Project Orion Crew Impact Attenuation System

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Abstract

The Project Orion Crew Impact Attenuation System (CIAS) is a structural energy attenuating mechanism that attaches to each crew seat and the backbone structure in the Orion Multi-Purpose Crew Vehicle (MPCV) to protect an Orion crew from excessive g-load during landing. This paper provides an overview of that system and focuses on design issues involving the Energy Absorber (EA) Selector Mechanism within CIAS and the resolution of those issues. The CIAS has two EA selector mechanisms that did not function as intended in their initial design. Operation of the Full-Scale Development (FSD) unit CIAS EA selector mechanisms was very rough and the mechanisms tended to lock up and no longer function without partial disassembly making re-design necessary. The effectiveness of implemented design solutions was verified through additional testing and the lessons learned are summarized. The paper also describes how demanding procurement specification requirements were addressed with an efficient, low weight, straightforward mechanical mechanism design. Finally, the paper includes a discussion on system and subsystem testing accomplished to verify proper operation and performance.

Introduction

To protect the Orion crew from excessive acceleration (g-load) upon landing (primarily off-nominal landings) the Orion MPCV utilizes the CIAS. Figure 1 shows a completed Artemis-2 configuration CIAS flight unit. Each crew seat within Orion (qty 4) independently attaches to a single CIAS (reference Figure 2). During an off-nominal water landing (e.g., one parachute out, high winds/sea state, launch abort), the crew's possible exposure to excessive acceleration (g-load) upon water impact is mitigated by the CIAS which provides crew-mass-specific spinal axis (MPCV Z-axis) energy attenuation at each seat independently.

Figure 1. Artemis-2 Configuration CIAS Ready for Final Packaging and Shipment

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*** NASA Johnson Space Center, Houston, TX
+ Lockheed Martin Space, Denver, CO
++ NASA Glenn Research Center, Cleveland, OH

Proceedings of the 46th Aerospace Mechanisms Symposium, Virtual, May 11-13, 2022

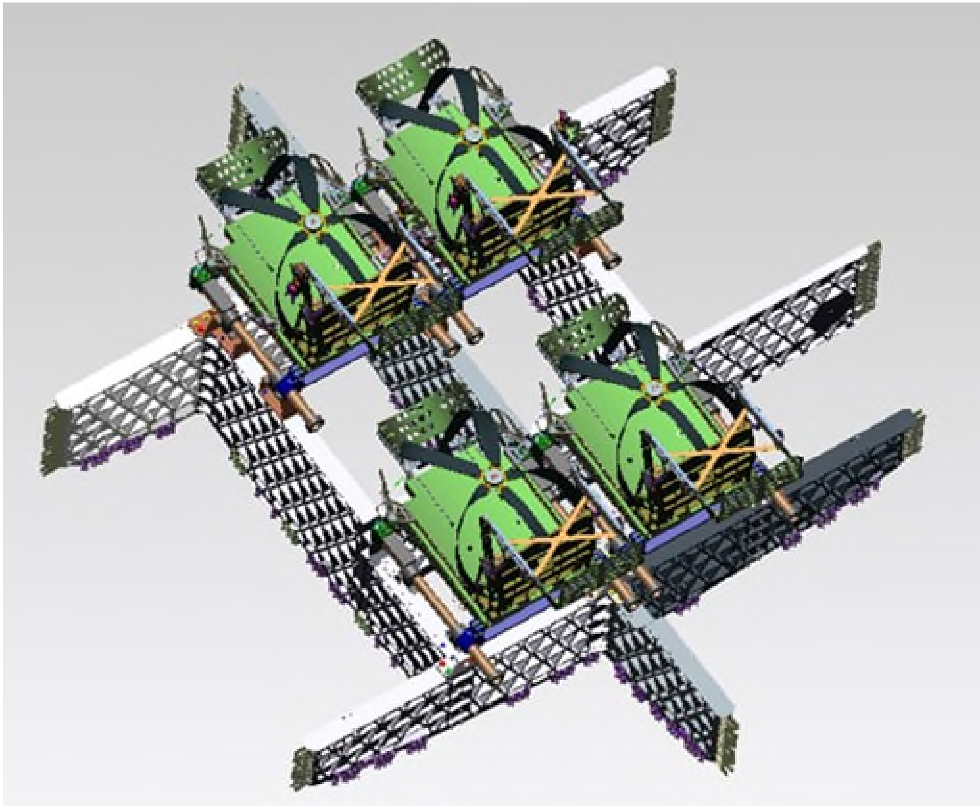

Figure 2. CIAS Attached to MPVC Backbone Structure and Crew Seats Attached to CIAS

CIAS Background

When the landing impact energy exceeds the selected stroking loads for a given crew seat-occupant mass combination, the CIAS limits the load in the Z-axis by stroking along guide rails using controlled material deformation of engaged energy absorber (EA) tubes. CIAS incorporates Safe, Inc.'s Selectable Profile EA technology (U.S. Patent No. 10,543,798) which includes manual EA selector mechanisms to select (i.e., tune) the appropriate amount of energy attenuation based on the total stroking mass. The total stroking mass consists of the crew seat mass, seat occupant mass, and the mass of the stroking portion of CIAS.

Like any aerospace mechanism, size, weight, and power are critical design drivers. In addition to being limited in size and weight, CIAS was required to provide equivalent load attenuation regardless of crew member mass and allow the Orion crew to change seat positions prior to reentry (if necessary) thus requiring the system to be tunable. This was accomplished by two primary means. The first was the performance-driven design of the EA tubes and the second was the ability to mechanically select, on the ground or in flight, various combinations of EA tubes to be engaged/active. This is referred to as tuning the system for a given total stroking mass.

The CIAS design incorporates a total of six crushable EA tubes, three EA tubes on each side of the CIAS. Locating three EA tubes on each side of the CIAS helps to minimize the imbalance of force potentially being applied to the CIAS and seat by the EAs, side to side. The EA force exerted on the seat does not need to be precisely balanced, as the guide rail linear bearings are designed to guide the seat's stroke with significant imbalance; however, good engineering practice suggests minimizing the imbalance to the extent possible without over-complicating the system.

In a landing where the load exceeds the stroking load threshold (typically off-nominal), the EA tubes are deformed (i.e., crushed) by rollers as the seat strokes. The selected EA tubes are engaged by use of the EA selector mechanisms atop each guide rail that are unlocked and rotated to the appropriate setting for the seat occupant. During an impact, the engaged tubes are drawn through precisely placed rollers, deforming the EA tubes in a controlled manner to produce the force profiles necessary to decelerate the occupant at the desired load. Each EA tube is sized to produce a specific load-stroke result that, when added to another engaged EA tube, provides the required composite energy attenuation profile for that occupant's weight range.

This is accomplished by selecting various combinations of EA tubes, appropriate for the entire stroking mass (i.e., seat system, occupant, suit, stroking portion of CIAS), to be engaged (i.e., actively deform) during a high load impact. The guide rails and linear bearings are designed to control the seat motion along the Z-axis and to allow for an adequate amount of off-axis loading. The CIAS is designed to stop stroking within a short distance (reference Figure 3) and can accommodate substantial off-axis, asymmetric loading throughout the stroking.

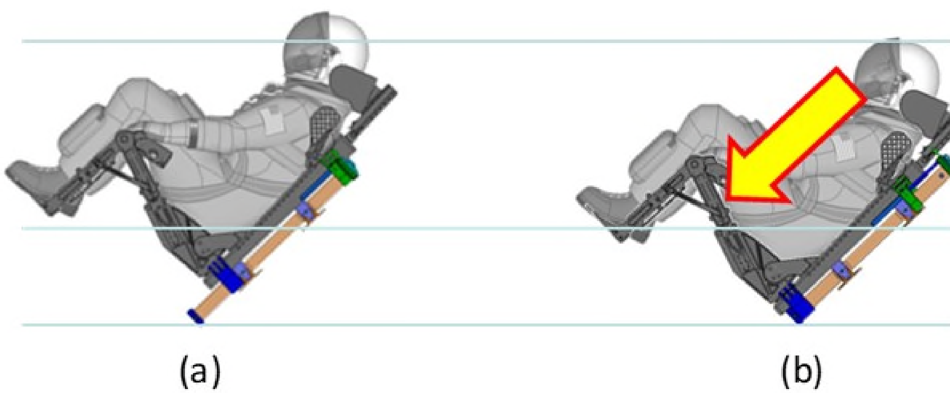

Figure 3. a) Unstroked CIAS and b) Fully Stroked CIAS

CIAS is designed to protect the seated crew occupants by limiting the crew seat accelerations to achieve acceptable Dynamic Response (DR) values for the worst cases of landing impulses (acceleration versus time) most likely to result from off-nominal landing scenarios/cases studied. The requirement is for CIAS to protect seat occupants to the low (deconditioned) DR limits (Reference Table M2.2-2 in [1]) primarily for the Z-axis (i.e., DRz) as that is the direction of travel for CIAS.

CIAS Design

Figure 4 illustrates the primary components of CIAS. Two guide rails control and direct the stroking portion of CIAS. The CIAS components that interface with the spacecraft (i.e., female guide rail supports) bolt to the backbone structure of the crew vehicle. There are four (two upper and two lower) female guide rail supports to which the guide rails are joined thus securing the CIAS into position in the crew vehicle. Two EA selector mechanisms are joined to the top of each guide rail and these mechanisms enable ground and in-flight operations crews to "tune" the CIAS for a specific weight seat and suited seat occupant combination for optimal stroking load should the need arise. The EA tubes are positioned behind the bilateral protective covers that join to the upper seat interface adapters as can be noted by close inspection of the sectioned left-hand side (LHS). The stroking portion of CIAS includes the upper and lower seat interface adapters, lateral braces, EA rollers and axles, protective covers, disengaged EA tubes, and bearings all shown in Figure 4. The EA selector mechanism design will be discussed in more detail.

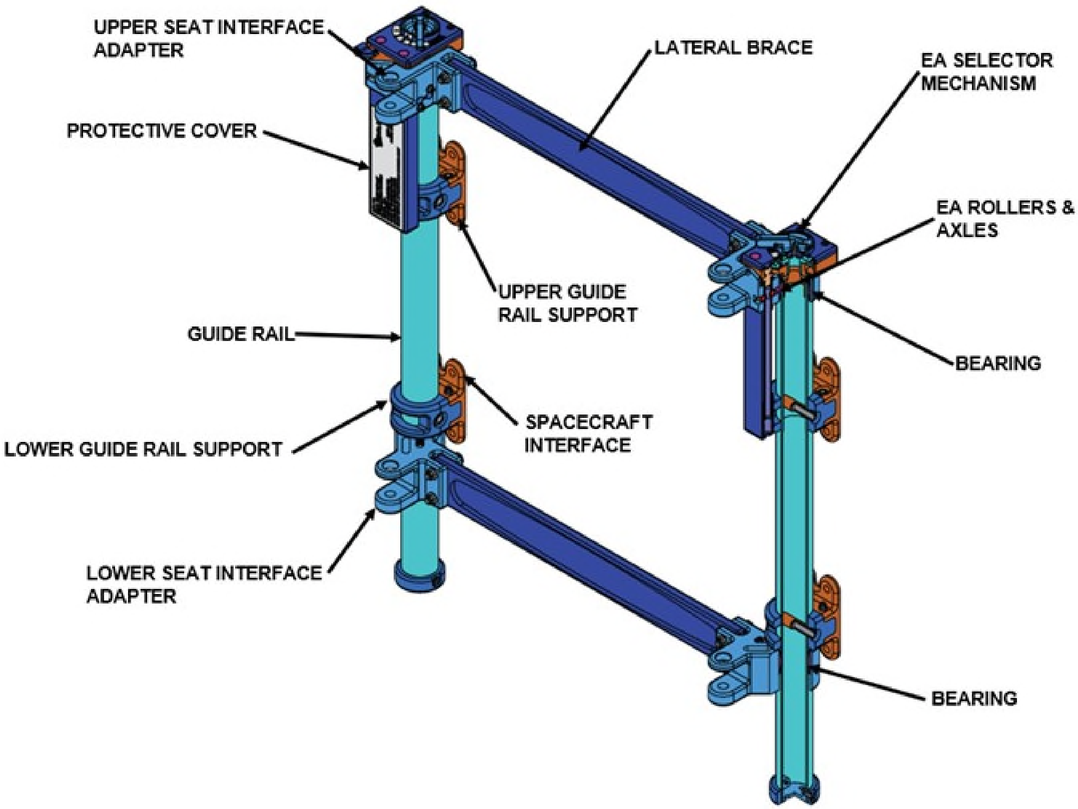

Figure 4. CIAS Primary Components

The center EA tube on each side is always engaged for each CIAS unit and these EA tubes are referred to as “fixed” EA tubes. The other two EA tubes on each side of the fixed EA tube (on each side of the CIAS – left hand side (LHS) and denoted “left” in Table 1 and right-hand side (RHS) and denoted “right” in Table 1 all with respect to the seated occupant) are referred to as “selectable” EA tubes that are selectively engaged via the EA selector mechanisms. The various combinations of these “outer” and “inner” selectable EA tubes along with the fixed EA tubes provide the appropriate energy attenuation for eight different stroking mass ranges (reference Table 1) that are subsets of the overall stroking mass range that must be accommodated by CIAS. Note the increasing number of tubes selected as the stroking mass range increases. This is necessary to adequately attenuate the higher loads associated with the greater stroking masses. This can also be noted in Figure 5 which provides a notional reference for the load versus stroke profile of the various EA tubes as the actual y-axis load and x-axis stroke distance data are redacted to protect intellectual property. Figure 6 illustrates the composite load versus stroke profile for each of the eight profiles (stroking mass ranges) noted in Table 1. Note that the composite profiles are all increasing in load per unit of stroke as stroking mass increases.

Careful inspection of Table 1 shows more EA tubes engaged on one side of CIAS as opposed to the other in several instances. Also, the load-stroke profiles of the EA tubes vary. Thus, the aforementioned significant asymmetric loading that can occur from one side of CIAS to the other must be accommodated in the structural design. In addition to the structural design strength of CIAS, the design also incorporates specially configured linear bearings in the upper and lower seat interface adapters that provide the necessary bearing support throughout the range of asymmetric load.

Table 1. Eight Stroking Mass Range Profiles with Corresponding EA Selector Lever Settings and EA Tube Engagements (Note: "Left" refers to the seated occupant's left shoulder and "Right" refers to the seated occupant's right shoulder.)

Profile	Stroking Mass Range (lb)	Left Selector Setting	Right Selector Setting	Tubes Selected					
				LF	RF	LI	RI	LO	RO
1	204 – 223	7	1	X	X	X			
2	224 – 240	8	2	X	X		X		
3	241 – 262	8	4	X	X				X
4	263 – 288	7	2	X	X	X	X		
5	289 – 310	7	4	X	X	X			X
6	311 – 340	5	4	X	X			X	X
7	341 – 365	6	2	X	X	X	X	X	
8	366 – 402	5	3	X	X		X	X	X

1, 8 = Neither
2, 7 = Inner
3, 6 = Both
4, 5 = Outer

LF = Left Fixed
RF = Right Fixed
LI = Left Inner
RI = Right Inner
LO = Left Outer
RO = Right Outer

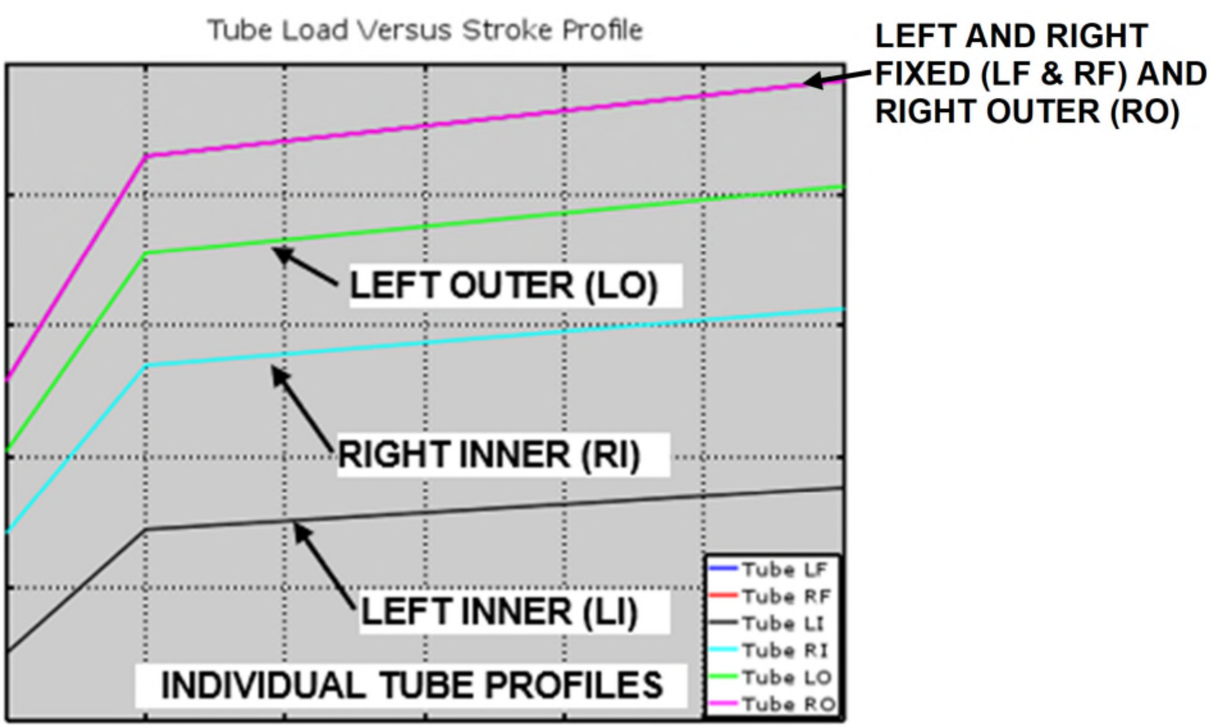

Figure 5. EA tube Load vs. Stroke Profiles Designed to Provide Adequate Range of Protection

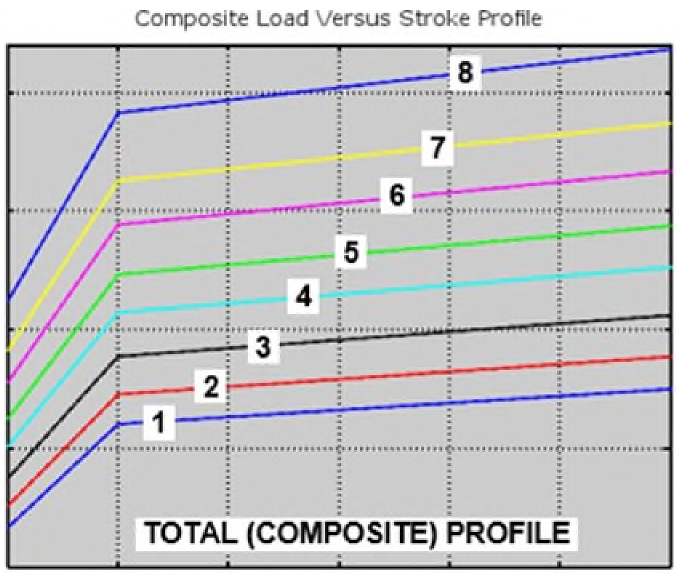

Figure 6. Escalating Load vs. Stroke Profiles for the Eight Selectable Ranges Shown in Table 1

Figure 7 illustrates the improvement in DRz (i.e., DR in the Z-axis) obtained using CIAS to attenuate high landing loads. The reduction in DRz is substantial for the more severe landing cases analyzed.

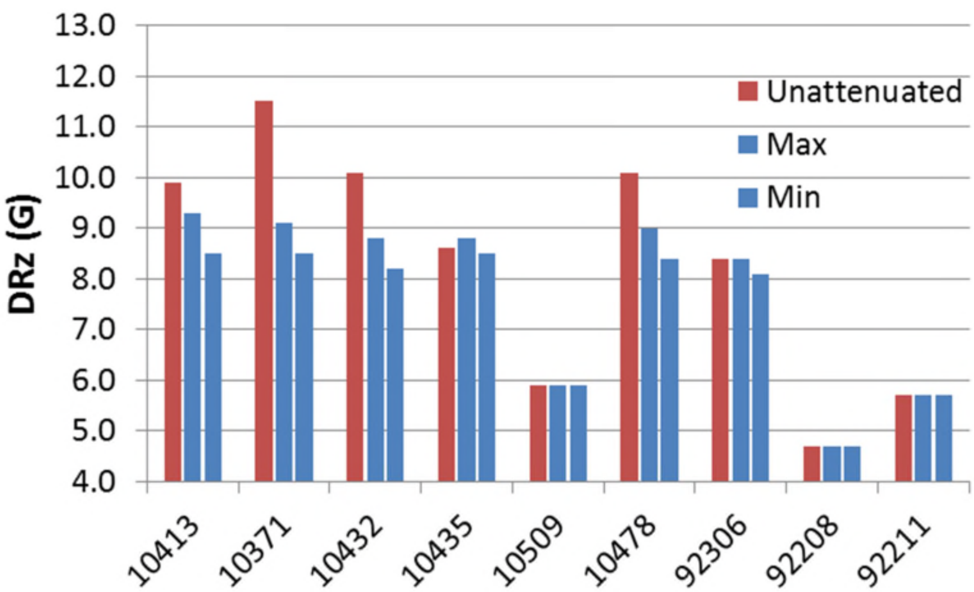

Figure 7. Reduction in DRz for Unattenuated and Attenuated Stroking Masses at Each Range Endpoint for Various Landing Cases

EA Selector Mechanism Design

In order to utilize the composite load stroke profiles and provide tuning capability for all crew member masses, a mechanism was designed to enable selection of EA tube combination in order to provide tunability. The EA selector mechanisms sit atop each guide rail and a close-up photograph of a fully assembled RHS EA selector mechanism is shown in Figure 8. The two EA selector mechanisms each have four selectable positions. One position does not engage either selectable EA tube, a second position engages only the inner EA tube, a third position engages only the outer EA tube, and a fourth position engages both the inner and outer EA tubes. The EA selector mechanism makes use of engaging (selector) “keys” that either engage a selectable EA or disengage it based on the selector lever’s numerically identified position. Table 1 shows the profile selection for eight total stroking mass ranges. It also indicates which EA tubes are engaged for each profile selection. Figure 6 illustrates the increasing load versus stroke capability of the CIAS as increasing numbers of EA tubes are engaged for the total stroking mass range accommodated in the design. Each independent EA selector mechanism includes a two-step manual lock/unlock lever (referred to as a ¼ Turn Lock Pin Assembly). To change a selection (i.e., tailor the load-stroke profile differently – to reset for a different stroking mass), the EA selector must first be unlocked by pushing in on the ¼ turn lock pin assembly compressing the contained spring and then rotating it 90 deg. This disengages the locking pin assembly from the position locating plate (not visible in Figure 8) enabling reselection by manually rotating the lever assembly to a new selection position. After the intended EA engagement selection is made, the unlocking process is reversed to re-lock the EA selector. This locking mechanism is designed to preclude inadvertent, performance degrading EA selection changes. Too high a load selection and too low a load selection are both detrimental to the safety of the seated occupant. The proper EA tube engagement can be visually verified via the EA tube engagement key view ports provided in the EA selector mechanism cover assembly.

Interior EA selector mechanism components also include a dual path cam, the EA engagement keys, and spring plunger assemblies. The dual path cam extends and retracts the EA tube engagement keys to engage/disengage the selectable EA tubes in the inner and outer positions. The spring plunger assemblies provide tactile feedback when each EA selection option position is reached. Then, re-locking the EA selector using the ¼ turn lock pin assembly further confirms the EA selection for the indicated selection number is complete.

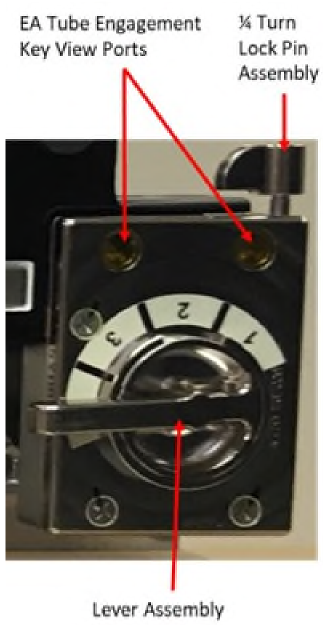

Figure 8. CIAS RHS EA Selector Mechanism Assembly

EA Selector Mechanism Design Evolution

The initial FSD design of the EA selector mechanism did not function as intended. When the FSD test article was initially fabricated and assembled, the EA selector mechanisms jammed when operated and, in some EA selection positions, they tended to lock up. Upon further inspection of the FSD EA selector mechanisms, it was determined that the original single path cam that was designed to drive both keys simultaneously had poor transition angles at some points along the cam path. The EA engagement keys are pinned to the cams and the pins, that move in the cam path, would bind at these poor transition angles. This is shown in Figure 9.

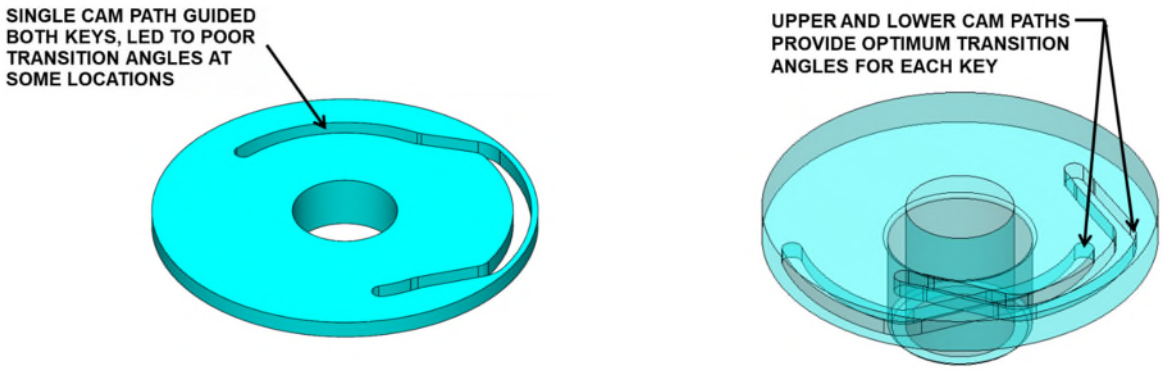

Figure 9. CIAS EA Selector Mechanism Cam FSD Design (left) and Redesign (right)

It was also determined that the original EA engagement key design led to a propensity to jam when sliding in the EA selector housing pockets. The design provided minimal support to one side of each EA engagement key. The revised design altered both the EA selector housing pockets and the EA engagement keys themselves were redesigned to ensure equal support on both sides of the key. Figure 10 shows the EA selector mechanism EA engagement keys for the FSD design and for the redesigned mechanism. Each key in the redesigned mechanism now moves linearly within a corresponding full-walled pocket in the EA selector housing and each is moved in its own cam path with the dual path cam design. Additionally, EA selector mechanism components were coated with dry film lubricant to further reduce operating friction.

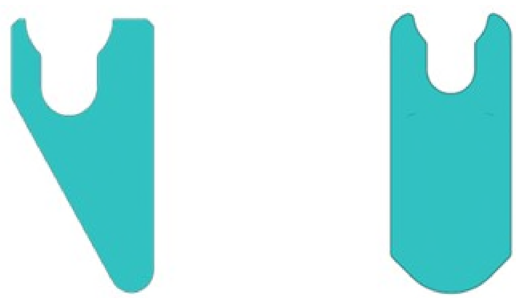

Figure 10. CIAS EA Selector Mechanism EA Engagement Key FSD Design (left) and Redesign (right)

The redesigned EA selector mechanism was modeled for a kinematic analysis to determine the functionality of the design prior to fabrication of new components. The model converged on a reasonable torque versus time solution. It is interesting to note that when the initial FSD EA selector mechanism was subsequently modeled for a like kinematic analysis, the model would not converge indicating a problematic design from an operational perspective.

Life Test Results of EA Selection Mechanisms

The EA selector mechanism functionality was life cycle tested during qualification testing to verify performance throughout intended functional life requirements. Each tuning mechanism (i.e., EA selector mechanism) of the qualification test article was fully cycled 200 times to demonstrate adequate service life. Proper EA tube engagement for each tuning mechanism selection was verified for each cycle.

The life test verified that the CIAS EA tuning mechanisms functioned normally over the total number of cycles expected to be put on the mechanism during assembly, test, and in operation with adequate margin. Operational parameters were measured throughout the test to provide quantitative data to assess acceptable and consistent EA selector mechanism operation.

Lock pin force was measured using a force gauge applied to the handle of the lock pin. A light rotation-inducing force was applied to the lever as the force to compress the lock pin was measured. Lever assembly torque was measured with a dial type torque wrench and a purpose-built adapter to interface with the selector mechanism lever. Proper EA engagement key engagement of the applicable EA tube(s) for each EA selector mechanism position was visually verified for each change in selection. Reference Figure 11 for this process.

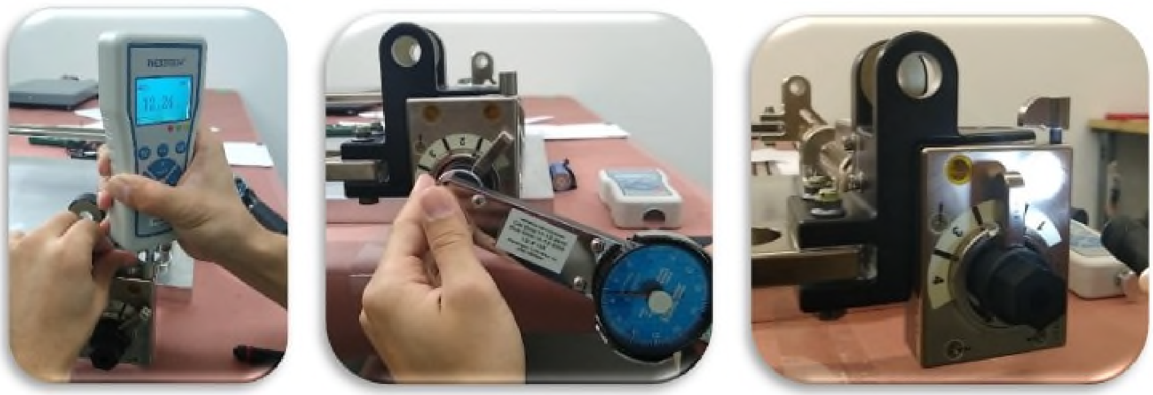

Figure 11. Measuring RHS EA Selector Lock Pin Force (Left) and Selector Torque (Center) and Visually Verifying Proper Engagement of the EA Engagement Keys (Right)

No binding, jamming, or damage was noted during testing nor was there any observed dry film lubricant debris. The maximum lock pin compression force was well below the limit for both the right and left EA selector mechanisms. The maximum lever torque was also well below the limit for both the right and left EA selector mechanisms. Data for the entire 200 cycles of life testing are plotted in Figures 12 and 13. Note that the vertical dashed lines in each graph represent the demarcation between the 15 wear-in/run-in cycles performed as part of acceptance testing and additional life cycle tests subsequently conducted as part of qualification testing. Figure 13 indicates that the RHS EA selector has slightly increasing selector torque until approximately 150 cycles. At approximately 150 cycles, the RHS EA selector torque stabilized and ran at a relatively steady state well below the limit. The higher noted selector torques are associated with the transition from position 3 to position 4 (indicated by a “+” overlay) and from position 1 to position 2 (indicated by a “×” overlay). Both of these transitions are associated with the most aggressive changes in the upper cam path within the applicable EA selector emphasizing the importance of designing in generous transition radii in cam paths.

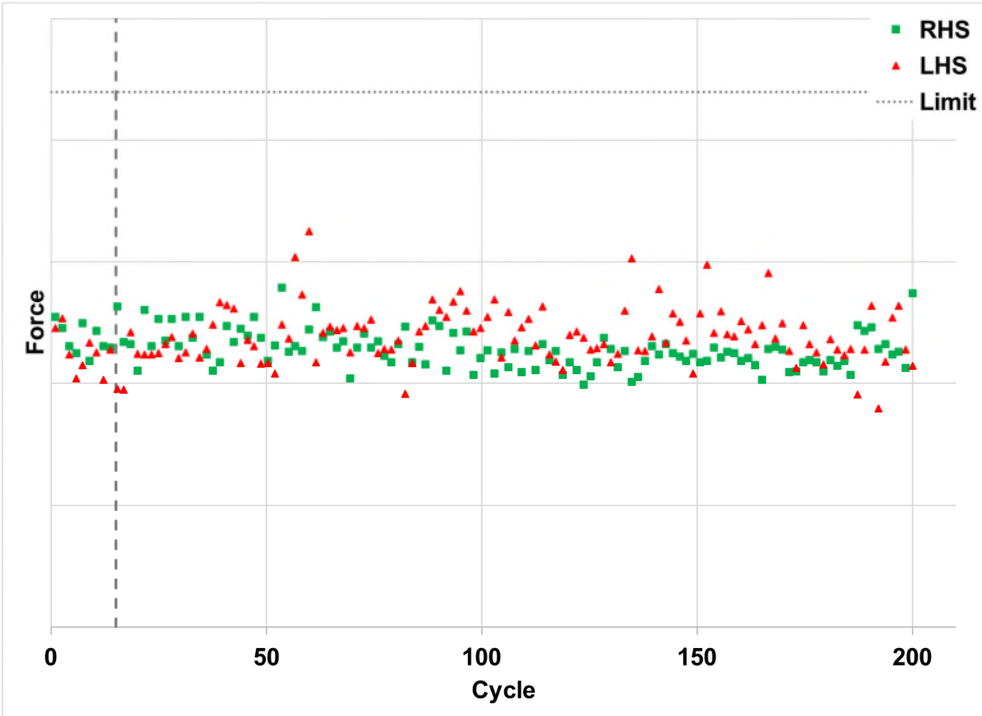

Figure 12. Measured Lock Pin Force

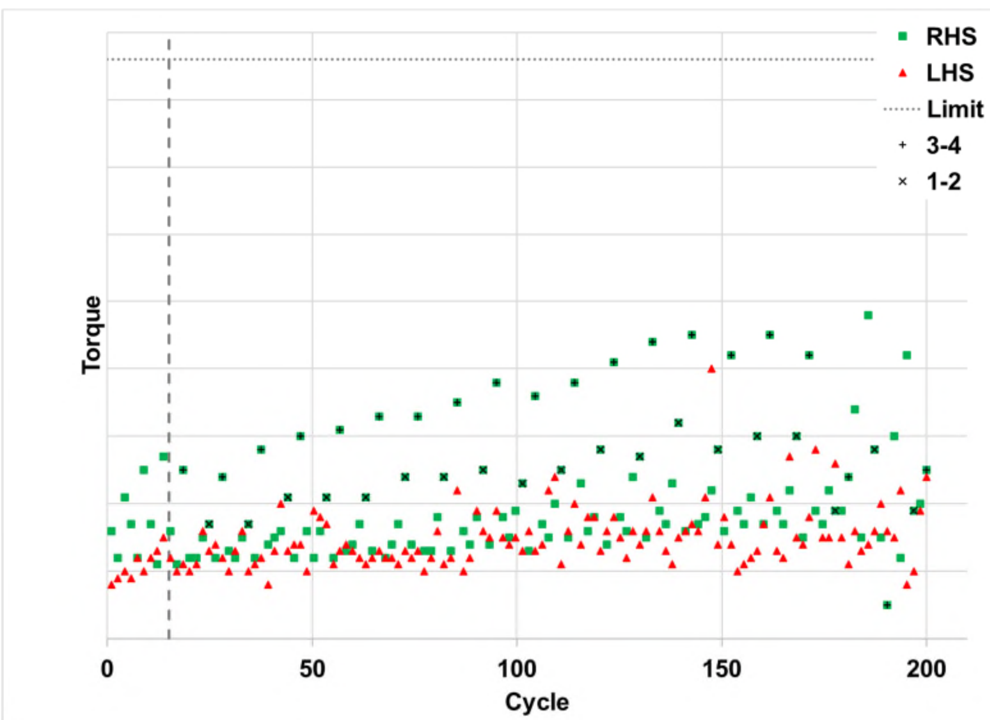

Figure 13. Measured Lever Assembly Torque

The CIAS mechanism was dynamically tested in FSD (reference Figure 14 for test setup) and qualification (reference Figure 15 for test setup for both the 1^{st}-percentile female and the 99^{th}-percentile male mass simulators). This testing was accomplished to verify load-stroke and DR performance. Maximum imbalance was also evaluated and verified acceptable. EA load-stroke was evaluated for each test case and the DR_i values were all verified acceptable. There was some small amount of pre-stroking of the CIAS observed after FSD random vibration testing at launch abort levels was performed. This was just prior to the start of dynamic impact sled FSD testing. This resulted in the design team ultimately deciding to add additional load carrying capability at the neck area of the two fixed EA tubes to reduce the likelihood of pre-stroking in flight under similar conditions. This design revision was included in qualification testing and no pre-stroking was observed post integrated vibration testing.

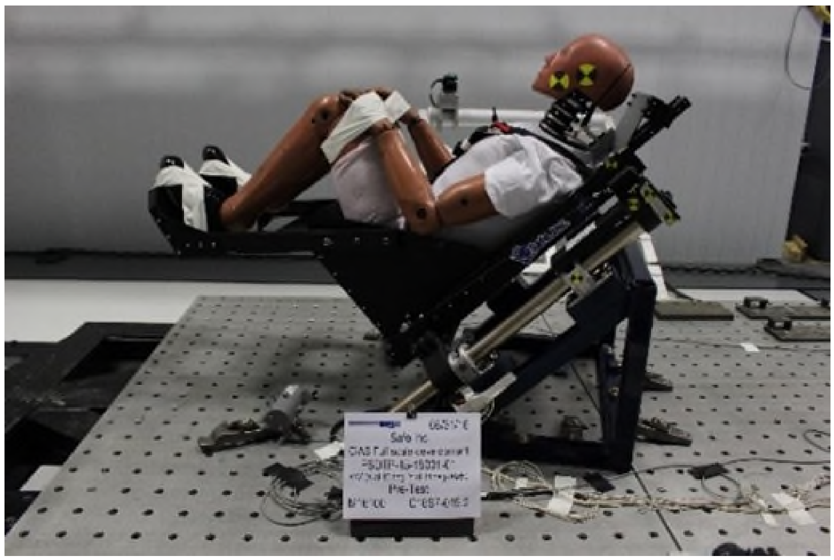

Figure 14. Dynamic Impact Sled Test Setup for CIAS FSD Testing

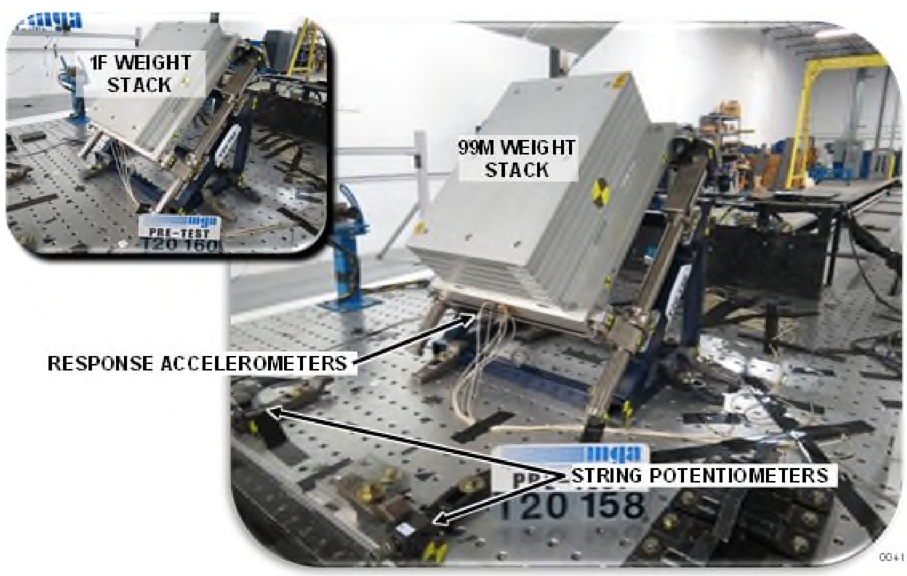

Figure 15. Dynamic Impact Sled Test Setups for CIAS Qualification Testing

Figure 16 shows a close-up of the CIAS qualification test article post-sled test #1 which used a mass simulator for the 99th-percentile male, crew seat, suit and helmet. Figure 16 is a close-up photo of the LHS EA Selector and upper seat interface adapter to provide a visual of the stroked EA tubes.

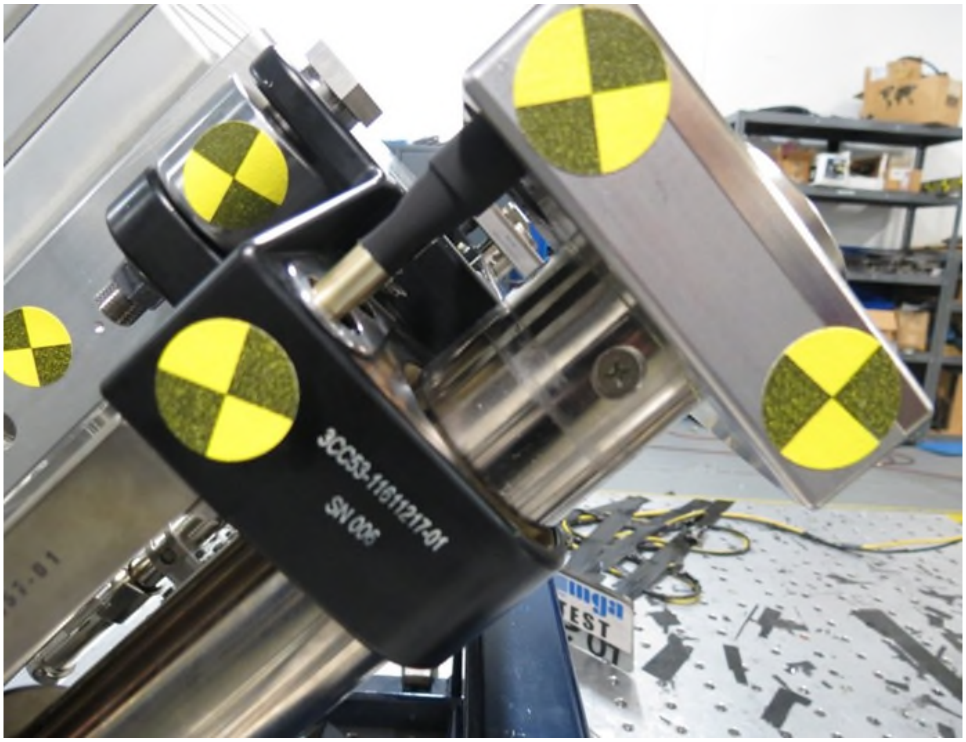

Figure 16. Dynamic Impact Sled Qualification Testing – Post Test #1 Showing Stroked LHS EA Tubes

Conclusion

The available space for CIAS limited both the number of EA tubes that could be incorporated into the CIAS, and it limited the total amount of available stroke distance. It was determined that six EA tubes of varying load-stroke profiles could be designed into the CIAS, and this would provide sufficient energy attenuation throughout the entire required stroking mass range. Two EA tubes, one on each side of the CIAS framework, remain “fixed,” meaning that they are always engaged and will stroke given an impact of sufficient energy. The remaining four EA tubes (two each side) are referred to as “selectable.” Figure 5 illustrates the load-stroke profiles of the EA tubes (numerical data removed from axes for proprietary reasons). Optimizing load-stroke profiles across the entire expected stroking mass range enables a significant reduction in Dynamic Response Index (DRI), Z-axis (DRz), as illustrated in Figure 7 for unattenuated versus attenuated high energy landing impact cases.

Several lessons learned resulted from the CIAS EA selector mechanism design to improve the likelihood of like systems functioning successfully. First, use generous cam path transition angles and do not overload the cam by attempting to transition multiple components in a single cam path. Second, design for symmetric or near symmetric support of components that must slide in tight housing channels. Third, use kinematic modeling analysis early in the design process to help identify design deficiencies likely to cause problematic/suboptimal functionality.

References

1. MPCV 70024 Revision A dated January 22, 2014, titled “Orion Multi-Purpose Crew Vehicle (MPCV) Program Human-Systems Integration Requirements.