Estimation of the failure-free operation for deployment of transformable space structures

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Abstract. High reliability is required for the deployment of the transformable structures as this process is crucial for successful spacecraft mission. Computational evaluation of the reliability parameters for the deployment is of a great importance as it is not possible to fully reproduce the real conditions of outer space during ground-based tests. The presented approach to estimate the probability of failure-free deployment is based on the condition of exceeding the driving torque over the resisting moment at each of the angular positions of the structure. The approach was used to compute the reliability functions for deployment of a space reflector. The calculations were carried out based on kinematic and dynamic analysis of the structure.

1. Introduction

The development of transformable space structures demands the solution of a number of technical and mechanical problems conditioned by the uniqueness of objects and the combination of conflicting requirements to increase overall dimensions and provide a high rigidity under strict weight limitations on the power frame [1-3]. As a rule, such structures are delivered to space orbits within a space vehicle in a transportation state being folded in compact volume. Brining them to the operating position is associated with the implementation of the deployment process. High requirements for the probability of failure-free operation are imposed on the transformable structures as the deployment process belongs to dynamic operations that directly affect the successful execution of a spacecraft’s mission. Ground testing is mandatory for the deployment process. However, the ground-based tests are limited as it is not possible to fully reproduce the real conditions of the deployment in outer space. Therefore, evaluation of the reliability parameters for the deployment of mechanical systems is of a great importance [4, 5].

Reliability of the deployment of transformable structures from the transportation to operating position is determined by the functioning of mechanisms when turning to the latching position. The failure-free operation is satisfied through the fulfillment of the equilibrium condition in the case of rotational motion [3, 6]:

\[ M_d(\varphi) - M_r(\varphi) = 0 \quad \forall \varphi \in [\varphi_i, \varphi_f], \]

where \(M_d\) – is the actual value of the drive torque; \(M_r\) – is the actual values of the moment from resistance forces on the motion path of the angle bar; \(\varphi_i, \varphi_f\) – are the initial and final angle, respectively.

The drive torque is produced by the deployment actuators such as tape-springs, pneumatic piston, electromechanical devices etc. The resisting forces are generated by friction, loads from gravity etc. In
the general case, the deployment is possible provided that the inequality of moments is observed (the sign of the functional dependence on the rotation angle is omitted hereinafter):

\[ M_d > M_r \] (2)

The probability of failure-free deployment \( P_d \) in this case is defined as the probability of meeting the operating conditions (2) at each of the angular positions of the structure:

\[ P_d = P(M_d > M_r) \] (3)

In the domestic practice of design for single-used mechanical devices of rotary type, the condition of exceeding the drive torque over the moment from resistance forces on the turning path of the structure is generally defined in the following form [5, 6]:

\[ M_d > k \cdot M_r \] (4)

where \( k \) is the margin of driving torque.

The margin expresses the idea of necessity to separate the average values of the driving torque and the resistance moment in order to increase the reliability. Torque or force margins are similar to safety factors used in structural design and relate to the ratio between the driving torque (force) and resistance moments (loads) [7]. By established practice, the margins assigned for driving torques (forces) in movable mechanical units (hinges, friction pairs, etc.) are no less than 100% (the ratio 2:1) to the worst-case value of the moments from resistance forces. This rule was applied in the Russian space engineering industry before the implementation of joint projects with European partners aimed to development of communication satellites, the first of which was Sesat (Siberian-European Satellite). Under the influence of the requirements from European partners, the margins of driving torques began to be assigned at least 200% (ration 3:1), although the ratio 2:1 was used in some cases, depending on the dynamics of deployment processes and available (confirmed) experience. Choice criteria and values of margins for driving torques (forces) have not yet been standardized neither by industrial nor state standards in Russia.

It should be noted that in the United States there is a somewhat different approach. The first standard MIL-A-83577 issued in 1975 provided for the presence of static margins for driving moments and forces in the movable mechanical units of spacecraft. The required margins in the specified standard were recommended to be assigned in the ranges from 100% to 200% to the worst case of resistance moments or forces. In cases of weight restrictions and available practice, it was allowed using the margins less than 100%. Kinetic torque and force margins are defined as follows:

\[
\text{Kinetic Torque Margin} = \left[ \frac{\text{Drive Torque} - \text{Resisting Torque}}{\text{Torque Required for Acceleration}} - 1 \right] \times 100
\] (5)

\[
\text{Kinetic Force Margin} = \left[ \frac{\text{Drive Force} - \text{Resisting Force}}{\text{Force Required for Acceleration}} - 1 \right] \times 100
\] (6)

At present, standards AIAA S-114-2005 (issued by American Institute of Aeronautics and Astronautics, AIAA) and NASA-STD-5017 (National Aeronautics and Space Administration, NASA) substitute MIL-A-83577B and specify general requirements for the testing of movable mechanical units. In AIAA S-114-2005, the kinetic margins specified in (5) and (6) are named as dynamic margins.

The maximum value of the moment from the resistance forces \( M_r^{\max} \) is unknown in advance, since it is determined by the conditions and modes of the structure operation in outer space. However, the actual values of the resistance moment have a pronounced dependence on the ambient temperature. Coefficients of sliding friction in friction pairs and the stiffness of transit electric cables, as a rule, increase with changing ambient temperatures from \( T_{\text{warm}}^{\max} \) to \( T_{\text{cold}}^{\max} \). The maximum actual value of the
The resistance moment $M^\text{max}_{r,\text{actual}}$ can be determined as a result of ground tests of the rotary structure with transit electric cables at an abnormally low temperature $T^\text{max}_{\text{cold}}$ corresponding to the operating conditions. If the maximum value of the moment from resistance forces is taken as the maximum value at the abnormally low temperature:

$$M^* = M^\text{max}_{r,\text{actual}}(T^\text{max}_{\text{cold}})$$ (7)

then the maximum value of the resistance forces moment in the formula (4) can be determined by the relation:

$$M^\text{max}_r = k \cdot M^\text{max}_{r,\text{actual}}(T^\text{max}_{\text{cold}})$$ (8)

The influence of various technological and operational factors, including temperature, can lead to fluctuation of the driving and resisting moment values. Assume that this fluctuation is defined by the Gauss probability functions with given expected values and coefficients of variation (standard deviations). Taking into account the foregoing, the expression (3) can be written in the following form:

$$P_k = \Phi \left\{ \frac{\mu_d - \mu_r}{\sigma_d - \sigma_r} \right\} = \Phi \left\{ \frac{k - 1}{\sqrt{V^2/k^2 - V^2}} \right\}$$ (9)

where $\mu_d, \mu_r$ – are the expected values of the driving moment and the moment of resistance; $\sigma_d$ and $\sigma_r$, $V_d$ and $V_c$ are the corresponding standard deviations and coefficients of variation; $k$ is the torque margin.

The above approach was used to compute the reliability functions for deployment of a space reflector. The calculations were carried out, based on kinematic and dynamic analysis of the structure. The results of the analysis included the forces and moments in kinematic pairs, velocities, accelerations, trajectories, driving and resisting torques. The calculation scheme is presented on the figure 1. The displacement rate of the input link of 4.23 mm/s was taken to ensure an average angular velocity of the radial ribs of about 0.03 rad/s, which corresponded to 30 seconds of deployment time.

![Figure 1. Kinematic scheme of the reflector deployment mechanism in the operation position: 1 – connection of the input link to the base; 2-10 – pivot points](image-url)
The reliability functions calculated for the range of $V_r$ from 0.08 to 0.12 and $V_d = 0.10$ to 0.15 are presented on figure 2. As seen in figure 2, the deployment reliability does not fall below 0.99 even for maximum coefficients of variation. The results of ground tests on deployment of reflectors and solar arrays [3, 6] revealed that the coefficient of variation $V_d$ does not exceed 0.12, while $V_c$ does not exceed 0.08.

![Figure 2. Projected reliability functions: 1 - $V_r = 0.08$; 2 - $V_r = 0.12$](image)

Assuming that the torque margin equals 3.0, according to (9) one gets the probability of failure-free deployment above 0.999999. At $k = 2.0$, the probability of failure-free deployment still remains at a level above 0.99999. However, if we examine the available statistics on failure of deployment of the transformable mechanical systems on orbit, the above estimates are overly optimistic.

The history of space launches shows, the failures of deployment and fixing mechanisms are not such rare events. In the review [8] the exploitation of 449 European and American geostationary satellites for the period from January 1995 to October 2008 was analyzed. The given data demonstrate that the combined share of failures of mechanisms and structures (including systems of deploying) amounted to 2.4% of the total number of failures.

Statistical information on the implementation of 236 missions on the orbital stations Salyut-4, -6, -7, the Mir orbital complex and the ISS for the period 1974-2012 was presented in [9]. It was noted that during 130 spacewalk performed, about 4% of the total number of operations were caused by the need to act upon the undeployed structures. Summarizing these data yields the average probability of failure $Q_m$ of $1.698 \cdot 10^{-2}$ per spacecraft. The average probability of failure at deployment of transformable space structures in 2009-2016 amounts to $1.072 \cdot 10^{-2}$ per spacecraft.

Taking into account these statistical estimates and the results of calculations based on the above scheme, the average probability of failure-free deployment comes to 0.9892. Since the analysis did not include all the failures, the estimate obtained can be considered as the lower probability level for failure-free deployment of space transformable structures.

Thus, the proposed model considering the features of kinematic and dynamic analysis can be used to estimate the reliability functions for the transformable space structures.

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