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NASA Space Shuttle Lightweight Seat

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Abstract

The Space Shuttle Lightweight Seat - Mission Specialist (LWS-MS) is a crew seat for the mission specialists who fly aboard the Space Shuttle. The LWS-MS is a lightweight replacement for the mission specialist seats currently flown on the Shuttle. Using state-of-the-art analysis techniques, a team of NASA and Lockheed engineers from the Johnson Space Center (JSC) designed a seat that met the more stringent requirements demanded of the new seats by the Shuttle program, and reduced the weight of the seats by 52%.

This paper describes the design approach used in developing the seat and the unique requirements of the seat itself. The paper also discusses the techniques that the engineers used to improve the safety and reliability of the seat, and to reduce its weight. The techniques used include a heavy emphasis on design optimization, analysis, and a simplified design.

Introduction

The Lightweight Seat project was performed in-house by civil servants and contractor personnel at JSC. The LWS-MS project became a reality after it was determined that significant weight savings, as well as safety improvements, could be realized if the present seats flown on the Space Shuttle were redesigned using state-of-the-art engineering technologies. The seat itself is a mechanism that must be capable of detaching from the floor of the orbiter and folding into a small volume. The seat is shown in Figure 1 in its installed configuration. Figure 2 shows the seat in its stowed configuration. The fact that the seat itself is a mechanism rather than a static structure improves the seat's safety by giving flexibility to the structure and allowing the seat to withstand significant floor deformations during a crash event. The seat is also an example of a new emphasis in the aerospace community towards less complex designs. This approach improves reliability, decreases cost and manufacturing times, and in the case of the Lightweight Seat, reduces weight, the primary goal of the LWS-MS project. Within the seat itself, there are several unique mechanisms that perform multiple functions.

Several unique requirements made the LWS-MS design challenging. The main requirement was a dramatic reduction in weight. To make the project economically feasible, a weight reduction of 45% had to be achieved. The weight savings was necessitated by a need to reduce the weight of the entire Shuttle to support the heavy First Element launch of the Space Station in 1997. Removing weight in the crew compartment was of even greater importance due to its location far forward of the

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Shuttle's center of gravity. Weight removed from the crew compartment has the magnified effect of allowing ballast weight to be removed from the aft end of the Shuttle, allowing an even greater weight savings.

In addition to weight, several safety improvements (relative to the current crew seats) were to be made to the LWS-MS. The seat was to be subjected to a military and FAA requirement known as floor warping. The seat structure had to be capable of tolerating significant floor deformations being applied to the seat's attach points while undergoing its expected external loading. For external loading, the seat had to withstand a statically applied 20-g load, which is the crash environment specified by the Shuttle program. Using a 95th percentile crew member and equipment, with a mass of 142 kg (313 lb), led to an external load being applied to the seat of 27.8 kN (6260 lb) as well as inertial loads from the seat mass itself. The high loading conditions meant that the seat had to be strong, but the seat also had to be flexible enough to avoid subjecting the seat to high, concentrated loads during the enforced displacements demanded by floor warping. The floor warping requirement was instituted by the FAA after crash investigations determined that many seats designed for aircraft were very strong, yet because of their high stiffness were breaking free of the floor in actual crashes where the floor structure was deformed, resulting in occupant deaths. The floor warping requirement ensured that designers made their seats flexible enough to avoid this dangerous situation. The FAA also began requiring that aircraft seats undergo dynamic crash testing, similar to the auto industry. The FAA felt that the crash environment could not be simulated adequately with a statically applied load environment. The LWS-MS team felt that the new crew seat should also be subjected to a dynamic crash test in recognition of the FAA's recommendations.

Design Philosophy

Because the requirements for designing seats demand high strength and high flexibility, commercial seat designers use a "design by test" philosophy. Seats are designed and subjected to crash tests, redesigned and re-tested until a satisfactory design is found. This process is expensive and requires the use of a crash test facility. It also does not adequately address the issue of variance in material properties. If a seat has unusually high material property values, its chances of passing a given test are increased. If the test is passed and the seat design is accepted, many of the production units may have significantly lower strength than the qualification unit. In addition, it is not practical to test to all worst-case conditions. There may be more than twenty load cases that are relevant to the seat structure, and it would be very expensive to test all cases. Therefore, our team used a method which ensures that the seat is capable of withstanding all load environments, using specified minimum material property allowables. These factors led the LWS-MS team to use state-of-the-art analysis techniques to drive the seat design. The knowledge of structural analysis and the computer infrastructure at NASA allowed the engineers to develop complex mathematical models to predict the behavior of the seat during all load environments, including the static applied loads, enforced displacements due to floor warping, and the dynamic crash environment. Using these tools, the design of the seat could be tested and optimized using the analysis models, saving the cost of expensive prototype testing, and ensuring that the final seat design would be capable of meeting its strength and flexibility requirements. The plan was not to neglect testing, but rather to use testing as a verification tool to assure that the math models were behaving properly. Once this was assured, the math models could be used to perform detailed studies of the seat without the risk of damaging expensive prototype units. With this philosophy in mind, a detailed analysis program was instituted at the beginning of the program. The analysis was used to drive the design and find design solutions that could meet the demanding requirements.

Another of the seat requirements that made the design of the seat more complicated was its on-orbit folding. The seat had to be easily removable from the floor and stowable in a small volume to allow more room for crew operations on the flight deck and the mid deck. This meant that the seat itself had to be a mechanism. A quick-disconnect floor fitting had to be designed as well as the seat folding mechanism. These mechanisms also had to be modeled analytically since they were a major contribution to the flexibility of the seat. The challenge was to utilize the mechanisms' joint flexibility to help tolerate floor warping, utilize their structural strength to carry high crash loads, and yet make them simple enough to be manufactured and maintained at a low cost.

Design Overview

The LWS-MS was designed to be removable and collapsible from the Space Shuttle mid deck and flight deck floors to facilitate on-orbit stowage. To accomplish on-orbit stowage, a quick disconnect floor fitting was designed. The quick disconnect floor fitting is located at the base of each leg. The floor fitting and spherical floor stud are shown in Figure 3. Because the seat had to tolerate significant floor deformations, it was undesirable to have a rigid connection at the seat to floor interface. The spherical joint in the orbiter floor fitting prevents large bending moments from being transferred to the seat legs, allowing the necessary flexibility and stiffness required to handle the crash loads as well as floor warping. The floor fitting assembly contains a housing that slips around the spherical floor stud, a retaining collar which slides down to capture the stud, and a spring loaded button that holds the collar in place. If the button is depressed, the collar can slide upwards, allowing the floor fitting to slide off of the spherical stud. The button slides into a detent which keeps the collar from sliding down into the locked position until the fittings are placed back on the floor studs. When locked onto the spherical floor stud, each floor fitting can tolerate a combination of 10° floor rotation in the pitch and roll axes.

Once the legs are released from the floor they can be folded under the seat pan for stowage. The rear legs fold forward, allowing the floor fittings to engage dummy studs, locking the legs in the folded position. Both front legs fold inward with the right leg having a lower pivot point, allowing the left leg to be folded and held captive by the right leg when in the folded configuration. Both legs are then held in place with a Velcro strap attached to the seat pan.

Another feature designed into the seat is an adjustable and removable headrest, shown in Figure 4. To accommodate the range in height of the crew members, the headrest needed to be adjustable. The headrest is a single, machined piece which uses two posts that are inserted into the top of the seat back. The adjustment feature comes from a series of holes in the side of the right post. These holes can be engaged by a spring-loaded pin that is actuated from the side of the seat. This design also accommodates stowage, allowing the headrest to be removed from the top of the seat and inserted into the seat back, reducing the stored volume.

An operational requirement which drove the seat design was that the seat back had to be adjustable between a 2° forward launch position and a 10° back landing position, relative to a vertical reference plane. One of the primary load paths between the seat back and the floor attach points are two struts, shown in Figure 5, which connect the seat back to the seat pan. These struts are also used to accomplish the seat back angle changes. The upper end of the struts are attached to "sliders" which are captive in a track located on the side of the seat back. The sliders, shown in detail in Figure 7, are held in place within the track by spring-loaded, adjustable latches. In the launch position, the latches engage a hole in the slider, preventing the slider from moving within the track and thereby locking the seat back in place. When the latch is actuated, the sliders are free to slide below the latches to a hard stop. The latches move back into position and block the slider from traveling upward, locking the seat back in place at a different angle. The mechanism is shown in cross-section, describing the two positions, in Figure 9. To accommodate stowage, the latches can be actuated and the sliders moved past them upward in the track to the folded position where they are locked in place by smaller retention locks at the top of the track, shown in Figures 4 and 10. Once released from the retention locks, the sliders can move down in the tracks and the seat back can be returned to its launch or landing position.

The seat back folding mechanism consists of three main components. Titanium struts with rod-end bearings at each end are fixed at the lower end to the seat pan and connected at the upper end to the slider which allows rotation of the seat back. A latch mechanism consisting of a spring-loaded latch fixes the slider within the lower track and can be actuated by a cable and controller. An aluminum upper track acts as a guide for the slider when moving between the stowed position and the lower track which houses the latch mechanisms.

The strut is a solid, fixed-length rod with swaged bearings, shown in Figure 6. One of the main design drivers for the strut was clearance between the seats. Weight could have been saved if a hollow thin-walled tube had been used for the strut, however the diameter would have been larger, violating clearance constraints. To save weight the strut was fabricated from titanium, saving 0.23 kg (0.5 lb) per strut compared to previous stainless steel struts.

The latch mechanism, shown globally in Figures 5 and 8, consists of a latch which is held captive inside the lower track housing by a cap screw through a slot that limits latch travel. The latch is positively loaded outward with a captive compression spring. A small rod affixed to the back end of the latch runs down the middle of the compression spring and through the spring housing bracket that is attached with the same cap screw to the lower track housing. The two latch mechanisms (one on each side of the seat) are tied together in the middle of the seat back with a 4-sided pivoting lever arm. It is designed to be adjustable so that any rotation of the lever arm actuates both latches simultaneously. However, one of the main design challenges with this device was ensuring that both sides of the seat and latch mechanisms would act together when sliding or latching. To address this problem, the latch mechanism was designed to be adjustable using laminated shims and a set screw, shown in detail in Figure 9. The seat is assembled using a nominal shim thickness above and below the latch. Once the seat is together, the seat back is rotated to the latched position and the sliders are monitored as they latch. If the two sides do not latch properly, the shims are adjusted until both sides act together. This method adjusts the slider when the seat back is in the forward, or launch, position. A set screw at the bottom of the lower track completes the necessary adjustments, controlling the gap size which sets the slider location in the 10° back, or landing, position.

The aluminum upper tracks, shown in Figure 10, are designed to allow translation of the sliders along the side of the seat back, allowing the seat to fold. No significant loading occurs through the upper track so weight and cost savings are gained by using a lower strength, lighter material like aluminum. The lower end of the upper track is inset into the upper end of the lower track to aid in alignment and to ensure a smooth transition between the two.

Analysis

Finite Element Modeling

Many detailed finite element models have been used to design and analyze the LWS-MS. These models consist of detailed local models used to predict stresses and deformations in local areas where large models are inefficient. There is also a large, global finite element model (FEM) of the entire seat primary structure. This non-linear model was used to analyze the seat structure as a system and to determine critical loads and load paths, as well as post-yielding behavior of the seat structure and the effects of this behavior on the seat's structural performance. The global model has roots back to the beginning of the LWS program. When the LWS-MS concept was developed, a simple finite element model using beam and plate elements was created to verify that the seat design had potential as a solution to the aggressive requirements of the project. As the project proceeded, detailed upgrades were made to the model to increase its fidelity and to reflect the design changes that occurred as the project progressed. The final global model was verified through several static and dynamic load tests performed specifically to verify the accuracy of the global model. The global FEM, shown in Figure 11, is an accurate representation of the stiffness of the seat. Non-linear solution sequences are used to account for material non-linearities as well as geometric non-linearities due to the large deformations created by the enforced displacements from floor warping at the floor interface. The global FEM was created using SDRC's I-DEAS finite element modeling software. The model was then solved using MSC's NASTRAN finite element code.

The global FEM also demonstrates the ability to structurally model mechanisms. In those design tasks that require a mechanism to tolerate high stresses during operation, several finite element modeling tools exist, such as NASTRAN, which can greatly facilitate design and optimization. Joint stiffness, material non-linear behavior, and large displacement solutions can be used to develop design concepts before any actual units are manufactured. This design approach saves time, money, and lowers the chance of having a mechanical failure later in the program.

Dynamic Crash Analysis

Dynamic analysis of the seat and its occupant was performed to predict and even design the type of dynamic loading the seat and occupant would experience during a crash. By performing this analysis during the seat design process, the amount of dynamic crash testing required to develop the LWS-MS was significantly reduced when compared to conventional design approaches.

The analysis uses the Dynamic Analysis and Design Software (DADS) package by Computer Aided Design Software, Incorporated. DADS was chosen over other multi-body simulation codes because of its ability to incorporate flexible-body information from NASTRAN. Custom code written by NASA JSC was added to the DADS software to model the seat restraint system, and to model contact between the occupant and the seat. The equations of motion are solved using a modal formulation. The large mass technique is used to input an acceleration profile to the base of the seat.

The occupant is modeled as a group of fifteen rigid bodies which are connected at fourteen joints. The body mass properties and joint locations are the same as the Wright Patterson Air Force Base Articulated Total Body model of a 50% Hybrid II crash test dummy. Additional mass was added to account for the equipment worn by the orbiter crew. The model is shown in two configurations in Figures 12 and 13. Figure 12 shows the model in its initial state, at simulation time of 0.0 milliseconds. Figure 13 shows the model at the end of its dynamic analysis run at a simulation time of 200.0 milliseconds.

The harness is modeled as cables running over frictionless pulleys. The cables have a nonlinear load deflection curve which was determined using test data. A series of crash tests using a rigid boilerplate seat was conducted at the Federal Aviation Administration's Civil Aeromedical Institute (CAMI) in Oklahoma City. In these tests a 50% Hybrid II crash test dummy was fitted with the LWS-MS restraint system. These tests provided data to characterize the restraint system.

The seat mass and stiffness is represented in the DADS model. Alter statements are used in MSC/NASTRAN to output the mass matrix, stiffness matrix, and the first six eigenmodes of the LWS global finite element model. Modal transient analysis of the seat alone was performed using MSC/NASTRAN to determine that the first six eigenmodes were sufficient to represent the seat response. The NASTRAN analysis also was used to verify the DADS flexible model of the seat alone.

The dynamic analysis and the CAMI boilerplate tests showed the potential for strut loads in excess of those resulting from static analysis. The strut and mechanism were beefed up accordingly. The LWS-MS successfully passed its dynamic testing and the

DADS model shows good correlation with test data for both low and high level input tests.

Testing

While analysis played an important and comprehensive role in the design of the LWS-MS, a detailed testing program was incorporated to verify and insure the structural integrity of the LWS-MS, as well as correlate the many math models used in the LWS program. Several small tests were performed on I-Beam cross sections to verify the ability of the NASTRAN models to predict crippling failures in the material plastic region. These tests demonstrated excellent correlation with the NASTRAN models.

An ultimate static load test was performed on the seat, using hydraulic actuators to apply loads at the seat belt attach locations. The total load distribution between the shoulder strap and the lap belts had been characterized during CAMI boilerplate tests, and was used to simulate the loads which would be applied during a crash. The seat was loaded to an equivalent 20-g static load. Deflection gages, strain gages, and load cells at the seat/floor attach points were used to characterize the seat's structural load paths and verify the global FEM. Pre-test predictions of all the deflection and strain gages as well as the load cells were made using the global FEM. Real-time data was taken during the test and predictions were compared to actual values at every 10% load step. Model correlation was excellent, achieving deviations of less than 10% from predictions. No post-test model corrections were needed.

Dynamic crash testing of the LWS-MS was performed at the Federal Aviation Administration's Civil Aeromedical Institute (CAMI) in Oklahoma City. While the seat was being designed, a series of tests were done using the restraint system and a rigid seat. These tests aided in the characterization of the restraint system for dynamic analysis. A low level dynamic test (7g input) was performed on the second qualification unit. The purpose of this test was to verify the math model of the seat and occupant. Finally a high level dynamic test (16g input) was performed on the third qualification unit. The purpose of this test was to produce loads at the floor equivalent to the floor's design strength. All tests were passed successfully.

The seat also had to pass vibration and cycle testing to insure that it could survive certification to 100 Shuttle missions, a project requirement. A flight-like qualification unit was subjected to a vibration environment of 6.5 g_{rms} for 48 minutes on each of its three axes. Since the seat is to be flown with crew members attached, the vibration tests were done using an anthropomorphically correct test dummy wearing a launch and entry suit.

The mechanisms on the seat, including the floor fittings, seat back folding mechanism, and headrest were subjected to life cycle tests which simulated their use over the life of the seats.

Conclusions

The Lightweight Seat - Mission Specialist is scheduled to fly aboard the Space Shuttle in February of 1997 for the second Hubble Telescope servicing mission and continue to fly afterwards for the life of the shuttle program. The final weight of the LWS-MS was measured at 22.62 kg (49.87 lb), 4.99 kg (11 lb) under the design goal, and a weight savings of 52% over the original shuttle mission specialist seats. There were several lessons learned on this project:

1. Mechanisms can be used to solve a variety of problems related not only to movement and transfer of forces, but also to solve flexibility problems. The flexibility inherent in mechanisms helped the LWS meet a structural flexibility requirement which greatly improved the safety of the seat design.

2. Investing a large amount of time in performing analysis early in a program can save time and money later by taking the mystery out of testing and avoiding costly failures and redesigns. If a mechanism or structure can be well understood in the early stages of a design, many of the potential problems can be found before the design is even complete.

3. The analysis tools available commercially for evaluating mechanisms and structures are very capable and can solve many classes of mechanism problems.

4. Designing simple mechanisms leads to fewer number of parts and can dramatically increase the reliability of your system. With fewer and less complex mechanisms, design, analysis, and testing efforts can be spent on optimization problems such as reducing weight, cost, and manufacturing time.

5. Involving designers, analysts, manufacturers, and customers early in the project, even as early as the conceptual design phase, can solve many potential problems before they become expensive later in the design process. The success of LWS project is the direct result of a serious commitment by the LWS team to this philosophy.

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Acknowledgments

The authors would like to thank the Lightweight Seat team for making this project successful and contributing many dedicated hours toward reaching our goals and making a lighter and safer crew seat. We would also like to thank the Federal Aviation Administration for the generous use of their expertise and their test facilities at the Civil Aeromedical Institute in Oklahoma City.

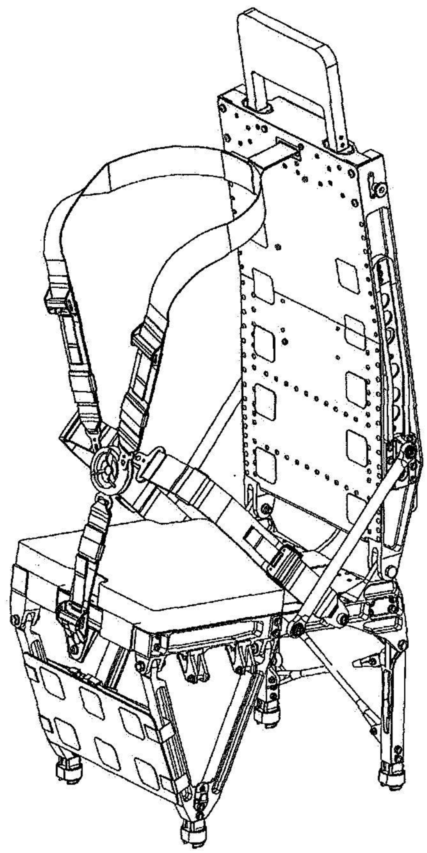

Figure 1. Lightweight Seat - Installed Configuration

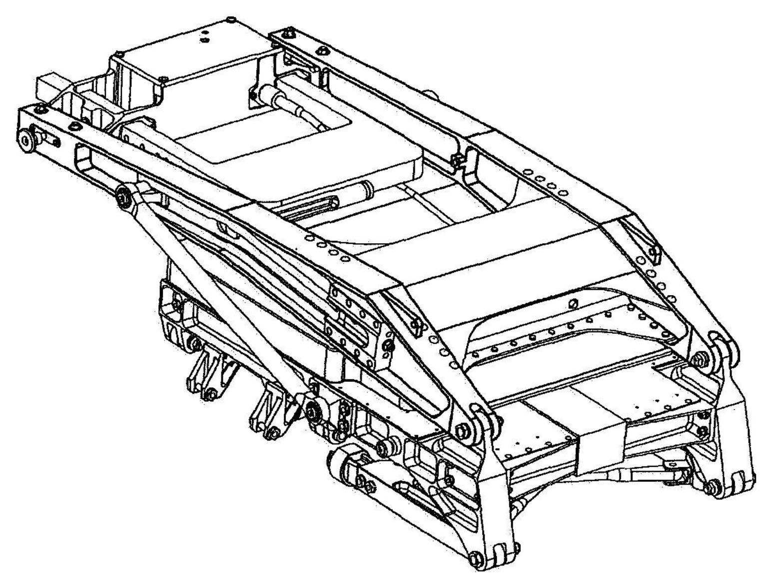

Figure 2. Lightweight Seat - Stowed Configuration

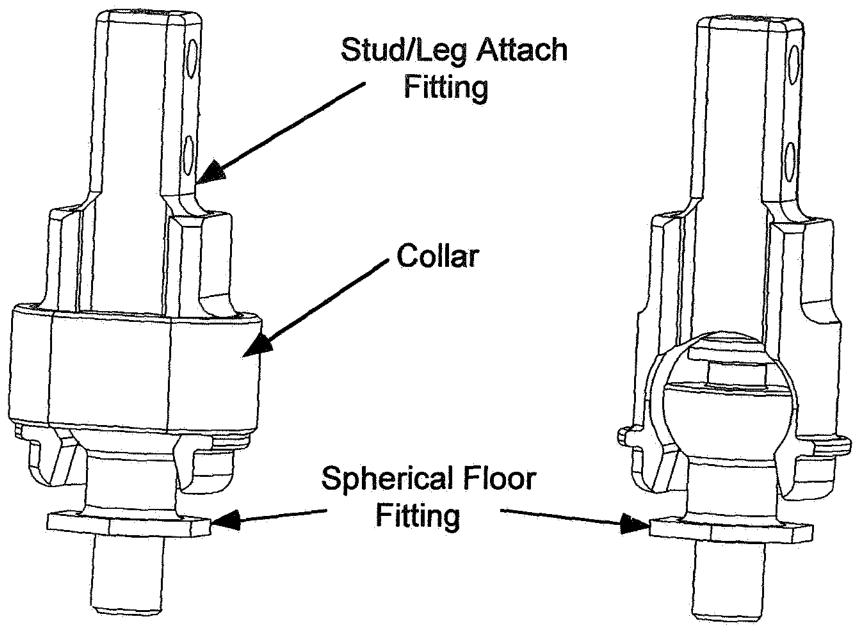

Figure 3. Floor Fitting

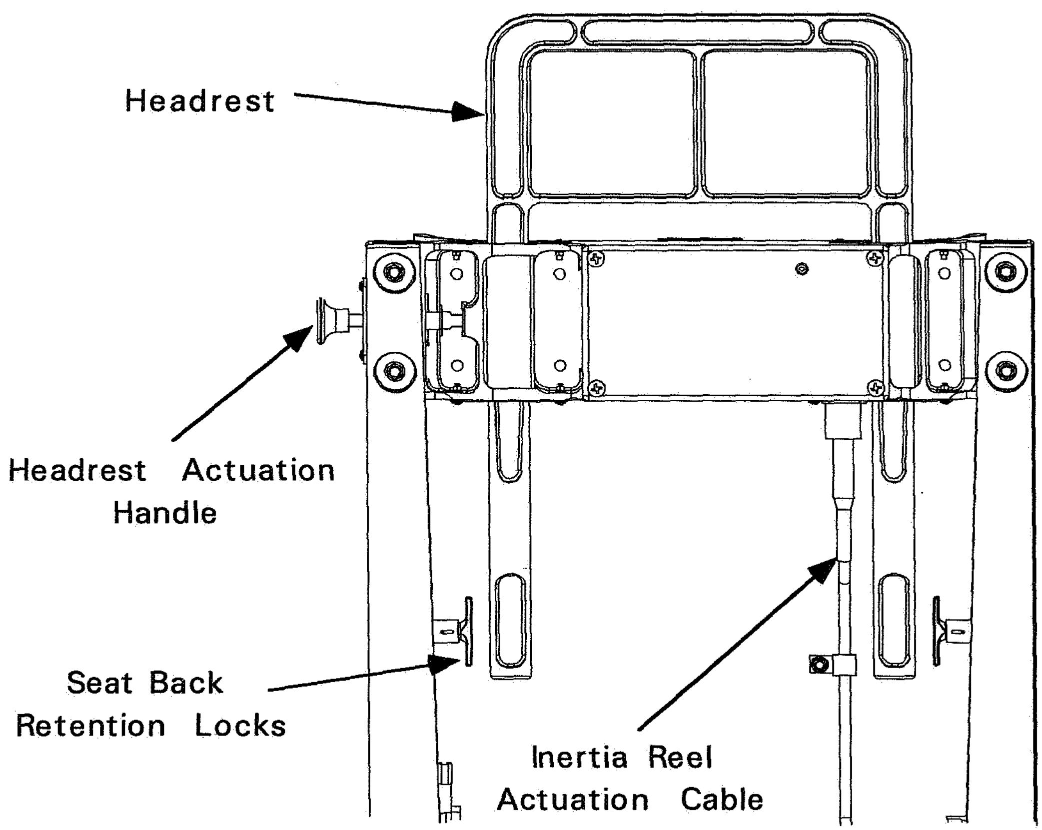

Figure 4. Headrest Mechanism

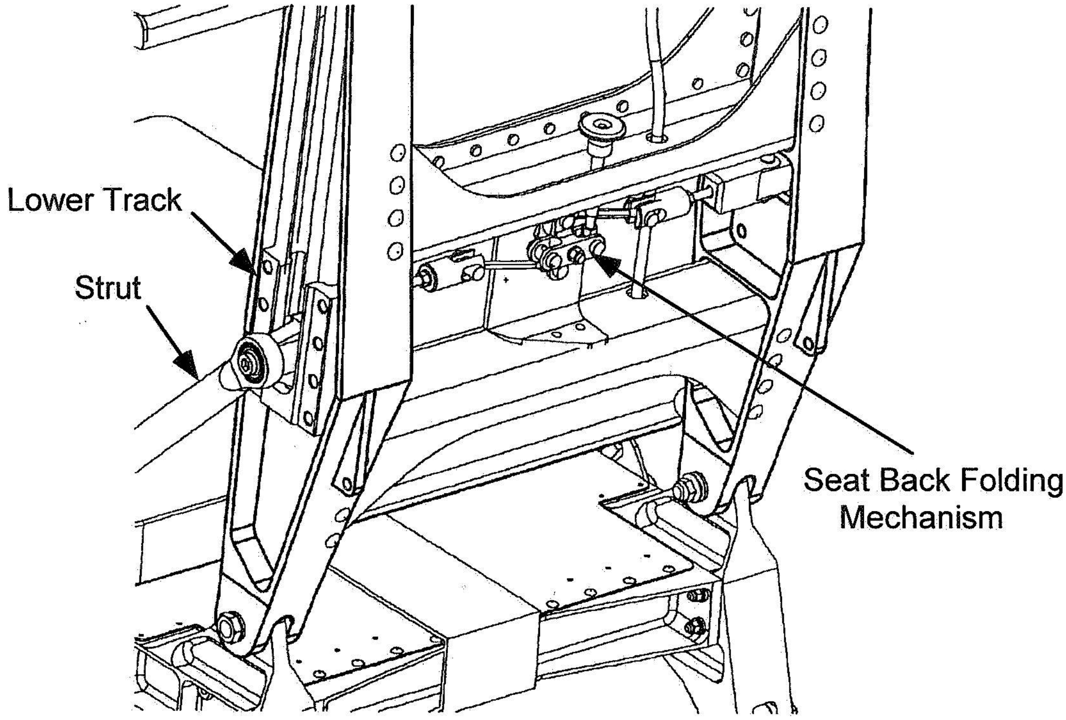

Figure 5. Seat Back Folding Mechanism

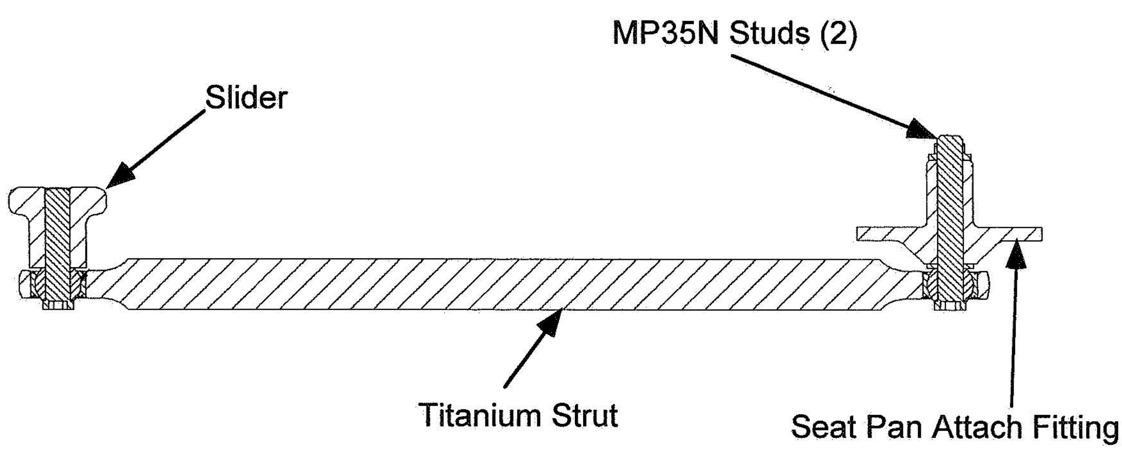

Figure 6. Titanium Strut and Slider

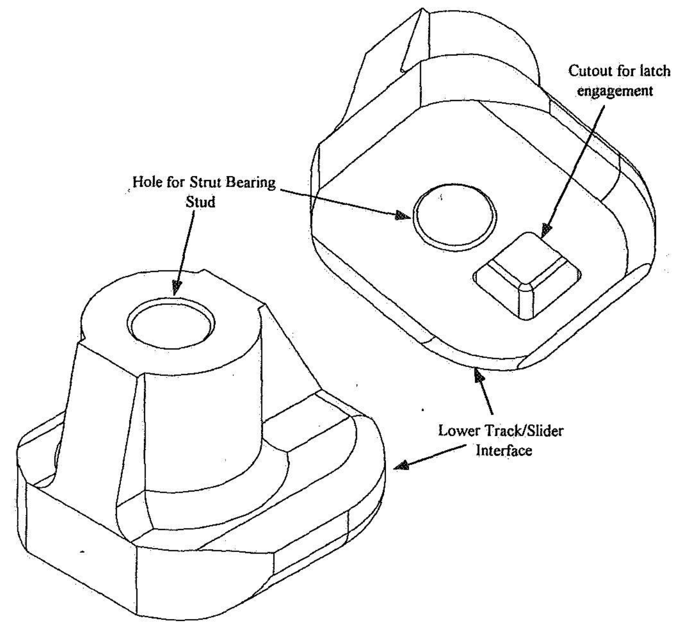

Figure 7. Slider

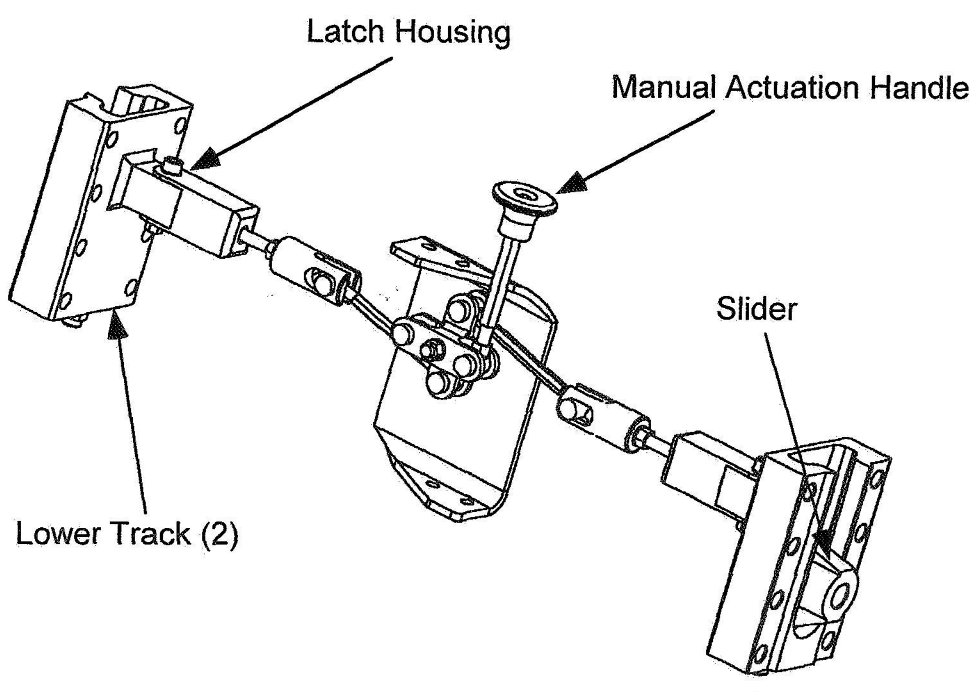

Figure 8. Seat Back Actuation Mechanism

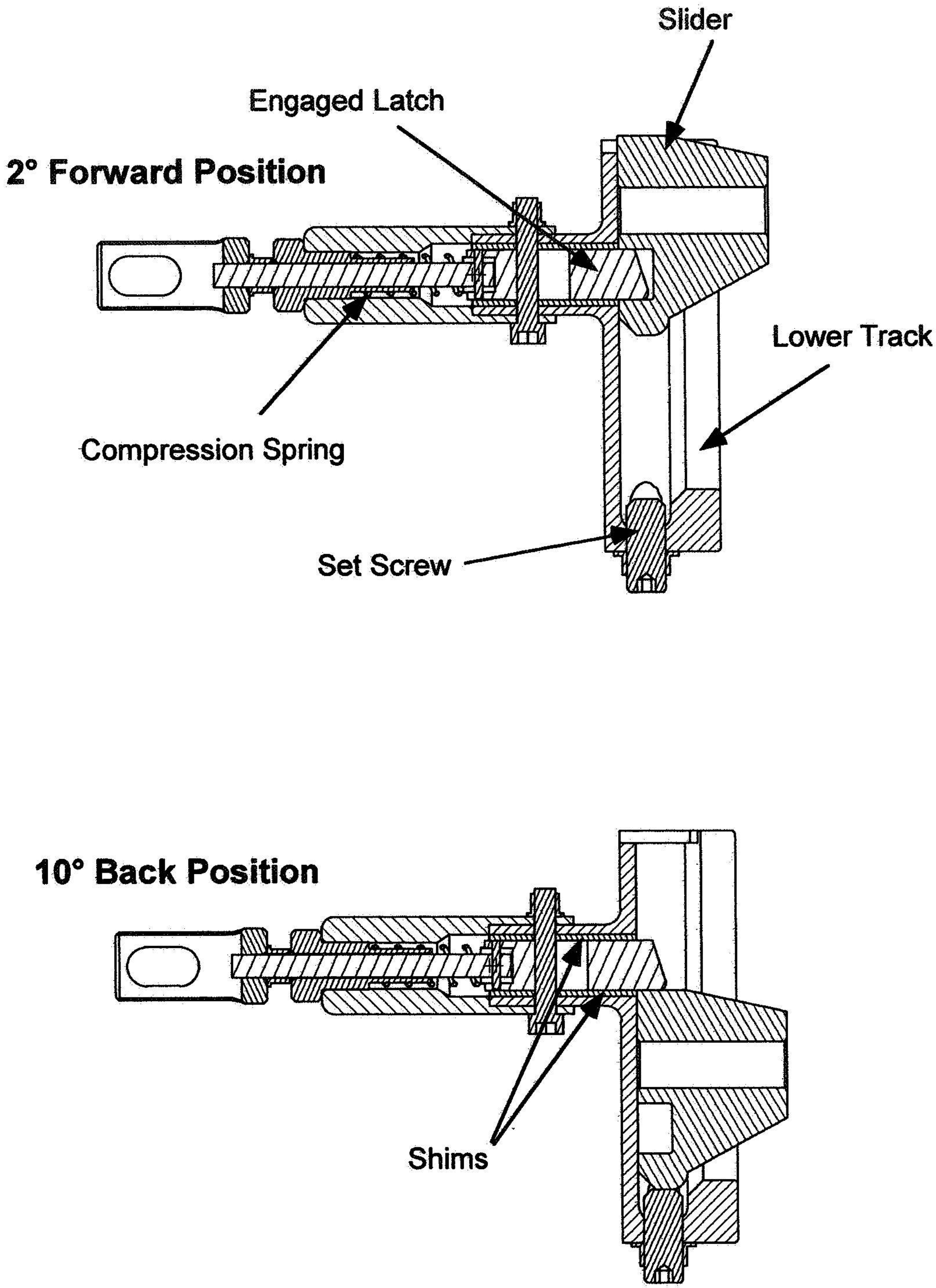

Figure 9. Lower Track Housing and Latch Cross Sectional Views - 2 Seat Back Angle Positions

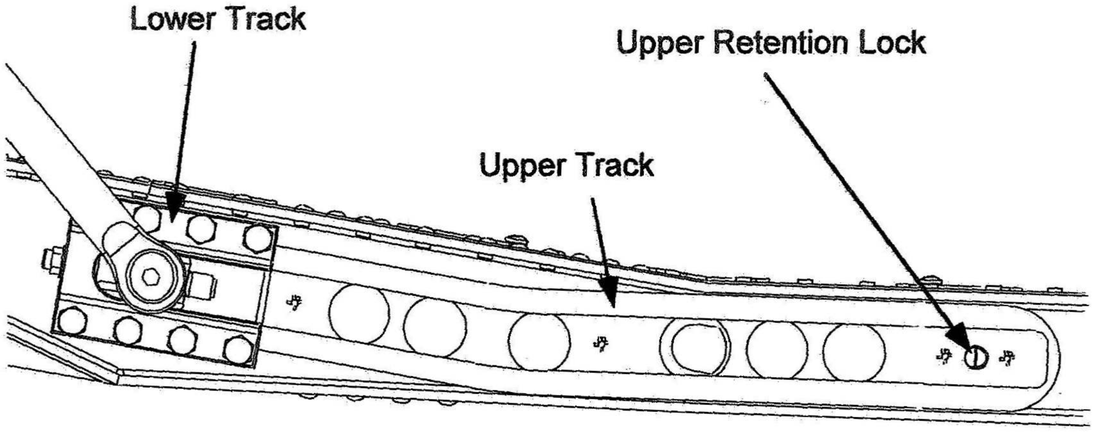

Figure 10. Upper Track

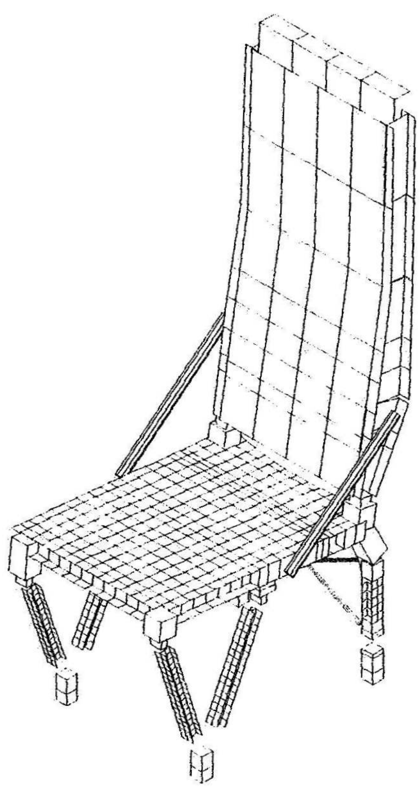

Figure 11. Global Finite Element Model of the Lightweight Seat

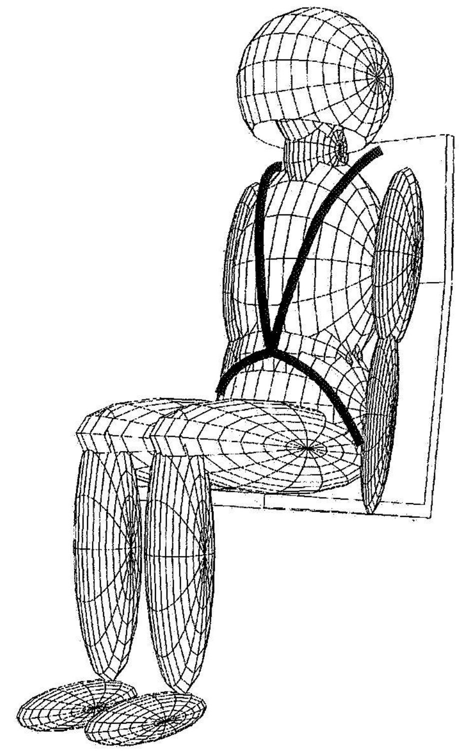

Figure 12. DADS Model at Initial Time Step - 0.0 milliseconds

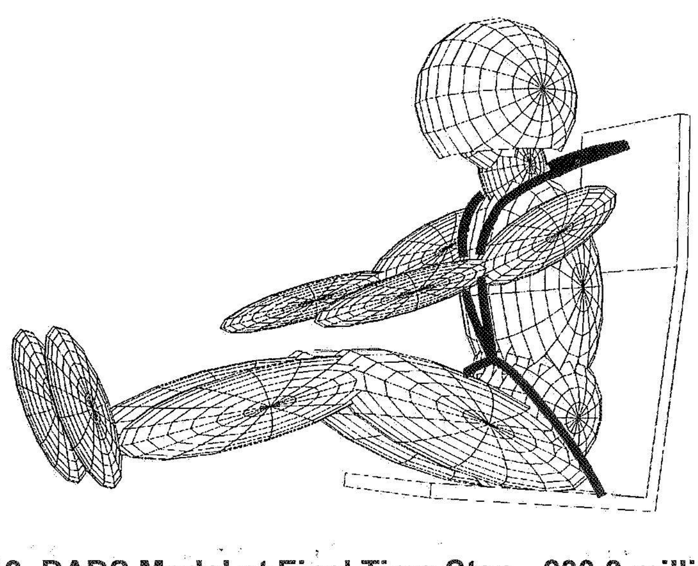

Figure 13. DADS Model at Final Time Step - 200.0 milliseconds