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Deployment Reliability Prediction for Large Satellite Antennas Driven by Spring Mechanisms

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A method to predict the deployment reliability of large satellite antennas is proposed. This method uses torque distributions of deployment mechanism constituents. Deployment reliability is defined as the probability that the driving torque distribution is greater than the resistance torque distribution. The prediction method is applied to the deployable antennas for the Japanese Engineering Test Satellite VI (ETS-VI) scheduled for launch in 1994. The torque properties of the mechanism parts are found to be dependent on temperature, but they appear to be independent of deployment velocity. The bearing resistance torque appears to increase as the thrust force increases. However, the increase in torque is very small. Therefore, only temperature dependence is considered in the deployment reliability prediction. The torque measurements show that the torque distribution of the mechanism parts can be fitted with a normal distribution. The torque distributions of the mechanism, obtained by the torque distribution sum of its parts, can also be considered a normal distribution. Using these torque distributions, the deployment reliability is calculated at three different temperatures. Deployment reliability of 0.9999999 is predicted at 23°C in a vacuum. The validity of the prediction method is shown by comparing the deployment test results with the predicted ones obtained from the measured part torque characteristics.

Nomenclature

E_D = driving energy, N·m·rad
E_F = resistance energy, N·m·rad
I = moment of inertia of an antenna about a hinge line, N·m·s^2/rad
K = spring constant, N·m/rad
R = deployment reliability
T_D = driving torque of the deployment mechanism, N·m
$\hat{T}_D$ = driving torque distribution of the deployment mechanism, N·m
T_F = resistance torque of the deployment mechanism, N·m
$\hat{T}_F$ = resistance torque distribution of the deployment mechanism, N·m
T_I = initial driving torque of the deployment mechanism, N·m
κ = parameter defined by Eq. (8)
θ = deployment angle, rad
$\dot{\theta}$ = deployment velocity, rad/s
$\ddot{\theta}$ = deployment acceleration, rad/s^2
μ_D = average of deployment torque, N·m
μ_F = average of resistance torque, N·m
σ_D = standard deviation of deployment torque, N·m
σ_F = standard deviation of resistance torque, N·m

Introduction

A LARGE satellite antenna provides the high antenna gain that is indispensable in economical satellite communication systems. In large antennas, however, size is a serious problem because the shroud diameter of the launch vehicle is limited. This problem can be solved by using deployable antennas, and it is for this reason that they have been extensively studied in recent years[1–3] and that antenna concepts and technical difficulties such as thermal deformation and weight reduction have been receiving increased attention.[4,5]

One of the major design considerations is antenna deployment. Redundancy in a large antenna is not possible for reasons of weight. This implies that the failure of antenna deployment results in the inability to accomplish the satellite's mission objectives. Because we have very little knowledge of deployment anomalies, it is important to confirm design validity from various aspects. Several papers deal with dynamic phenomena from initial release to latchup[6,7] and the torque properties of mechanical parts such as bearings.[8] Deployment test methods are also being studied to predict on-orbit deployment properties by compensating for gravity and air effects.[9]

For complete deployment of the antenna, deployment mechanisms have been designed to provide an adequate torque margin relative to the worst case in orbital environments.[10] The driving torque and the resistance torque are treated as definite values in such a mechanical design. It is unavoidable that a large torque margin is required to secure the antenna deployment. This makes it difficult to perform antenna deployment tests, because structural strength becomes critical at latchup. Although testing builds a higher level of confidence and validates designs, ground tests with an antenna are limited to the confirmation of the torque margin.

Reliability has been used as an indicator of a successful satellite mission, so it is reasonable to express the success of antenna deployment in terms of reliability. In reality, there are variations in the driving torque and the resistance torque.[11] This paper proposes a method to predict the deployment reliability of satellite antennas driven by spring mechanisms. In this paper, first, the reliability prediction method is described. Second, this method is applied to deployable antennas for the Japanese Engineering Test Satellite VI. Finally, the validity of this method is demonstrated by comparing the predicted deployment properties with the measured ones.

Prediction Method for Deployment Reliability

Fulfilling the function of antenna deployment depends on the relationship between the driving and resistance torques of the deployment mechanisms. This relationship can be derived from deployment dynamics. Assuming that an antenna can be considered a rigid body during the deployment, the undamped dynamic equation of motion is given by

$$I\ddot{\theta} + K\theta = T_I - T_F \tag{1}$$

An antenna must have positive acceleration from its initial release to latchup to ensure successful antenna deployment. From Eq. (1), we obtain the deployment acceleration as

$$\begin{aligned} I\ddot{\theta} &= T_I - K\theta - T_F \\ &= T_D - T_F \end{aligned} \tag{2}$$

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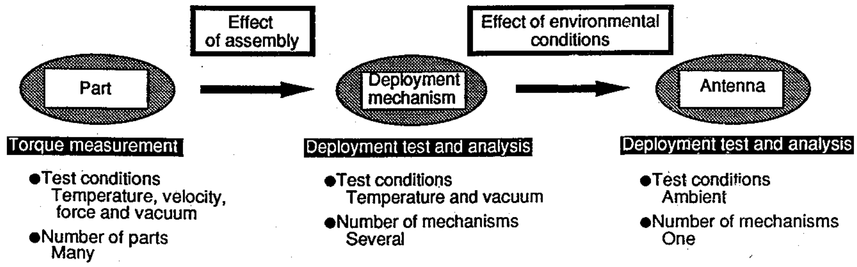

Fig. 1 Test and analysis performed at the part, mechanism, and antenna levels for deployment reliability prediction.

The following torque relationship can be deduced from the positive acceleration condition:

$$T_D > T_F \tag{3}$$

The other condition can be derived from energy equation given by

$$I\dot{\theta}^2/2 = (T_I\theta - K\theta^2/2) - T_F\theta \tag{4}$$

where the first and second terms of the right-hand side show the driving energy and resistance energy, respectively. Because the left-hand side of Eq. (4) is always positive, we have

$$E_D > E_F \tag{5}$$

Equations (3) and (5) indicate the necessary and sufficient conditions to insure full deployment of antennas. Therefore, it is proper to use these conditions for a deployment reliability definition. It should be noted that the torque relationship is securer than the energy one in deployment reliability considerations, because the deployment velocity increases throughout the deployment. Therefore, the torque relationship was chosen to define the deployment reliability.

Up to now both the driving torque and the resistance torque have had definite values. However, there are variations in the driving and resistance torques owing to manufacturing tolerance, materials variability, and quality control. It is appropriate to treat them as random variables. Accordingly, a statistical approach for predicting deployment reliability is implemented. The deployment reliability can be defined as the probability that the driving torque distribution is greater than the resistance torque distribution. The deployment reliability R is given by

$$R = \text{Prob}(\hat{T}_D > \hat{T}_F) \tag{6}$$

In this prediction method, the torque distribution of the deployment mechanisms must be identified. It is inadvisable to obtain torque distribution data from mechanism and antenna deployment tests for cost and time savings. This paper proposes estimating the mechanism torque as the sum of the measured torques of all the mechanism parts that constitute the deployment mechanisms. The flow of the test and analysis shown in Fig. 1 is used in this study. Torque measurement is performed only at the part level, because that results in fewer limitations on test conditions and the number of test specimens. Deployment properties are analyzed and measured at both the mechanism and antenna levels to confirm the effect of the assembly on torque properties. It is reasonable to determine the torque properties of the deployment mechanism by part torque characteristics, because deployment dynamics depends on those characteristics. Deployment tests are necessary to evaluate the effects of such environmental conditions as vibration, acoustics, and shock. Parameters in the equation of motion, which is Eq. (1) with several additional terms such as the setup error in the ground test, are identified by fitting the equation to the measured deployment properties[9] (e.g., deployment angle-time and deployment velocity-time relationships). On-orbit deployment properties are calculated using the parameters after removing the effects of the ground deployment test. To confirm the validity of the deployment reliability prediction proposed, these results are compared with the deployment properties obtained from the measured part torque data. This method has never been applied to mechanisms before, because operating conditions may change and part characteristics are different from those in the mechanisms. Thus, we have to consider torque changes due to assembling parts into a mechanism. Therefore, a verification process is required to demonstrate the effectiveness of this method.

The prediction method proposed was applied to the deployable antennas for the Japanese Engineering Test Satellite VI (ETS-VI).

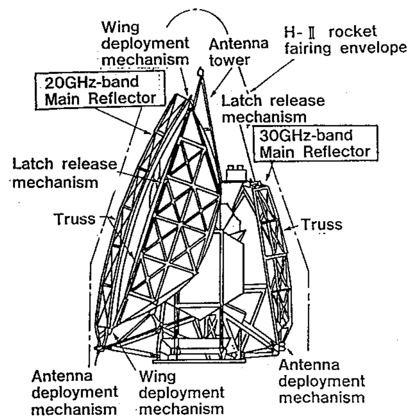

Fig. 2 ETS VI antenna in launch configuration.

Antenna Description

The antenna configuration for the ETS-VI is shown in Fig. 2. The antenna subsystem includes a 20 GHz-band antenna and a 30 GHz-band antenna. The aperture diameter is 3.5 m for the 20 GHz-band antenna and 2.5 m for the 30 GHz-band one. The antennas are stowed during launch to comply with the shroud diameter limitations of the H-II rocket. They are fixed on an antenna tower and deployed to their on-orbit configurations using deployment mechanisms. Antenna deployment is activated by pyrodevices and spring force. The 20 GHz-band antenna is divided into three parts: center, right, and left wing. The deployment of the antennas is accomplished in three stages. First, the right and left wings of the 20 GHz-band antenna are deployed simultaneously by wing deployment mechanisms (WDM). The deployment angle of these two wings is 1.22 rad. Next, the center wing is deployed with antenna deployment mechanisms (ADM). The deployment angle of the antenna is 1.27 rad. Finally, the 30 GHz-band antenna is deployed by the ADM. The deployment angle is 1.34 rad.

The ADM and WDM consist of two identical hinge mechanisms, each with a ball bearing, a helical spring, an arm, a latch assembly, a shaft, and a chassis. The ADM of the 20 GHz-band antenna is indicated in Fig. 3. The arm is connected to a shaft and interfaces with the antenna. A helical spring provides the driving torque. One end of the spring is fixed to the arm, and the other end is attached to the chassis. The latch assembly is used to limit deployment movement in the specified position. When deployed, the latch pin comes in contact with the pair of latch arms mounted on the side of the chassis. This pin is fixed by ratchets to prevent back travel. Bearings, springs, ratchets, and the latch pin are lubricated with MoS_2 solid lubricant film to minimize resistance torque.

There are thermocouples on the antenna to measure the temperature in orbit. An accelerometer is also installed to measure the acceleration response during antenna deployment and satellite ma-

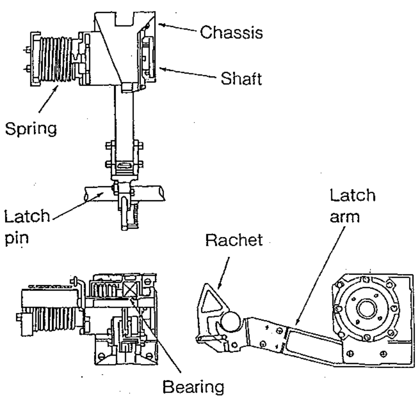

Fig. 3 Antenna deployment mechanism.

neuvers. The electrical cables of these sensors are connected with telemetry and command units through the ADM. The flexure of electrical cables caused by antenna deployment generates resistance torque (harness torque), which depends on the electrical cable routes. Therefore, several groups of electrical cables were fixed at appropriate locations on the ADM to minimize the harness torque and to get good repeatability.

Torque Properties of Mechanical Parts

The torque margin requirement should be established by considering torque variations in the worst case. However, the lack of torque variation data makes it difficult to establish the requirement. Therefore, detailed tests were performed on constituent parts of the deployment mechanism such as bearings, latch mechanisms, harnesses, and springs. Because of space limitations, this section deals mainly with the ADM data on the 20 GHz-band antenna.

Test Conditions

The ADM is sensitive to the environmental conditions imposed during launch and on orbit. Torque measurements were conducted for the parts of the ADM to confirm torque distribution and variation in torque properties due to environmental conditions. The test conditions are shown in Table 1. Temperature and vacuum were selected as environmental factors, and the deployment velocity and the thrust force of the bearing as operating conditions. Care was taken in setting up the test of each part. The difference in torque measurement between the mechanical parts and the ADM affects test results. Therefore, the test setup was established to simulate the actual condition of the part assembled into the ADM. For example, for the harness torque measurement, cables were installed across the hinge to simulate the resistance torque that cables would produce.

Measurement temperatures were selected on the basis of the qualification temperature range of −90 to 100°C, which ensures a successful operation. Three different deployment velocities in torque measurement were chosen, based on the maximum velocity obtained from the deployment analysis results using the part torque measured in a pretest. The thrust force applied to the bearings was determined by antenna thermal deformation analysis, because thermal deformation generates the maximum thrust force. Three different thrust forces were selected from the analytical results.

Test Results

The measured part torque in a vacuum condition versus temperature is shown in Fig. 4. Variation in the bearing resistance torque is less than 0.05 N·m in the temperature range of −90 to 100°C. Therefore, the temperature effect on the bearing resistance torque is negligible. On the other hand, the driving, latch, and harness torques vary with temperature, and they have a tendency to increase as temperature decreases. The increase in the driving torque in the low-temperature range is due to variations in lubricant properties and the coil diameter of the spring. The variation in driving torque is large in the temperature range of 23 to 100°C.

The dependence of the deployment velocity on torque properties is much less than its sensitivity to temperature changes, as shown in Fig. 5. However, Fig. 6 shows that the thrust force appears to affect the deployment-velocity dependence of the bearing resistance torque. Therefore, the effect of the deployment velocity will not be neglected for the bearing resistance torque when the thrust force of the bearing is large. Fortunately, the torque variations due to the thrust force can be neglected because the maximum deployment velocity of 0.006 rad/s predicted in this study is very small. Therefore, only temperature dependence is to be considered in the deployment reliability prediction. The velocity profile during deployment is expressed as a sine function. An antenna has different deployment-velocity values at different deployment angles. Thus, deployment-velocity independence of torque properties simplifies the reliability prediction, and also eliminates some trouble in torque data acquisition.

Table 1 Measurement conditions for constituent parts of deployment mechanisms

Item	Temperatures, °C	Angular velocity, 10^{-2} rad/s	Thrust force,[a] N
20ADM[b]	−90, 23, 100	0.6, 3.6, 6.4	10, 20, 30
20WDM[c]	−90, 23, 100	3, 28, 105	10, 20, 50
30ADM[d]	−90, 23, 100	20, 40, 150	49, 74

[a]Applicable to bearings only.
[b]20GHz-band antenna deployment mechanism.
[c]20GHz-band antenna wing deployment mechanism.
[d]30GHz-band antenna deployment mechanism.

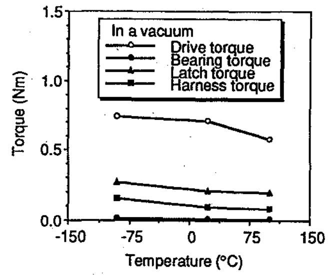

Fig. 4 Variation in torque with temperature (thrust force of bearing = 20 N).

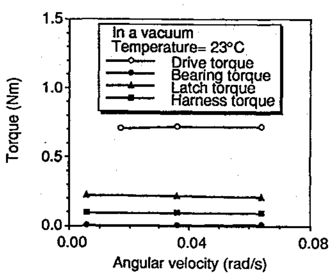

Fig. 5 Variation in torque with angular velocity (thrust force of bearing = 20 N).

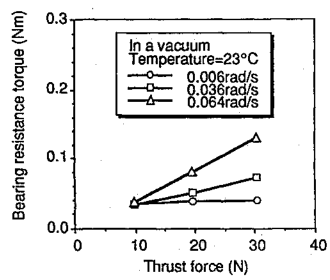

Fig. 6 Variation in bearing resistance torque with thrust force.

Deployment Reliability

Torque measurement of the mechanical parts shows that the torque varies and that the torque distribution can be fitted well with a normal distribution.[11] Figure 7 shows the torque distribution pa-

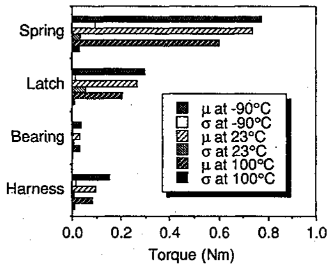

Fig. 7 Torque distribution of mechanical parts in a vacuum (μ: average, σ: standard deviation).

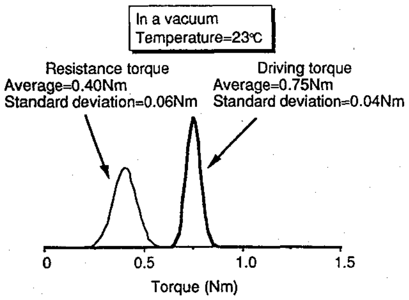

Fig. 8 Torque distribution of the ADM.

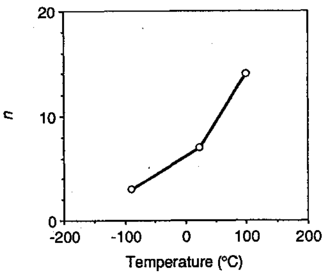

Fig. 9 Variation in deployment reliability with temperature in a vacuum.

rameter for each mechanical part. These parameters were obtained using torque data measured in a vacuum. The average torque of each part decreases with increasing temperature. As part torque distributions are independent of each other, the ADM torque distribution can be expressed as the sum of the part torque distributions. Figure 8 shows the driving and resistance torque distributions of the ADM at 23°C in a vacuum. The peak value is in inverse proportion to the standard deviation. The deployment reliability can be expressed using average and standard deviation as

$$R = 1 - \frac{1}{\sqrt{2\pi}} \int_k^\infty e^{-t^2/2}\, dt \tag{7}$$

where

$$k = \frac{\mu_D - \mu_F}{\sqrt{\sigma_D^2 + \sigma_F^2}} \tag{8}$$

Let R denote the deployment reliability expressed as

$$R = 0.9_n \tag{9}$$

where n is the number of consecutive nines. Using the torque distribution of the ADM, the deployment reliability was calculated at three different temperatures. Figure 9 shows the predicted results. The value of n is 3 at −90, 7 at 23, and 14 at 100°C. As stated in the "Test Results" section, all the torques decrease with increasing temperature. However, the deployment reliability increases with increasing temperature because the decrease in the resistance torque is larger than that in the driving torque as the temperature increases.

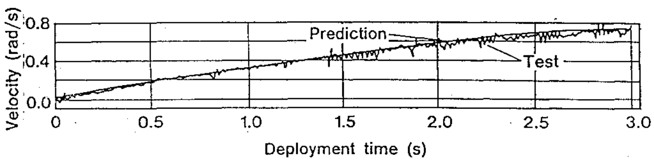

Fig. 10 Comparison with predicted and measured velocity for the WDM.

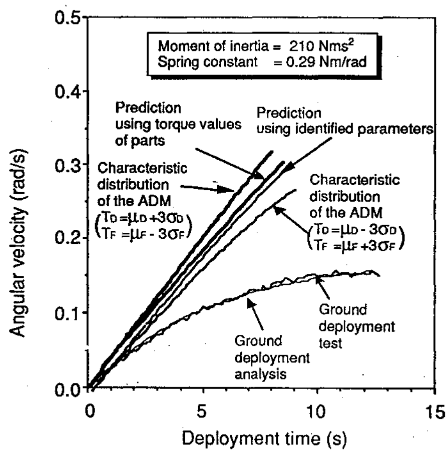

Fig. 11 Comparison with predicted and measured velocity in antenna deployment.

Verification of the Prediction Method

In predicting deployment reliability, a supposition was used to estimate the driving and resistance torque of the mechanisms as the sum of measured part torques. There were two reasons for this. One was that the part torques are nearly normally distributed and the torque distributions are independent of each other. The other was that there will be a slight difference in each part torque before and after the part is incorporated into the mechanism. It is necessary to demonstrate the validity of the supposition. It is difficult, however, to identify the torque of each part assembled into the mechanism. If a part torque varies in the process of assembly in the deployment mechanisms, that should affect deployment properties. We therefore examined variations in the deployment properties to confirm the validity of the supposition.

Analytical deployment properties were compared with test results on the mechanisms and antenna. Figure 10 shows the comparison between the measured and predicted deployment velocities in the WDM deployment test. This test was conducted at 23°C in a vacuum. The predicted velocity profile was obtained using the measured torque characteristics of each part. The two velocity profiles are in good agreement. This shows that changes in the torques of parts due to assembly are small. Figure 11 shows the deployment velocity in the antenna deployment test. The weight of the antenna was offloaded by several counter weights to cancel the gravity effect that generates unwanted torque. Parameters in the equation of motion were so identified as to fit the velocity curve in a ground deployment test. Each parameter was checked by comparing it with the part torque and disturbance torque calculated from the setup error in the test. The on-orbit deployment velocity was found by removing the parameters representing the gravity and air effects peculiar to the ground deployment test. This velocity is much closer to the velocity calculated from the part torque data. Therefore, it can be concluded that the supposition is valid.

Conclusion

A method to predict the deployment reliability of large satellite antennas is proposed. This method uses the torque distribution of deployment mechanism components. Deployment reliability is defined as the probability that the driving torque distribution is greater than the resistance torque distribution of deployment mechanisms. The prediction method is applied to the deployable antennas for the Japanese Engineering Test Satellite VI scheduled for launch in 1994. The following conclusions are obtained.

1) Torque properties of mechanical parts are dependent on temperature, but they appear to be only slightly dependent on deployment velocity. The bearing resistance torque appears to increase as the thrust force increases. However, the torque increase is very small in the force range considered in this study. Therefore, only temperature dependence is considered in the deployment reliability prediction.

2) The torque distribution of each mechanical part is very similar to a normal distribution.

3) A supposition is used to estimate the driving and resistance torque of mechanisms as the sum of the measured part torque. The validity of this supposition is demonstrated by comparing the deployment test results with the predicted ones obtained from the measured part torque characteristics.

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