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LOCK-UP FAILURE OF A FOUR-BAR LINKAGE DEPLOYMENT MECHANISM

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ABSTRACT

A successful failure investigation of a four-bar linkage deployment mechanism has been performed. Possible failure causes such as the mismatch of material coefficient of thermal expansion (CTE), excessive hinge friction, limit switch interference, and thermal-gradient-induced resistive preload were investigated and are discussed. The final conclusions and corrective actions taken are described. Finally, valuable lessons learned during the investigation are discussed.

INTRODUCTION

Four-bar linkages have been used extensively in aerospace mechanisms to transmit torque, motion, and power, and/or to transform one type of motion or force to another (e.g. linear to rotary). The popularity of four-bar mechanisms among aerospace mechanism designers is due to their unique characteristics including (1) the rapid increase in their effective gear ratio (mechanical advantage) as the linkage approaches the top-dead-center toggle position and (2) the ability of a four-bar linkage to provide positive lock-up at the end of travel without the increased resistive torque associated with latching mechanisms.

The work described in this paper was performed in response to a functional failure of a panel deployment system which employs a set of eight four-bar linkages to transmit torque and to provide positive lock-up at the end-of-travel (Figures 1 and 2). During a gravity off-loaded cold thermal-vacuum deployment test, three of the four outboard hinge four-bar linkages failed to lock-up into their over-center position after the panel had fully deployed. Review of high-speed film showed that the input (drive) links of the three outboard four-bar linkages that had failed had come within approximately 5 to 10 degrees of their top-dead-center positions (see Figure 3). After the test, as the chamber

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temperature was increased, each of the four-bar mechanisms that had failed to lock-up at -100°C moved into their over-center positions by the time the chamber temperature had reached 0°C - 5°C. The four inboard hinge four-bar linkages, which had functioned properly during the cold thermal-vacuum deployment test and are of a different design than the outboard linkages, are not discussed in this paper.

MECHANISM DESCRIPTION

The panel deployment system is made up of a set of four spring-driven four-bar linkages that were designed to provide a redundant deployment system for a two-panel configuration (see Figure 1). There are two inboard and two outboard hinges. Each hinge has two four-bar linkage mechanisms which provide redundant drive torque sources. The individual spring-driven four-bar mechanism of the outboard hinge consists of a helical torsion spring, a monoball main hinge bearing, and a four-bar linkage. The outboard four-bar linkage is formed by a drive (input) link, a turnbuckle link, and the structural frame of the inboard and outboard panels (see Figure 2). The driving or input torque of the torsion spring is applied to the input link and is transmitted through the linkage to the main (output) hinge. The output torque about the main hinge causes the outboard panel to rotate 180° with respect to the inboard panel, from its stowed position to its deployed position.

The four-bar linkage is designed so that it reaches its top-dead-center position when the outboard panel has fully rotated (deployed) from the inboard panel. As the linkage moves beyond it top-dead-center position the input link hits the input link stop which arrests the deployment. The high mechanical advantage of the input link just beyond the top-dead-center position prevents any back-driving of the input link. In addition, there is a hard stop between the inboard and outboard panels that (1) helps absorb the lock-up load forces and (2) provides a bearing surface between the inboard and outboard panels through which a "locking" preload is applied to eliminate any backlash in the joint after deployment (see Figure 2).

During assembly, the inboard and outboard panels are aligned to each other (coplanar in their deployed configuration) by adjusting the hard stop between the inboard and outboard panels. The next adjustment involves setting the over-center distance of the four-bar linkage (see Figure 4). This adjustment is performed by adjusting the input link stop. The over-center distance is set nominally to 0.762 mm

(0.030 inch). Finally, the four-bar linkage turnbuckle is adjusted such that the mechanism preloads the outboard panel into the inboard panel in order to eliminate hinge backlash while still being able to travel over-center and lock-up.

INITIAL FAILURE INVESTIGATION

Initially, the failure investigation focused on the most probable causes which included (1) possible mismatch of the linkage material's coefficient of thermal expansion which could cause binding in the mechanism pivots, (2) possible excessive hinge friction torque of a monoball bearing which had caused a deployment failure in a previous cold deployment test, or (3) excessive actuation force produced from mechanically actuated limit switches which are used to verify four-bar over-center motion.

CTE Mismatch

An initial review of the linkage design revealed that the material of the linkage pins was different than that of the linkage itself. Because of the difference in their CTEs, suspicion arose that interference between the linkage and the pivot pins had caused the mechanism to seize. However, the possible mismatch of the linkage material's CTE was eliminated as a failure cause after a review of the design showed that the clearance between the linkage pins and links was more than sufficient for the temperature range of the test. The analysis included the differential expansion of the pins and links due to their different material CTE, worst-case cold bulk temperature change and temperature gradients between the pin and link. In addition, analysis of the friction torque that would be present if the pin-link interference did occur, showed that the maximum possible level of linkage hinge friction (0.2 N-m) was well below the drive capabilities of the input torsion spring after having been transmitted through the four-bar linkage (>5 N-m).

Excessive Hinge Friction

In an earlier deployment test of the panel, the main hinge monoball bearing had caused a deployment failure of the panel. Very high monoball friction, caused by the differential growth of the steel monoball and its aluminum housing, had caused the deployment motion of the panel to stop (at approximately 120°) before it reached its deployed position (180°) during cold temperature deployment. As a result, the monoball bearing was immediately suspected as the cause of the recent failure. However, after reviewing high-speed camera data of the deployment, the possibility that excessive monoball bearing torque had caused the failure was eliminated. The camera data clearly showed that the panel deployment motion proceeded in a normal fashion and within the expected deployment time, which proved that the hinge friction torque was no greater than in prior successful deployments. In addition, the monoball bearing design flaw[1] that had caused the previous deployment failure had since been corrected.

Limit Switch Resistive Force

To verify four-bar mechanism lock-up, a limit switch had been incorporated into the mechanism design. When the linkage moves over-center, the input link actuates the spring-loaded limit switch (see Figure 4). The resistive spring force applied to the input link from the limit switch is not insignificant and, as a result, during assembly, special care is taken to properly adjust the limit switch so that it does not interfere with the over-center motion of the linkage. Because the panel deployment failure involved the failure of the four-bar linkage to move over-center, a possible misadjustment of the limit switches was suspected as the cause of the failure. However, the limit switch actuation force was disproved as the cause of the failure when an additional cold vacuum deployment test, with the limit switches adjusted so as to minimize the limit switch resistive spring force, also failed. In addition, the limit switch resistive spring torque (<0.1 N), measured after the limit switches were readjusted, was much less than the measured deployment spring force[2] (>3.0 N) and, therefore, would

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[1] Epoxy that was applied to the threads on the exterior surface of the bearing outer race acted as a shim when exposed to cold thermal vacuum testing and caused the bearing to bind.

[2] The limit switch resistive torque and the available spring torque were measured about the input link pivot axis.

not be large enough to prevent over-center motion of the four-bar linkage.

DETAILED FAILURE INVESTIGATION

With the most probable failure causes eliminated, the investigation focused on the conditions of this test that might make it different from previous successful cold thermal vacuum tests. The investigation focused on what mechanism assembly adjustments were performed and how the cold thermal vacuum environment could affect the mechanism's behavior.

Linkage Kinematics

During assembly, the linkage is adjusted such that the hinge line of the panel is preloaded against a hard stop in its deployed position to prevent relative motion of the inboard and outboard panels (see Figure 4). As the linkage approaches the top-dead-center position, the hard stop on the outboard panel is preloaded against the end of the inboard panel by the spring force. The preload reaches a maximum at the linkage top-dead-center position. As the four-bar continues past top-dead-center to its final over-center position, the outboard panel backs away from the inboard panel because of the rocker-crank kinematic property of the four-bar mechanism [1], and the preload in the hard stop is reduced (see Figures 5 and 6). It is the reduced preload in the over-center position that prevents relative motion between the inboard and outboard panels. The assembly adjustment instructions require that the preload be adjusted such the outboard panel is securely preloaded against the inboard panel while still allowing the input link to be driven over-center by the deployment spring. As a result, the level of the preload force is not measured and is set purely by feel.

Effect of Linkage Thermal Gradients

During the cold thermal-vacuum test, the orientation of the cold wall in the thermal vacuum chamber creates a non-uniform temperature distribution in the four-bar mechanism links and surrounding hardware. The total gradient across the mechanism was approximately 10°C which was measured during the cold deployment test. The change in the four-bar geometry, brought on by the differential thermal expansion of the mechanism, modified the kinematic properties of the linkage such that the outboard hard-stop prematurely preloaded against the inboard panel (see Figure 7). As a result, an extremely high resistive torque develops as the four-bar mechanism approaches top-dead-center. The magnitude of this resistive torque is dependent upon the temperature gradient created as well as the stop stiffness of the four-bar mechanism. The stop stiffness depends on the instantaneous geometry of the linkage, the local stiffness of the mechanism links and pins, and the stiffness of the preload hard stop (see Figure 8). Note that the relative change in link lengths due to their differential thermal expansion is very small (0.011 mm for a 10° C gradient) while the corresponding change in resistive torque can be very high (> 30 N-m).

The resistive torque developed by the hard stop preload for various levels of linkage temperature gradient and the available input spring torque are shown in Figure 9. The torques in Figure 9 are measured about the main hinge of the panel and are plotted vs the input link angle as measured from the top-dead-center position. The torques are plotted vs the input link angle so as to increase the resolution of the torque calculations very close to the top-dead-center position. Note that the resistive torques developed are a direct result of the temperature gradient *across* the linkage, not as a result of a gross temperature change of the linkage which would not cause a change in the kinematic properties of the linkage. Figure 9 clearly shows that a temperature gradient of 10°C or greater could create a resistive torque which exceeds the available torque of the input spring.

Effect of Linkage Adjustments

During assembly, the linkage is adjusted such that the hinge line of the panel is preloaded against a hard stop in its deployed position to prevent relative motion of the inboard and outboard panels. The turnbuckle link is adjusted such that the spring force of the input link is capable of pushing the input link to its over-center position while maintaining the preload of the outboard to inboard panels. The preload developed is at a maximum at the top-dead-center position. As the linkage travels to its over-center position, the outboard hard stop backs away from the inboard panel and relaxes the preload. The amount of relaxation depends upon the over-center distance adjustment which is determined by the adjustment of the link stop (see Figure 2).

Because of the difficulty of taking measurements at the exact top-dead-center position of the linkage, the adjustments described below are performed as the linkage is in its over-center position. As a result, the measurable adjustment parameters include the linkage over-center distance and the gap between the hard stop on the outboard panel and inboard panel while the linkage is in its over-center position (see Figure 4). Both parameters affect the maximum level of hard stop preload which occurs at the linkage top-dead-center position.

The resistive torque developed by the hard-stop preload for various levels of hard stop gap and linkage over-center distance are shown in Figures 10 and 11, respectively. Figure 10 shows that as the hard stop gap is decreased, as measured in the over-center position, the maximum resistive torque developed at the top-dead-center position increases. In addition, Figure 11 shows that as the over-center distance is increased, as measured in the over-center position, the maximum resistive torque developed at the top-dead-center position increases. In fact, for a measured hard stop gap of less than 0.0025 mm (0.0001 inch) or for a measured over-center distance of greater than 1.143 mm (0.045 inch) the resistive torque exceeds the available torque of the input spring.

Affect on Torque Margin and Mechanism Function

Additionally, factors such as linkage-to-pin backlash and pin friction torques significantly contribute to the resistive torque as the linkage approaches top-dead-center. The sum of these resistive torques, created by and/or significantly increased by the effects of differential thermal expansion, can exceed the available torque from the torsion input spring and cause a negative torque margin[3] condition which could prevent over-center lock-up of the four-bar linkage. Figure 12 shows the minimum torque margin for various levels of linkage temperature gradient and hard stop gap. The over-center distance was set at its nominal 0.76 mm (0.03 inch) distance for Figure 12. Torque margin calculations of less than 0% indicate that the linkage will fail to move over-center and lock-up.

During the panel deployment lock-up failure, the total gradient across the mechanism was measured at approximately 10°C. The hard stop gap distance, measured in the over-center position, ranged from 0.000 mm (0.000 inch) to 0.0254 mm (0.001 inch) while the over-center distance was set precisely at 0.760 mm (0.030 inch). Figure 12

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[3] Torque margin is defined as the quotient of the quasi-static available torque to resistive torque minus 1.0.

clearly shows that the conditions described above would cause the panel deployment mechanism to fail.

CORRECTIVE ACTIONS AND SUBSEQUENT TESTING

In order to eliminate the cause of the failure, the preload requirement between the inboard and outboard panels had to be relaxed. In fact, discussions with experienced technicians revealed that during previous testing the linkage was adjusted with some hinge line backlash. The technicians had observed that the mechanism performed correctly when some backlash in the hinge was allowed. These previous units had all successfully passed their thermal vacuum deployment tests. This would explain why previous cold thermal vacuum tests of an identical mechanism were successful. However, relaxing or eliminating this requirement created additional concerns about backlash along the hinge line of the panel and how this might possibly interact with other system elements. The final solution involved modifying the four-bar mechanism adjustment and preload procedure such as to minimize the panel hinge line backlash while guaranteeing positive over-center lock-up for the worst-case thermal environment.

The new procedure specified that the turnbuckle linkage would be adjusted such that a 0.254 mm (0.01 inch) gap would exist between the hard stop of the outboard and inboard panels. In addition, the over-center distance of the linkage is to be adjusted to 0.760 mm (0.030 inch) or less. These adjustments would guarantee positive over-center lock-up for a worst-case temperature gradient of 55°C (100°F). Following the implementation of the modifications discussed above, there were three subsequent deployment tests, two in a cold vacuum and one at ambient. All three tests were 100% successful.

CONCLUSION

A successful failure investigation of a four-bar linkage deployment mechanism was performed. Possible failure causes such as the mismatch of material CTEs, excessive hinge friction, or limit switch interference were investigated and discarded. Further investigation revealed that thermal gradients across the linkage caused the outboard panel hard stop to prematurely preload against the inboard panel, which caused the resistive torques to exceed the available torque. Corrective adjustment procedures were implemented to minimize the panel hinge line backlash while guaranteeing positive over-center lock-up for worst-case thermal environment. Three subsequent deployment tests, two in a cold vacuum and one at ambient, have been successful.

Finally, the important "lessons learned" during our experience in this failure investigation include:

(1) Do not ignore resistive torque contributions close to the top-dead-center position: Mechanism designers often do not engage in a thorough analysis of the potential resistive torques that occur near the top-dead-center position because the analysis of a four-bar linkage is difficult and because of the presumption of near-infinite torque transmission. In fact, the large increase in resistive torque (>30 N-m), due to very small change in the four-bar linkage geometry (~0.01 mm relative length change), occurred as a result of the same kinematic properties that make a four-bar linkage attractive to mechanism designers. The major system-level thermal-vacuum test failure described in this report might have been avoided if a complete analysis had been performed beforehand.

(2) Importance of thermal gradient and direction of gradient: Thermal design considerations usually take into consideration only bulk temperature changes, which are important in the case of material CTE differences. However, because the kinematic properties of a four-bar linkage are dependent upon the ratio of link lengths and not on the absolute link lengths, the relative link temperatures are the determining factor. Mechanism designers should note that serious problems can arise in the presence of relatively small temperature gradients, as was the case in the test failure described in this report.

REFERENCES

1. Gans, Roger F. *Analytical Kinematics: Analysis and Synthesis of Planar Mechanisms.* Butterworth-Heinemannm: Stoneham, MA, ©1991

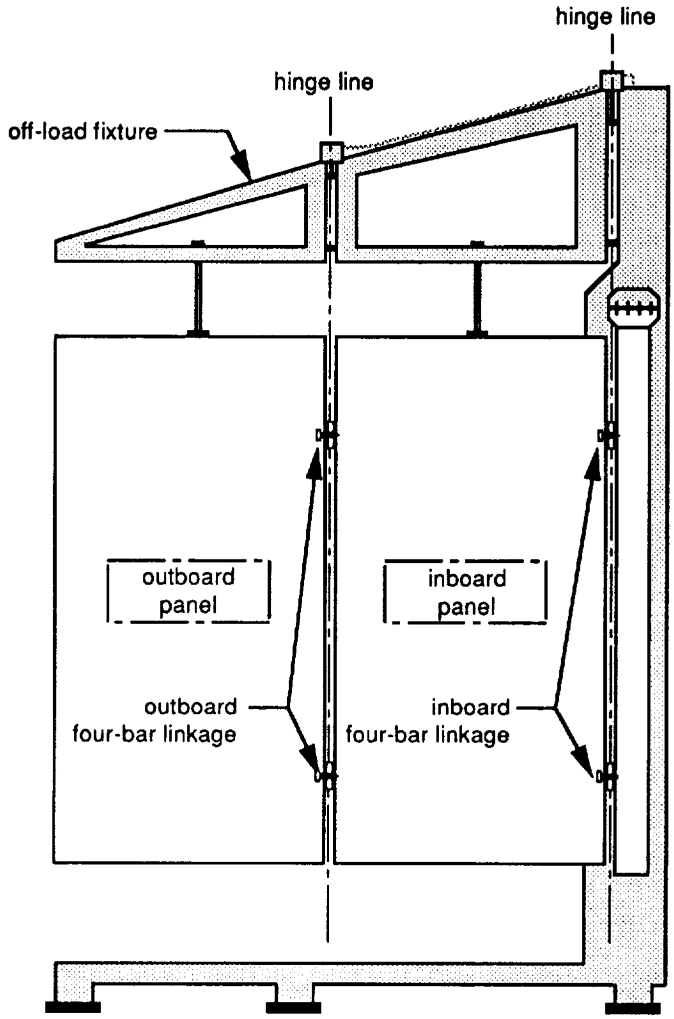


Figure 1. Panels Installed In Their Off-Load Special Test Equipment

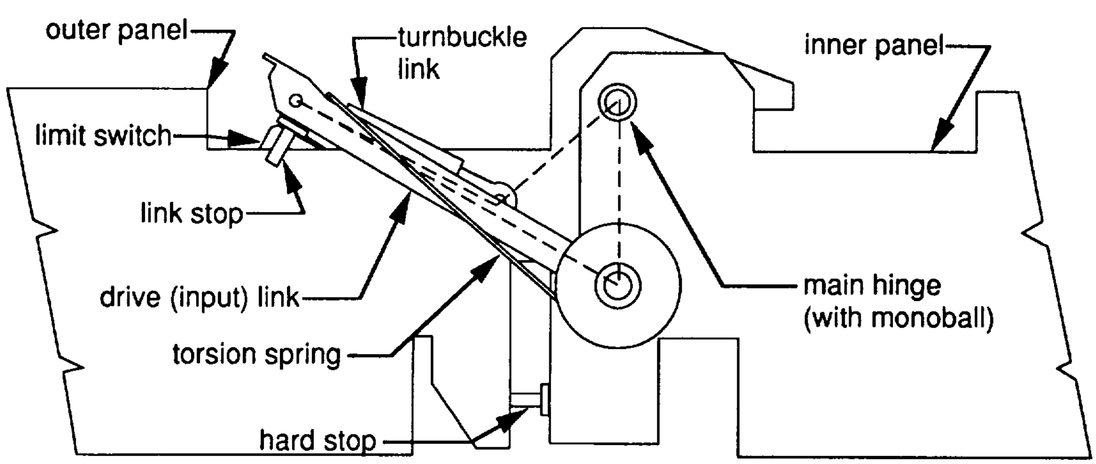


Figure 2. Linkage Schematic (Deployed Position)

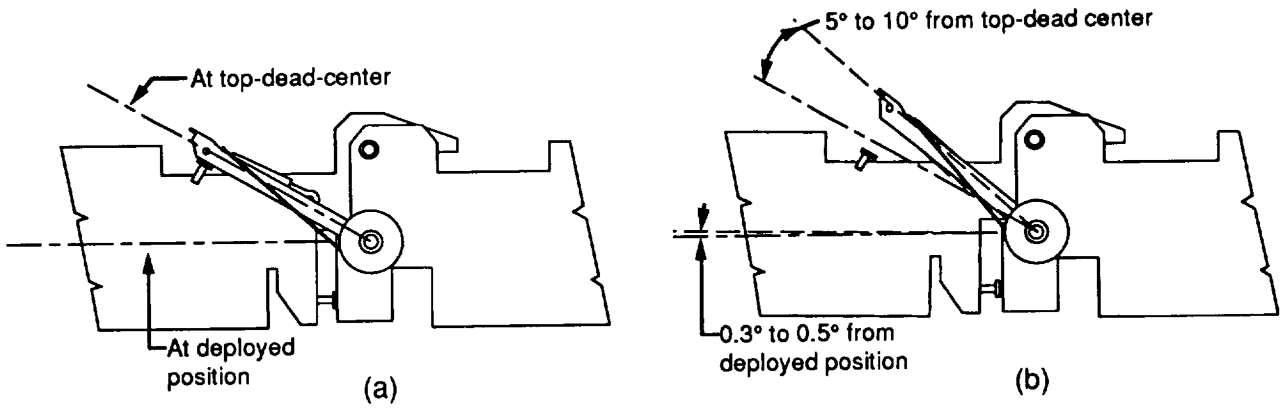
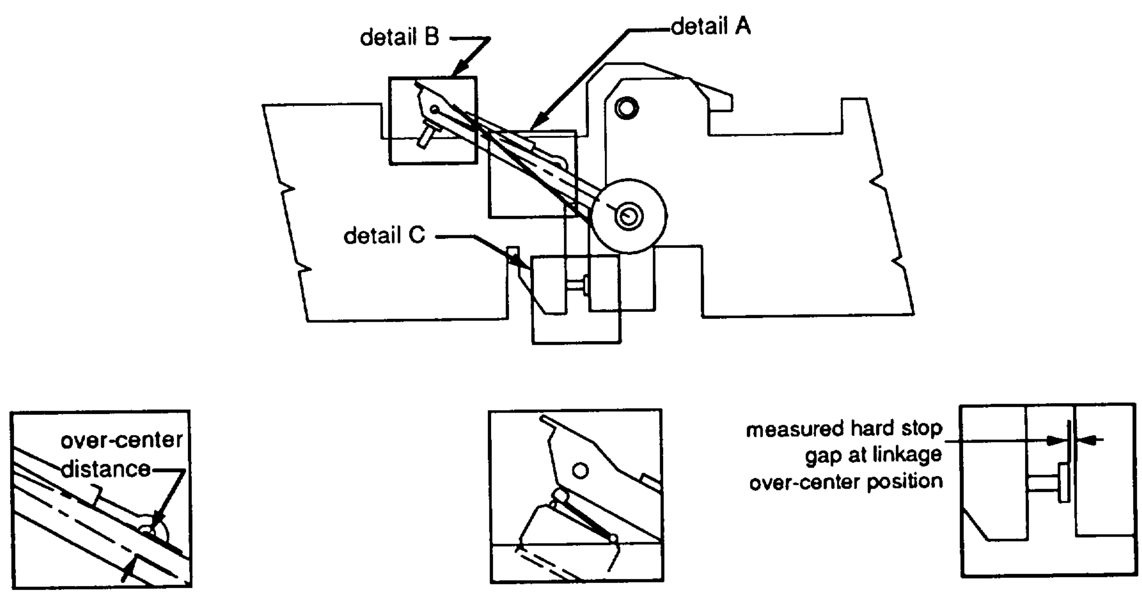


Figure 3. Linkage Deployed Configuration: (a) Sucessful Lockup (b) Failed Lockup



detail A: linkage over-center distance

detail B: linkage limit switch (link stop not shown for clarity)

detail C: inboard - outboard panel hard stop

Figure 4. Linkage Details: (A) Over-Center Distance, (B) Linkage Limit Switch, (C) Inboard-Outboard Panel Hard Stop

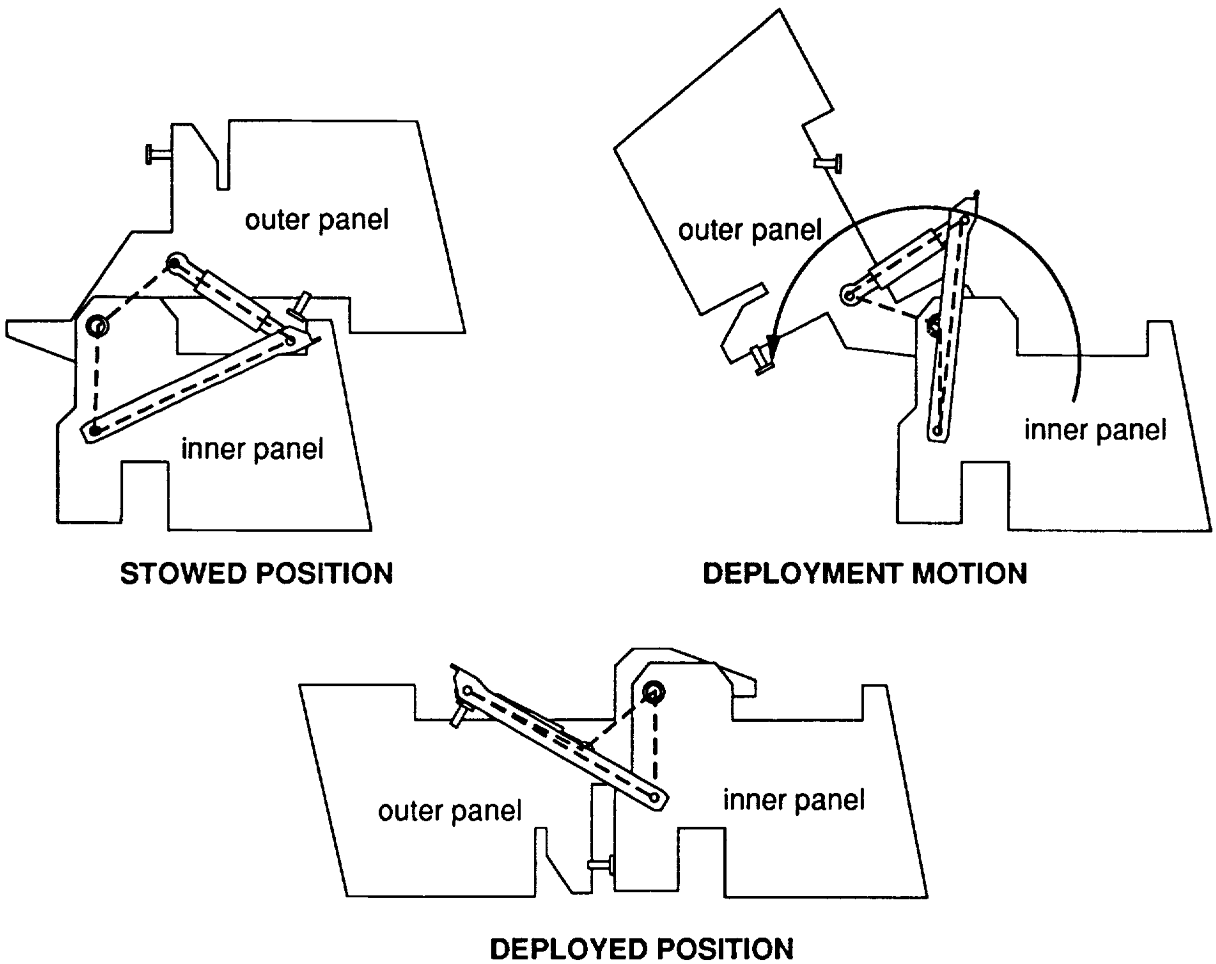


Figure 5. Linkage Deployment Sequence (Springs Not Shown For Clarity)

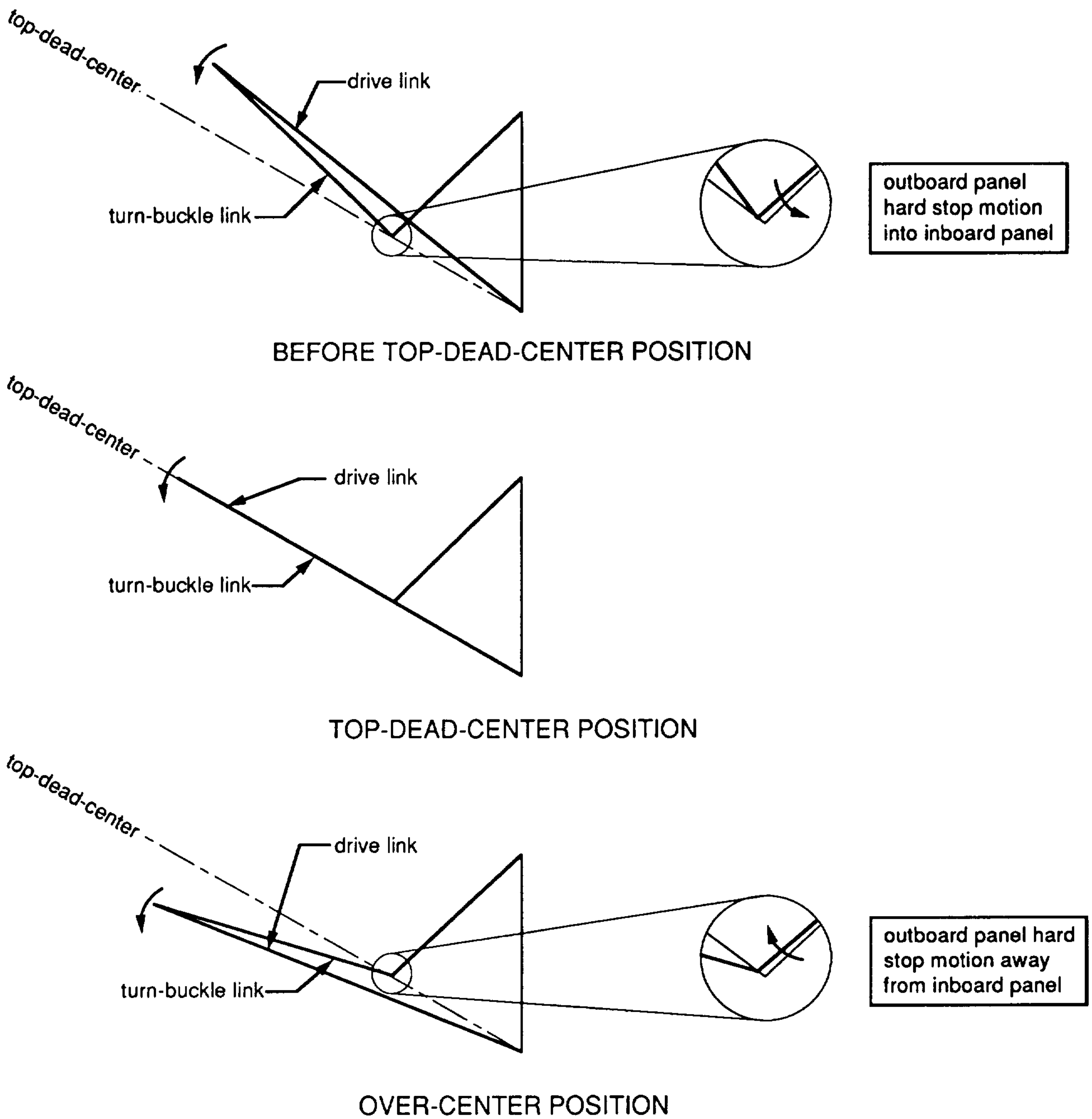


Figure 6. Kinematic Behavior Of Panel Four-Bar Mechanism

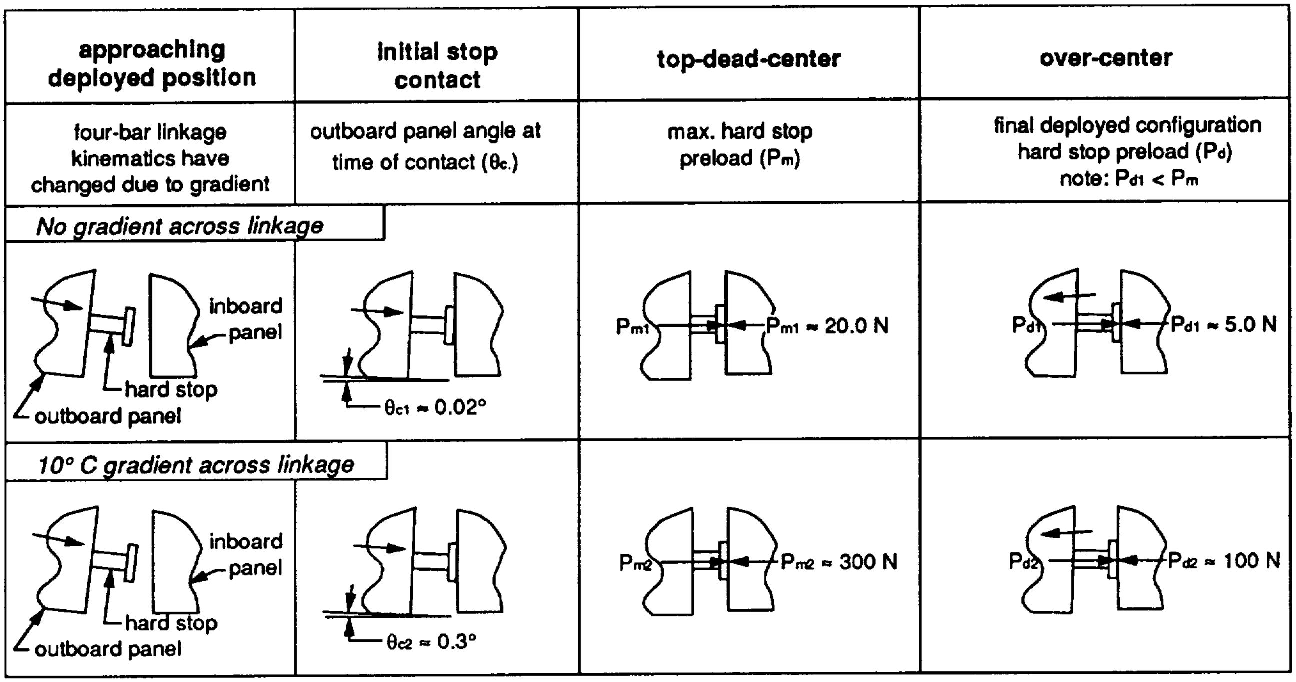


Figure 7. Inboard-Outboard Panel Hard Stop Kinematics (With and Without 10°C Gradient Across Linkage)

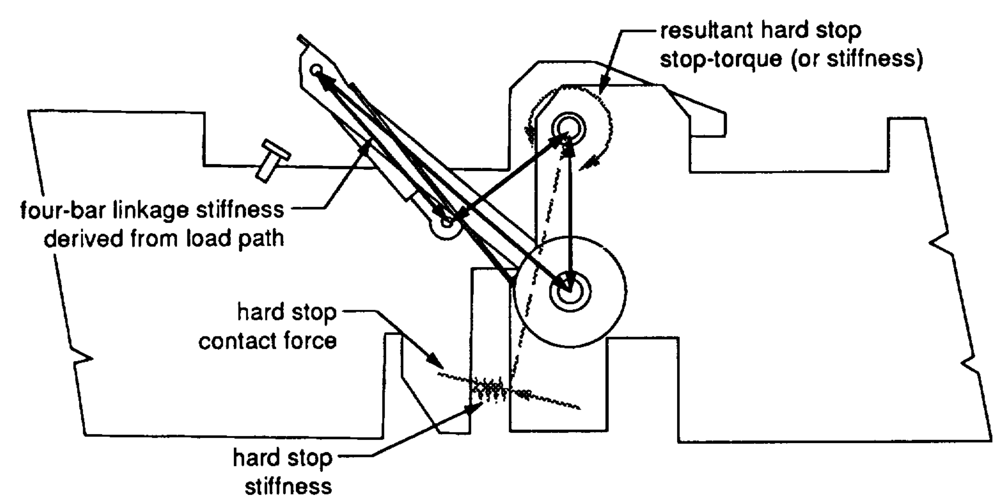


Figure 8. Schematic of Four-Bar Mechanism Stop Stiffness

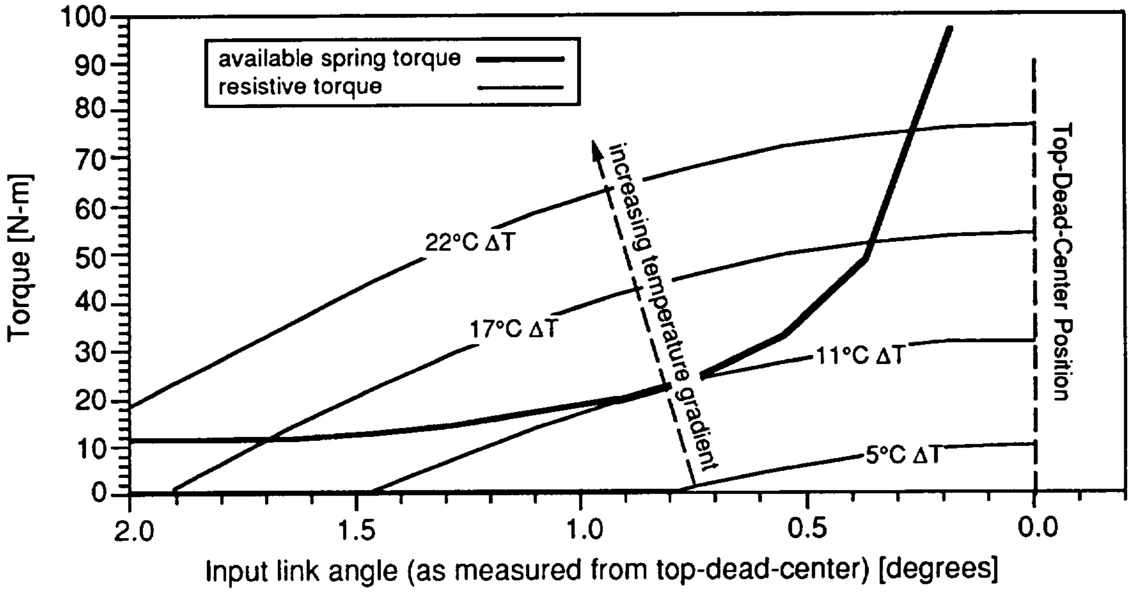


Figure 9. Effect of Temperature Gradient: Available Spring Torque and Resistive Hard Stop Torque

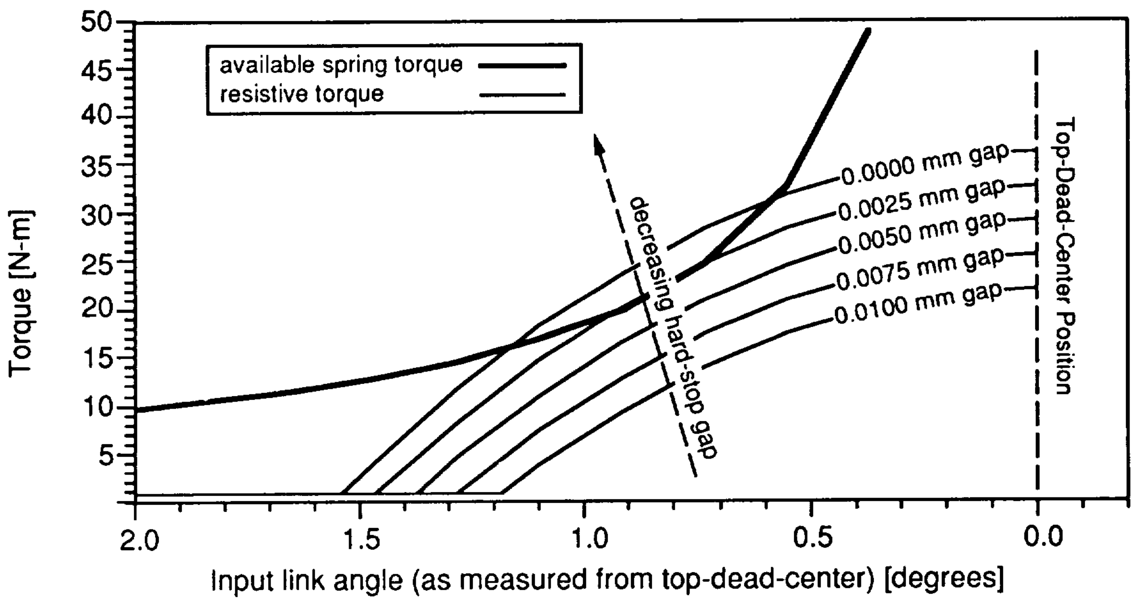


Figure 10. Effect of Hard Stop Gap Adjustment: Available Spring Torque and Resistive Hard Stop Torque

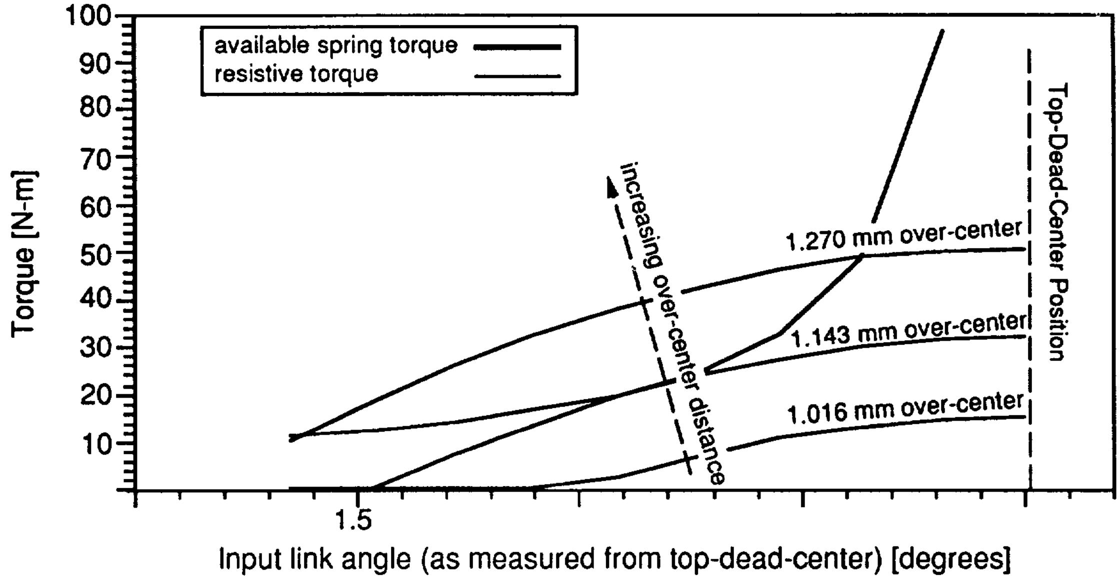


Figure 11. Effect of Over-Center Adjustment: Available Spring Torque and Resistive Hard Stop Torque

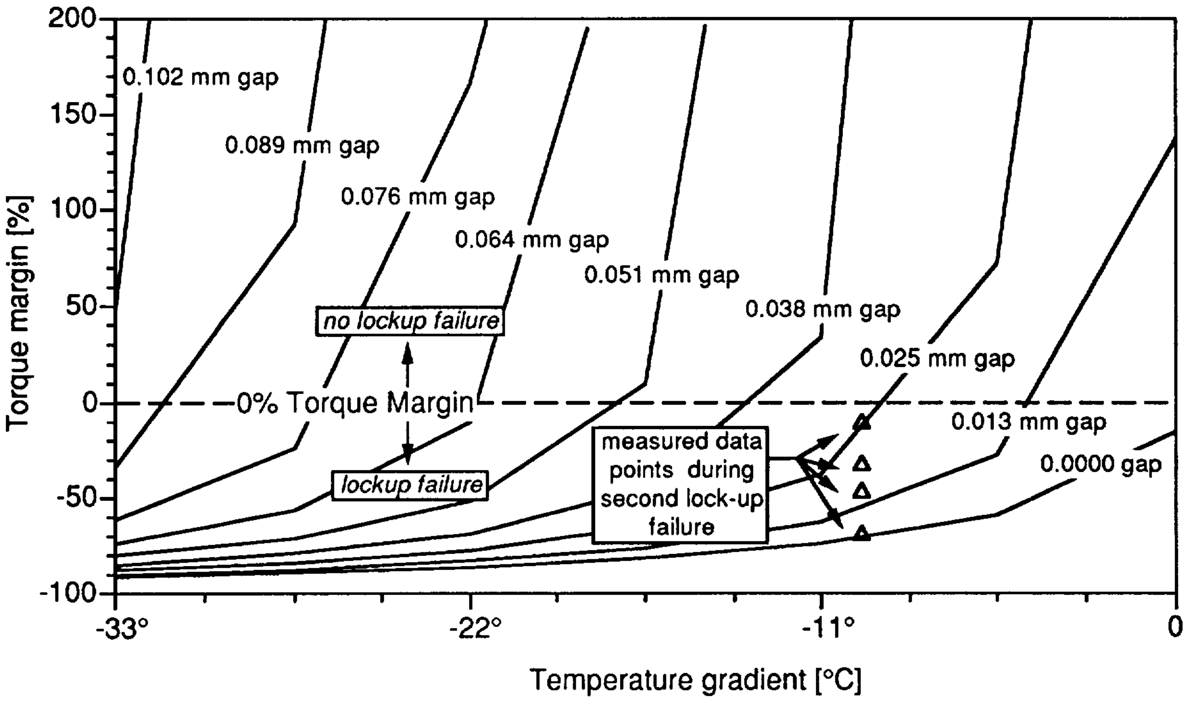


Figure 12. Minimum Torque Margin vs Temperature Gradient and Stop Gap Size