper is a cable-deployed rigid panel solar array of the type used in the European Retrievable Carrier (EURECA) spacecraft. This type of solar array exhibits features typical of large deployable space structures such as high, variable flexibility, and, hence, multiple supports are required to prevent excessive loading and deformation. Deployment tests on a small-scale laboratory model have revealed a complex interaction with the support system; the variations in the suspension forces observed even during quasi-static deployment were surprisingly large. The aim of this paper is to develop analytical models to capture this interaction, and then to adjust the suspension system to isolate as much as possible the structural behavior of the test article from that of its suspension.

Following a brief description of the model structure that will be investigated, the section Computational Models sets up the configuration-dependent stiffness matrix of the array and the constant stiffness matrix of its suspension system. Thus, a relationship between the adjustments of the suspension system and the associated changes in the suspension forces, for any configuration of the array, is obtained. In the section Variation of Suspension Forces During Deployment, it is found that there are considerable differences between the predicted, the experimentally observed, and the required suspension forces. Thus, in the following section a simple method for adjusting the suspension system and achieving predictable behavior is established. It is concluded that the suspension system currently used, which does not allow on-line adjustment, cannot produce accurate gravity compensation, but even a simple, actively controlled system would be able to.

Physical Model of Solar Array

The solar array that is examined in this paper is a simplified version of the retractable advanced rigid array of the EURECA mission. Figure 1 is a schematic view of the test rig, including the solar array model and the suspension system. Geometrical and material properties are listed in Table 1.
Table 1 Properties of solar array model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dimensions</strong></td>
<td></td>
</tr>
<tr>
<td>Array</td>
<td>Fully deployed length 2,200 mm</td>
</tr>
<tr>
<td>Panels</td>
<td>400(200) × 100 × 1.63 mm</td>
</tr>
<tr>
<td><strong>Panel material</strong></td>
<td></td>
</tr>
<tr>
<td>Al-alloy</td>
<td></td>
</tr>
<tr>
<td>$E$</td>
<td>70,000 N/mm$^2$</td>
</tr>
<tr>
<td>$v$</td>
<td>0.33</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.0027 g/mm$^3$</td>
</tr>
<tr>
<td><strong>Mass distribution</strong></td>
<td></td>
</tr>
<tr>
<td>Total mass</td>
<td>4,343 g</td>
</tr>
<tr>
<td>Tip mass</td>
<td>355 g</td>
</tr>
<tr>
<td>Mass of panels</td>
<td>0.405 g/mm</td>
</tr>
<tr>
<td>Mass of hinges</td>
<td></td>
</tr>
<tr>
<td>$m_1$</td>
<td>310 g</td>
</tr>
<tr>
<td>$m_2, \ldots, 6$</td>
<td>507 g</td>
</tr>
<tr>
<td>$m_7$</td>
<td>607 g</td>
</tr>
</tbody>
</table>

To avoid undesirable deformation of the array structure due to an unbalanced weight distribution amongst the suspension points, a tip mass is attached to the last hinge adding the weight of approximately half of a hinge and half of a panel.

### Computational Models

To investigate the interaction between the array structure and its suspension system, finite element models are set up for each, relating the displacements of the suspension points to the applied forces. Then the individual models are combined, with and without consideration of the length changes in the suspension cables, to derive a computational model of the complete system.

#### Model of Solar Array

The solar array is modeled as an assembly of six beam elements (Fig. 2) connected by revolute joints with vertical axes of rotation. Nodes 1–7 coincide with the hinges and with the suspension points. We are only interested in the vertical displacements at the suspension points and, hence, only in the out-of-plane stiffness of the array. According to an in-plane model of the array, the in-plane and out-of-plane behavior of the array are decoupled, provided that the out-of-plane deflections are small. The state of deployment or retraction is uniquely defined by the deployment angle $\alpha$, with $\alpha = 0$ and $90$ deg denoting the fully deployed and fully retracted configurations, respectively. For our study, it makes no difference whether the array is being deployed or retracted, and, hence, only deployment will be mentioned from now on.

The stiffness matrix $\hat{K}_A$ of the array structure, relating the displacements $\hat{d}_A$ to the forces $\hat{p}_A$ at the suspension points, is composed of the standard stiffness matrices for the individual beams. Here, $\hat{d}_A$ includes the vertical displacement components of all of the nodes plus the rotations $\theta_i$ and $\theta_j$ of nodes 2–7. Therefore, the stiffness matrix $\hat{K}_A$ of the array has dimensions $(19 \times 19)$, and the force-displacement relationship is given by

$$\hat{K}_A \hat{d}_A = \hat{p}_A$$

or, in block form,

$$\begin{pmatrix} \hat{K}_{A_{wv}} & \hat{K}_{A_{w\alpha}} \\ \hat{K}_{A_{\alpha v}} & \hat{K}_{A_{\alpha\alpha}} \end{pmatrix} \begin{pmatrix} \hat{w}_A \\ \hat{\theta}_A \end{pmatrix} = \begin{pmatrix} \hat{f}_A \\ \hat{m}_A \end{pmatrix}$$

Because we are not interested in the rotation components, we use standard matrix condensation techniques to obtain

$$K_A \hat{w}_A = \hat{p}_A$$

with

$$K_A = \hat{K}_{A_{wv}} - \hat{K}_{A_{w\alpha}} \hat{K}_{A_{\alpha\alpha}}^{-1} \hat{K}_{A_{\alpha v}}$$

The condensed stiffness matrix $K_A$ is of size $(7 \times 7)$. This model shows that the stiffness of the array changes considerably with the angle $\alpha$, as observed in the experiments. The reason for this is that the structure is far more flexible, during the middle portion of deployment, due to twisting of the panels, than it is when it is fully deployed or retracted. In these extreme configurations only bending occurs, a deformation mode where the panels exhibit a much stiffer behavior.

#### Model of Suspension System

The suspension system consists of the four independent suspension elements I, II, III, and IV. These are complex structures to model accurately, and, hence, it was decided to measure their stiffness experimentally.
where positive $\delta$ correspond to shortening of the suspension cables. Equations (3), (6), (10), and (11) give

$$\Delta \omega_A = (K_A + K_S)^{-1}K_S \delta$$

which provides the essential tool for the manipulation and redistribution of the suspension forces.

The $(7 \times 7)$ matrix $R$ is not a stiffness matrix in the usual sense because it relates internal forces and displacements, not externally applied loads and displacements.

### Variation of Suspension Forces During Deployment

#### Predicted and Measured Suspension Forces

The combined system formed by the solar array and the suspension system is loaded by the self-weight of the array. The self-weight of the suspension system need not be considered because it is equilibrated directly within the system itself. The mass distribution of the array has been estimated from measurements and calculations. In the physical model $\sim 80\%$ of the total mass is due to the hinges and the tip mass, and the remaining $\sim 20\%$ is due to the panels (see Table 1).

Forces resulting from the masses concentrated at the hinges are applied as single loads $F_H$. The uniformly distributed mass of the panels gives rise to appropriate equivalent nodal loads $F_P$, $M_{p_A}$, and $M_{p_C}$, that depend on the actual deployment configuration. Hence, the load vector $\bar{p}_C$ is

$$\bar{p}_C = \left( \begin{array}{c} f_c \\ m_c \\ \end{array} \right) = \left[ \begin{array}{c} F_H + F_P \\ M_{p_A} \\ M_{p_C} \end{array} \right]$$

In analogy with the matrix condensation of the array stiffness matrix $K_A$, the load vector $\bar{f}_C$ can be reduced from 19 to 7 elements to match the stiffness matrix $K_C$ of the combined system [Eq. (5)], and the condensed load vector $\bar{p}_C$ is then given by

$$\bar{p}_C = f_c - K_A^{-1}(K_A + K_S)^{-1}m_c$$

This loading is applied on the computational model of the combined system [Eq. (9)] to determine the resulting displacements at the suspension points.

Then, by using the stiffness relationship for the suspension system [Eq. (6)], the internal forces in the suspension cables can be recovered. Figure 4 shows the forces in the suspension cables throughout deployment.
The computational model represents an idealized structure with no misalignment or imperfections where the hinges are exactly vertical, the suspension elements are identical, and the rails supporting the bearings of the suspension system are straight and horizontally level. In practice, though, all of these imperfections occur to an unknown extent and, thus, it might be expected that the measured suspension forces will not even resemble the suspension forces resulting from a perfect computational model. Also, the initial length adjustments of the suspension cables influence significantly the variation of the suspension forces during deployment. Figure 5 shows only two examples of the many suspension force variations that were measured.

However, we can use the relationship for the redistribution of the suspension forces [Eq. (13)] to change the current force distribution by computing the adjustments that will best simulate a weightless environment.

### Required Suspension Forces

During deployment the forces carried by the hinges should be as small as possible if the suspension system is to accurately replicate the behavior of the structure in space. This requires that the deformation of the array be minimized and, hence, that the displacement of all suspension points be a pure translation.

The forces acting on the suspension points of the array are the loads $p_c$ due to self-weight, given by Eq. (16), and the suspension cable forces $s$:

$$ K_A w_A = p_c + s $$ \hspace{1cm} (17)

The stiffness matrix $K_A$ of the array without the suspension system is singular, because the structure has a degree of kinematic freedom in the vertical direction. Therefore, its displacements need to be considered relative to the displacement $w_1$ of suspension point one

$$ K_A \left( w_A - w_A^* \right) = p_c + s $$ \hspace{1cm} (18)

where $K_A^*$ is a $7 \times 6$ reduced version of $K_A$.

Pure translation of the array occurs for the relative displacements $(w_A - w_A^*) = 0$. To achieve this, no resulting forces are to act at the suspension points, which in turn implies that at any stage during deployment the suspension forces have to exactly equilibrate the self-weight loads at every suspension point. Hence, the required suspension forces $s_R$ for proper gravity compensation are

$$ s_R = -p_c $$ \hspace{1cm} (19)

whose dependence on the deployment angle $\alpha$ is plotted in Fig. 6.

As could be expected, the required distribution of suspension forces is almost constant because the main part of the loading is applied as concentrated loads that are supported right at the suspension points for any configuration of the array. However, there would be a more significant variation if the mass of the system were more uniformly distributed. Indeed, this would be the case for an array structure of larger scale, where the mass of the hinges would be much smaller than the mass of the panels.

The suspension force at node 1 is smaller than that at the other nodes because one of the panels connected to this hinge is only half as big as the other panels, and, hence, its mass is much lower.

### Adjustment of Suspension System

Experiments were carried out to verify the computational models and also to check the accuracy of the method for redistribution of the suspension forces by adjusting the length of the suspension cables.

In the experiments, deployment and retraction were set to last 90 s. Every second, the strain gauge readings were recorded by a data logger, so that the forces in the suspension cables are available
at intervals of 1 deg of the deployment angle $\alpha$. The preparation for these experiments included resetting the strain gauges to zero by unloading the suspension cables one after the other, so that the sum of the strain gauge readings always corresponded to the overall supported weight of the array. Measurements were taken for both deployment and retraction and then averaged at corresponding deployment angles. Noise was removed by smoothing out the data using polynomial fitting.

Comparing the measured suspension force distributions $s_M$ (Fig. 5) to the required suspension forces $s_R$ (Fig. 6) the necessary changes in suspension forces are determined by

$$\Delta s = s_M - s_R$$

(20)

Then, the necessary length adjustments of all seven suspension cables were calculated with Eq. (13) and are plotted in Fig. 7.

When comparing Figs. 5 and 6, note that their discrepancy is relatively big at either end of deployment, whereas the agreement is much better in the range $\alpha = 40$–70 deg. This is due to the reduction in stiffness of the array structure during the middle part of deployment, as described before. Therefore, vertical deviations of the suspension points from their required positions result in much larger reaction forces than in the end configurations. In intermediate configurations, the array can yield much more easily to the restraints imposed by the suspension system. For the same reason, the length adjustments there need to be impractically large to achieve only minor force corrections, in contrast to the end configurations where the deviation of the actual from the required forces is much bigger but can be corrected by much smaller adjustments.

Our experimental setup allows adjustment in only one particular configuration because the length changes at the suspension wires have to be imposed manually. Therefore, either the fully retracted or the fully deployed configuration is chosen, where large force discrepancies can be corrected by small length adjustments.

Because of the array structure itself having one degree of freedom in the vertical direction, identical length changes at all suspension cables would not affect the force distribution. The necessary length changes are, therefore, calculated with respect to suspension point 1. This implies reducing matrix $R$ in Eq. (13) from size $(7 \times 7)$ to $(7 \times 6)$ and then solving for the length changes in a least-squares sense. The length changes computed thus are then translated vertically to minimize the amount of manual adjustment at each point and to stay within the range of the turnbuckles.

The suspension forces $s_F$ that are predicted by the computational model when the suspension cables are adjusted a) in the fully deployed and b) in the fully retracted configuration, that is,

$$s_F = s_M + \Delta s$$

(21)

are shown in Fig. 8. As a comparison, Fig. 9 shows the forces that were measured on our model after actually making the required adjustments.

The theoretical predictions and measurements are in good agreement throughout deployment, thus showing that the model correctly describes the behavior of this shape-varying structure and its interaction with the gravity compensation system. In the fully deployed and retracted configurations, for which the adjustments were made, the agreement of both experiment and theoretical predictions with the required suspension force distributions is particularly satisfactory. The adjustment has also improved the suspension force distribution during the middle part of the deployment, but not at the respective other end.

Discussion

For every particular deployment configuration, the system consisting of array and suspension exhibits different behavior and properties, demanding varying adjustment throughout deployment. Also,
initial imperfections and misalignment of the hinges and panels, end support, supporting rails, and the support framework affect the necessary adjustments at any deployment angle $\alpha$. This becomes most apparent in the two end configurations, where the structure is relatively stiff. Here, improving the force distribution at one end has the effect of making it worse at the other end.

Figure 10 shows the theoretical predictions for the suspension force distribution that could be achieved with a simple open-loop, active suspension system that applies the required length adjustments both in the fully deployed and fully retracted configurations and, in between these configurations, applies linearly interpolated adjustments. Even such a simple adjustment achieves suspension forces that are remarkably close to the required distribution. In practice, though, this type of variable adjustment cannot yet be tested on the existing experimental setup. Similar good agreement between computational predictions and experimental data, however, can be expected, as exhibited in the cases where adjustment is only possible at either end of deployment.

Conclusions

In conclusion, this study has established a methodology for modeling the interaction between deployable structures and gravity compensation systems. It has been shown that the effects of adjustments to the suspension system can be accurately predicted and that some improvements in the distribution of forces applied by the system to the structure can be achieved by means of a single adjustment of the suspension system. However, to fully optimize the performance of the suspension system, active adjustment techniques will be required, allowing for variable adjustment while the structure moves. An even more advanced, closed-loop control algorithm may be needed to simulate zero gravity with respect to the dynamic behavior of the structure. Work on these topics has begun.

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References


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