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Overview of Integrated Random Vibration Testing of the NASA Orion Crew Survival Suit

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The launch ascent and abort random vibration environments from NASA's Orion spacecraft drove the need to test the NASA Orion Crew Survival Suit as an integrated system with exposure to the design levels. In order to properly characterize component responses, a series of integrated tests were designed to incorporate the interaction between a crew member, suit, seat, and the attenuation system. The first Development Test (2017) included human subjects, and was performed with early development seat and suit components, and low level inputs. It provided a baseline for frequency response and behavior of the integrated system. The next two tests, Development Test (2019) and Qualification Test (2020), used manikin surrogates to represent the crew member and increasing levels of component hardware fidelity in order to test to higher input levels. Testing was performed at NASA Johnson Space Center (JSC) and Kennedy Space Center (KSC) Vibration Labs and provided the input levels required to represent the ascent and abort vehicle profiles as well as recorded component response behavior from accelerometer instrumentation and high speed cameras. Inspection of the suit and related components showed that for all seat orientations, and input environments, no damage occurred. Additional pre and post-test checks confirmed the functionality of all suited hardware. Response data of the suited components generally showed heavy attenuation across most of the tested frequency range. Transmissibility plots showed some amplification of components at lower frequency ranges. Overall this series of integrated tests showed that 1) the use of surrogate manikins in the tests were adequate for representing crew in a vibration environment, 2) full vibration levels for ascent and abort were heavily attenuated in the suit components and were non-damaging, and 3) the suit and related components are qualified for the Orion random vibration environments.

Nomenclature

ACES = *Advanced Crew Escape System*
ATD = *Anthropometric Test Device*
CAD = *Crew Active Dosimeter*
CCA = *Communication Carrier Assy*
CIAS = *Crew Impact Attenuation System*
CM = *Crew Module*
DSC = *Dual Suit Controller*
EBS = *Emergency Breathing System*
FHSA = *Flexible Helmet Support Assembly*
Grms = *Acceleration Root Mean Square*
HHP = *Human Health and Performance*
JSC = *Johnson Space Center (NASA)*
KSC = *Kennedy Space Center (NASA)*
LPU = *Life Preserver Unit*
MPCV = *Multi-Purpose Crew Vehicle*
NASA = *National Aeronautics and Space Administration*
OCSS = *Orion Crew Survival Systems*
PGS = *Pressurized Garment System*
TCV = *Thermal Control Valve*
UIC = *Umbilical Interface Connector*

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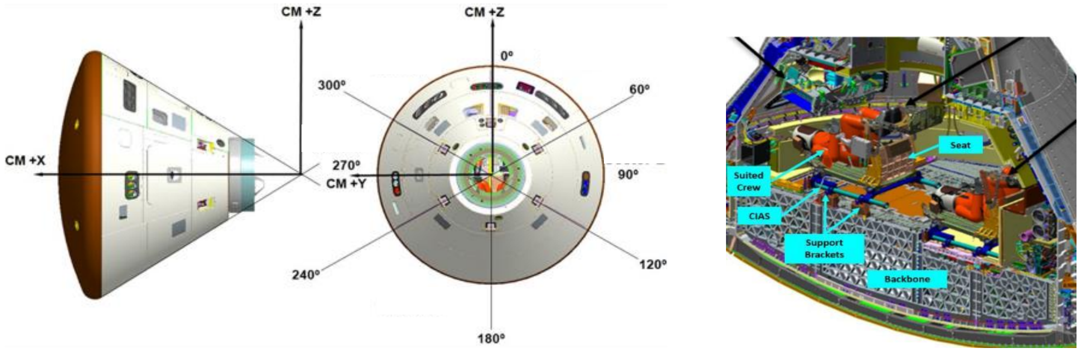
I. Introduction

NASA’s Orion Crew Module (CM) will carry four suited astronauts on the upcoming series of Artemis missions. The first mission, Artemis I, was un-manned and carried one manikin, as well as mass simulators and radiation torso simulators. All subsequent Artemis missions will carry crew, starting in 2025 with Artemis II. During flight, the crew wear Orion Crew Survival Systems (OCSS) Suits, which are protective pressure-capable flight suits that include a variety of hardware components. Crew will be restrained in adjustable seats, as shown in Figure 1, with each mounted to a Crew Impact Attenuation System (CIAS). In addition to other types of loading, the CM experiences random vibration as a consequence of the launch system design. The most significant environments are during typical launch ascent and in a potential mission abort. In order to qualify the seat, CIAS, and suit hardware components for these launch ascent and abort random vibration environments, a series of vibration tests were run from 2018-2020, named the Integrated Seat/Suit/Manikin Vibration Qualification Tests. Manikins wearing flight suits were used in the tests to represent the crew members, and the same medium-sized suited manikin used in this test series flew on the Artemis I mission. Initial tests in 2018 used human test subjects at lower environment levels. In order to capture the most realistic configuration and interface boundary conditions possible during the test, a subassembly of the CIAS, seat, OCSS Suit, and manikin was used on a vibration shaker table at both of NASA’s Johnson Space Center (JSC) and Kennedy Space Center (KSC). The test series’ were a collaboration between Lockheed Martin (LM) who developed the seat and CIAS, and NASA EC5 who developed the OCSS suit.



(a) (b)

Figure 1. Orion Crew Module (a) side and top views, and (b) cross-section internal view showing one upper and one lower seat with suited crew members.

II. Background

A. Orion Launch Environments

The Orion CM experiences random vibration throughout flight and in possible abort scenarios. The random vibration environments are broken up into X, Y, and Z axes and tested independently. The crew are recumbent upon ascent and during abort, which aligns the anatomical chest-to-back axis with vehicle X-axis and spine with the Z-axis. However, when conducting vibration testing on the CIAS-seat-suit-manikin subassembly, axis definitions and excitation directions are more meaningful when defined in a spatial reference frame with respect to the seated crewmember. Specifically, the bottom of the assembly is towards the boots, top towards the helmet, left and right sides relative to the manikin’s left and right when seated in the recumbent posture. The NASA Minimum Workmanship Standard, separate from predicted flight environments, is a minimum random vibration environment imposed on flight hardware as a requirement. For this hardware, the workmanship environment exceeded expected flight values and so was used to represent launch ascent in all axes. The maximum potential mission abort environment was used for tests Y-, Z-, and X-axes.

B. Suit and Component Overview

The OCSS Suit is worn by the crew for intravehicular activity usage in launch, re-entry, landing, and post-landing. The OCSS suits will be custom fit to each crewmember, but will retain two take-ups on each arm and leg (upper and lower) that provide adjustability in arm and leg length. The suit maintains pressure integrity and includes the multi-layer pressure garment layers, helmet, gloves, boots, non-removable connectors and fittings, emergency breathing system bottles fitting and lines, and occupant protection features, such as the helmet support assembly. Figure 2(a) shows the components of the assembly and Figure 2(b) shows the PGA layers composed of a gas containing bladder, a restraint layer to control expansion, and a protective cover layer. The TCV hardware allows the crew member to regulate the amount of cooling flowed through the Orion Suit Liquid Cooling Garment Loop system. The LPU is a dual-lobe life preserver system that provides positive buoyancy in the event of a crew member entering the water. The EBS provides emergency breathing oxygen to the crewmember for emergency pad egress, and on-orbit or post-landing emergencies. The CCA provides communications during all suited phases of flight, as well as low profile head bump protection and hearing protection during ascent or abort. The boots additionally contain integrated flail restraint interfaces that attach to a mating connector on the Orion seat footpan.

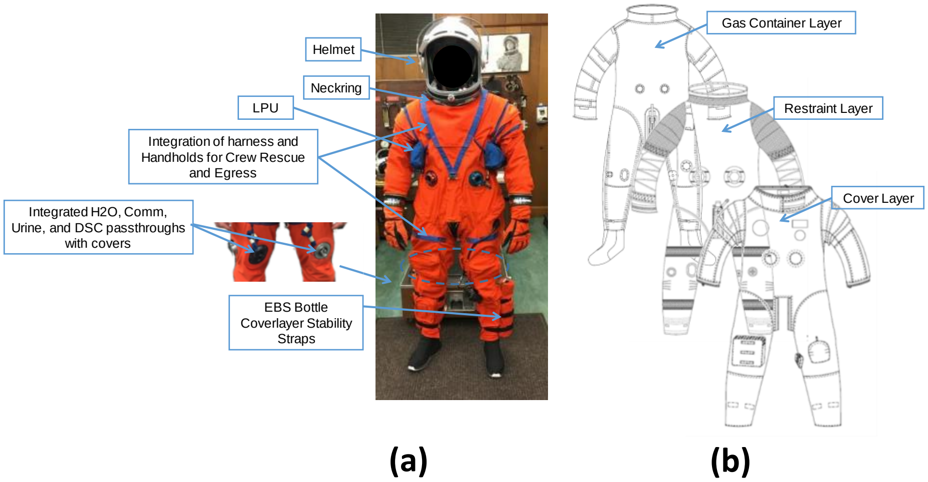


Figure 2. NASA OCSS Suit (a) assembly and components, and (b) pressure garment assembly layers.

C. Previous Testing

Another Development Test run and processed in the 2017/2018 timeframe used suited humans as the test subjects. The goal of the test was less focused on potential damage to the Suit hardware, and more focused on human factors, such as ability to operate computers under various random vibration environments. Accelerometers were placed on the chest of the Suit and on the Helmet to record responses at these locations. Comparisons of frequency content and overall energy transfer were made between these human subject tests and the 2019 Development Test in order to assess the suitability of using the suited manikin as a suited human surrogate. While not every location on the suit had response measurements for comparisons, the assessments at the chest and Helmet locations were enough to conclude that the thoracic cavity and head/neck complex behaved sufficiently similar between the human and manikin. These comparisons led to approval of using the manikin in the 2020 Qualification Test. Following the 2020 Qualification Test, the frequency content and overall energy in the responses was again compared back to the two development tests and found to be a sufficient match.

III. Methods

A. Test Setup

A shaker table provided the random vibration environment profiles used to test the integrated seat, manikin, and OCSS suit. Since different axes needed to be tested, the shaker table arrangement and seat mounting location onto the table were modified. Figure 3 shows examples of the seat orientation in the X, Y, and Z axes. Artemis I medium-sized and large-sized "Rescue Randy" manikins were used to represent crew members of 50th and 95th percentiles, respectively. Suit fabric and suit-worn components together added approximately 17% and 10% mass to the two manikins, respectively. The NASA OCSS team provided Modified ACES suits and hardware for the Artemis I medium-sized and large-sized "Rescue Randy" manikins, and suited the manikins at the Crew Survival Lab at NASA JSC prior to shipping to the test facility. The Liquid Cooling Garment (LCG) was also installed on the manikins under the exterior Pressure Garment Assembly (PGA). Final positioning and attachment of suit-worn components (e.g. Helmet, connectors, etc.) was done on-site by authorized personnel from the OCSS team. Table 1 shows the breakdown of instrumentation between tests, and Figure 4 shows the component locations. The OCSS Suit components that were considered to not have a mechanical effect during the previous developmental vibration tests and have therefore been eliminated from the Qualification Series include the Life Preserver Unit (LPU), Dual Suit Controller (DSC), Umbilical Interface Connector (UIC), Crew Active Dosimeter (CAD), and Search and Rescue Beacon.

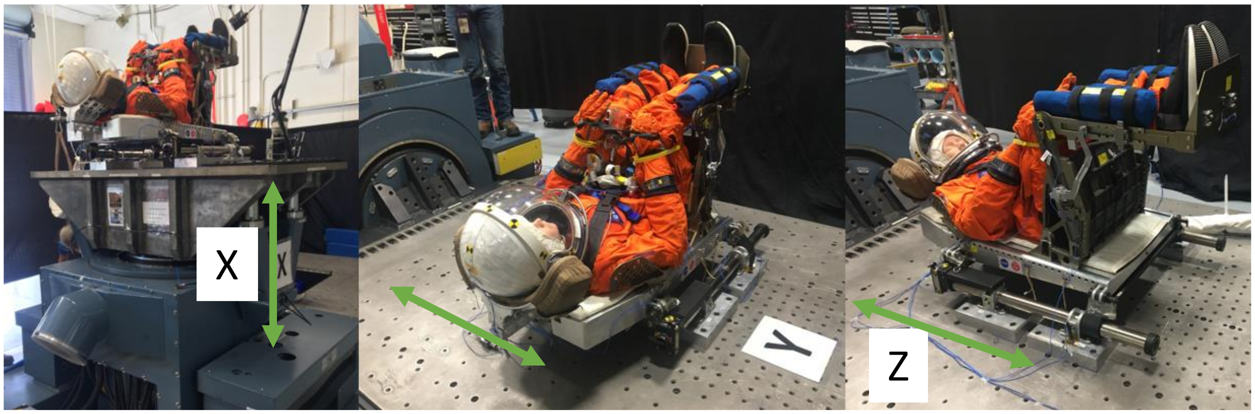
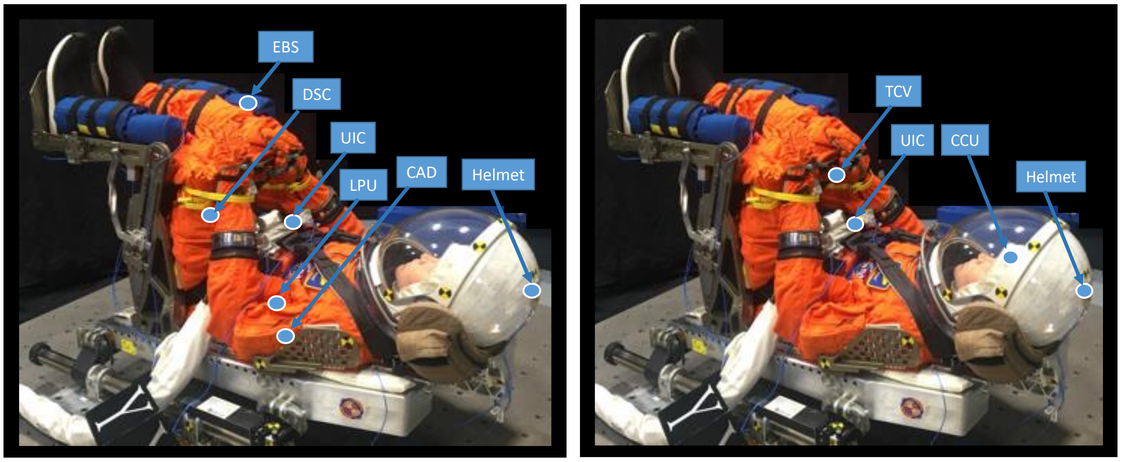


Figure 3. Vibration Shaker Table Test Setup Axis Orientations.

Table 1. Summary of Suit Components with Distinction of Instrumentation Between Development and Qualification Testing.

Suit Component	Instrumented in Dev Test	Instrumented in Qual Test	Justification
CommCap/Manikin Head (CCA)	No	Yes	Not tested in Development Test
Thermal Control Valve (TCV)	No	Yes	Not tested in Development Test
Umbilical Interface Connector (UIC)	Yes	Yes	Repeat data for comparison between Tests
EBS Bottle Reducer	Yes	No	Exempt based on Development Test and heritage
Helmet	Yes	Yes	Repeat data for comparison between Tests
Dual Suit Controller (DSC)	Yes	No	Similar hardware, mounting method, and location to TCV
Crew Active Dosimiter (CAD)	Yes	No	Soft mounted - Very low response in Development Test
Life Preserver Unit (LPU)	Yes	No	Soft mounted - Very low response in Development Test



(a) (b)

Figure 4. Location of Suit Component Accelerometers in the (a) Development Test and (b) Qualification Test.

B. Test Cases

Ideally every possible combination of variables involved in the testing would be varied and tested individually, but in order to achieve a practical test, a subset matrix was devised. The variables under consideration were manikin size, seat orientation, load scenario, and vibration level. After review of the vibration profiles that Orion could experience, the two loading scenarios selected for test were ascent and abort. The Minimum Workmanship Standard (MWS) vibration profile was found to envelope the ascent Case possibilities for Orion, and was therefore used to represent ascent. For both ascent and abort profiles, an additional test factor was applied to the input environments per NASA internal requirements. Since a cooperative goal with the suit testing was to test the Orion Seat, the largest manikin was chosen to pair with the abort case. That was predicted to be the most stressing case for the seat and CIAS, albeit a contingency abort case with the heaviest possible crew member. The 50th manikin was paired with the ascent Case to represent a most likely scenario. Due to the complex geometry of the seat, CIAS, manikin and suit assembly, all three axes were chosen to include in the test matrix. Table 2 shows the sequence of tests used in the Qualification Testing. For ascent, each axis contained four tests: 1) a random survey for pre-health check of all the hardware and instrumentation, 2) a fixture evaluation with the ascent profile but lowered, 3) the full test level including test factor, and 4) a post-health check identical to the pre-health check. For the abort cases, the fixture evaluations were removed since, by then, the table was performing as expected. The idea behind the sequence is to monitor the behavior of the system at a low even random level before and after testing to identify if hardware or instrumentation was damaged, disconnected or significantly shifted. The fixture evaluation was added to the ascent cases in order to verify the fixture was meeting the intended profile and allow for any adjustments to the table settings or control accelerometers.

Table 2. Summary of Qualification Test Sequence.

Flight Event Profile	Axis	Test	Purpose
Ascent Profile	Y	Random Survey (Low Level)	Pre Health Check
		Ascent Profile (Lowered)	Fixture Evaluation
		Ascent Profile including Test Factor	Full Level of Test
		Random Survey (Low Level)	Post Health Check
	Z	Random Survey (Low Level)	Pre Health Check
		Ascent Profile (Lowered)	Fixture Evaluation
		Ascent Profile including Test Factor	Full Level of Test
		Random Survey (Low Level)	Post Health Check
	X	Random Survey (Low Level)	Pre Health Check
		Ascent Profile including Test Factor	Fixture Evaluation
		Ascent Profile	Full Level of Test
		Random Survey (Low Level)	Post Health Check
Abort Profile	Y	Random Survey (Low Level)	Pre Health Check
		Abort Profile including Test Factor	Full Level of Test
		Random Survey (Low Level)	Post Health Check
	Z	Random Survey (Low Level)	Pre Health Check
		Abort Profile including Test Factor	Full Level of Test
		Random Survey (Low Level)	Post Health Check
	X	Random Survey (Low Level)	Pre Health Check
		Abort Profile including Test Factor	Full Level of Test
		Random Survey (Low Level)	Post Health Check

C. Measures of Performance

NASA Suit hardware is subject to a large set of requirements and follows a specific planned Qualification sequence of tests and assessments. Part of the sequence may include structural tests, vibration tests, specific functional tests, or more detailed inspections or disassembles performed at the end or in the middle of the Qualification sequence. Vibration tests discussed here are one in a series of the Qualification assessments with no visible structural damage by inspection as the assessment method. The Suit and associated hardware are expected to respond to the flight environments, but there are no required numerical limitations on the response. Disassembly of hardware was not approved as part of the vibration test portion of the larger sequence, as long as no damage was identified. The team relied on visual inspections, as thorough visual assessments by the team of the suit and related hardware before and after every test for any indications of damage. In addition to visual inspections, the random surveys before and after every test were compared before continuing to the next test. The goal was to identify if any of the instrument responses were notably different in magnitude or frequency as this would indicate a major change in the hardware, such as damage or major shifting. Additionally, a variety of performance measures were checked on the seat and CIAS, mainly checking for any mechanical damage. Test hardware, including instrumentation and associated cabling, was also checked for damage or any signs of loosening. Response measurements of the hardware taken in the test were not strictly required, but were performed to improve understanding of the system. While the details of the full Qualification sequence and subsequent assessments cannot be published, it can be noted that NASA would revisit approval of the Qualification upon any hardware issues tracing back to the vibration tests.

D. Test Objectives

The main test objective for the suit and related hardware was to survive the exposure to the vibration environments without loss of structural form fit or function. The LCG and TCV portions of the suit were ‘charged’ with water so an additional related goal was to visibly confirm no leakage from any of the components. Data recorded during the tests for the various components was used to evaluate amplification and attenuation at the frequency range of the input spectrum. While there was no specific limits for amplification, the development test was first used to explore the behavior of the system and to help guide the Qualification Test. After review of the Development Test data, the amplification was not considered to be extreme, nor at a large frequency band. The objective in the Qualification test was then decided to re-test with any updated hardware and identify if any significantly different behavior occurred.

E. Known Test Limitations

As with any test series, there are some known limitations. The Seat and suited hardware used throughout the testing series were as close to flight-like as possible using up-to-date designs at the time of test. With the available budget and schedule, the various test series were limited to 1-2 weeks of testing. The number of test cases was therefore limited to approximately 20 runs per series with some compromises on the test variables discussed in the Test Cases section of this paper. Limitations in the size of the DAS used in the test facility limited the number of channels available for hardware instrumentation. Additionally, some channels were needed to instrument for table control, and the Seat and CIAS hardware. With a limited number of channels available, the suit hardware was instrumented strategically between the Development and Qualification Test Series to cover the suit components.

Another test limitation was using manikins to represent humans as the transfer media between the vibration input and the Suit hardware. Assessments of previous testing showed good comparisons in frequency content and energy transfer using measurements at the chest and Helmet regions. While these comparisons were enough to approve the use of manikins in the Qualification Test of the Suit hardware, humans have a wide variety of anthropometry and there would likely be some differences in the vibratory responses across the entire Suit with differences in body composition. Additionally, locations away from the chest and head/neck region were not measured in the early tests, so no information about behavior at extremity locations is available. While variations in vibratory response of the Suit hardware locations would likely exist across the wide array of human anthropometry, it is believed the general response trends found through these test series would be consistent.

Nonlinear response behavior was expected for varying input environments due to the nature of hardware components incorporated onto softgood fabrics, and then worn on the body as a Suit. The tests were guided by imposed requirements for maximum duration of maximum ascent and abort environments with the goal of stressing the hardware components and mountings. Limitations on resources, funding, and schedule prevented further investigation that would be needed to fully quantify and understand any nonlinear trending.

IV. Results

Hardware components on the OCSS Suit were instrumented with accelerometers at the Integrated Seat/Suit/Manikin Vibration Development and Qualification Tests to measure suit level responses. Data was processed to calculate transmissibility over the tested frequency range as a ratio of output to input, using accelerometer measurements from the vibration table as the input. Figure 5 shows these on-axis calculated suit component transmissibilities plotted over the tested frequency range for ascent and abort input profiles as well as input axis. A horizontal dashed line was added to the plots to show the transition from attenuation to amplification on the transmissibility axis.

Figure 6 shows the same type of data as Figure 5, but highlights a direct comparison between two suited components, Helmet and UIC, that were both measured in the same location and using the same method between the Development Test and the Qualification Test. As discussed in Section III-A and shown in Table 1 of this paper, these two components were directly repeated in the two tests, but had slight differences in the hardware maturity.

Grms response values, representing total energy, were calculated for the full tested frequency for each axis of each component. Figure 7 then shows this as a ratio of output response to input, representing the percentage of total energy reaching each component. A Grms for the amplified portion of the response curve, representing the energy within the amplified frequency range, was also calculated for each component. Figure 8 then plots these amplified region response results for the Suit components, showing ratios of amplified response Grms to the total input Grms, as percentages. Because the off-axis component responses generally had fewer regions of amplification, a summary of the full frequency range Grms percentage, as well as the amplified region Grms percentage is shown in Table 3.

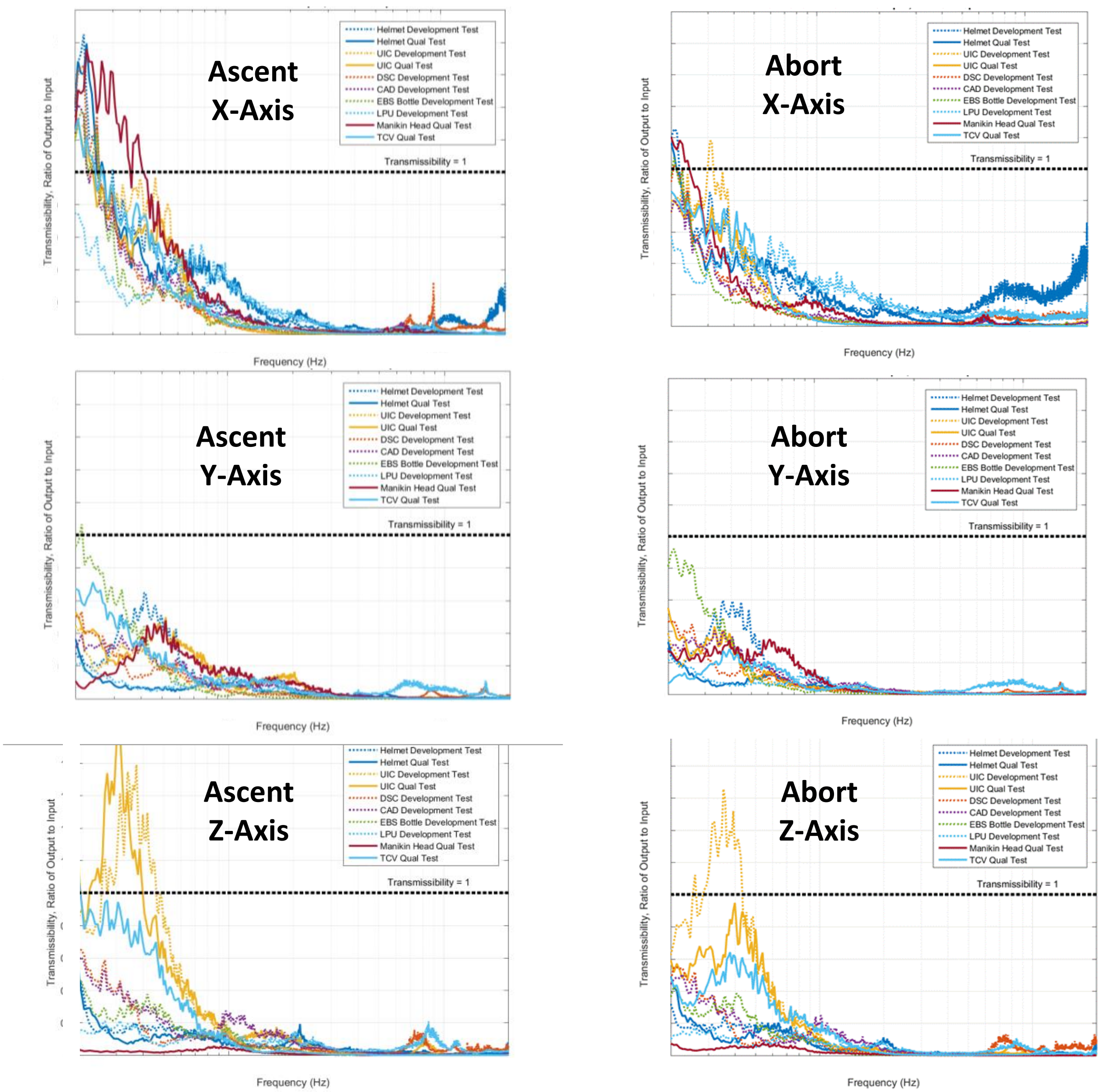


Figure 5. Development and Qualification Test On-Axis Transmissibility by Suit Component for X, Y, and Z Test Axes and Ascent and Abort Input Profiles.

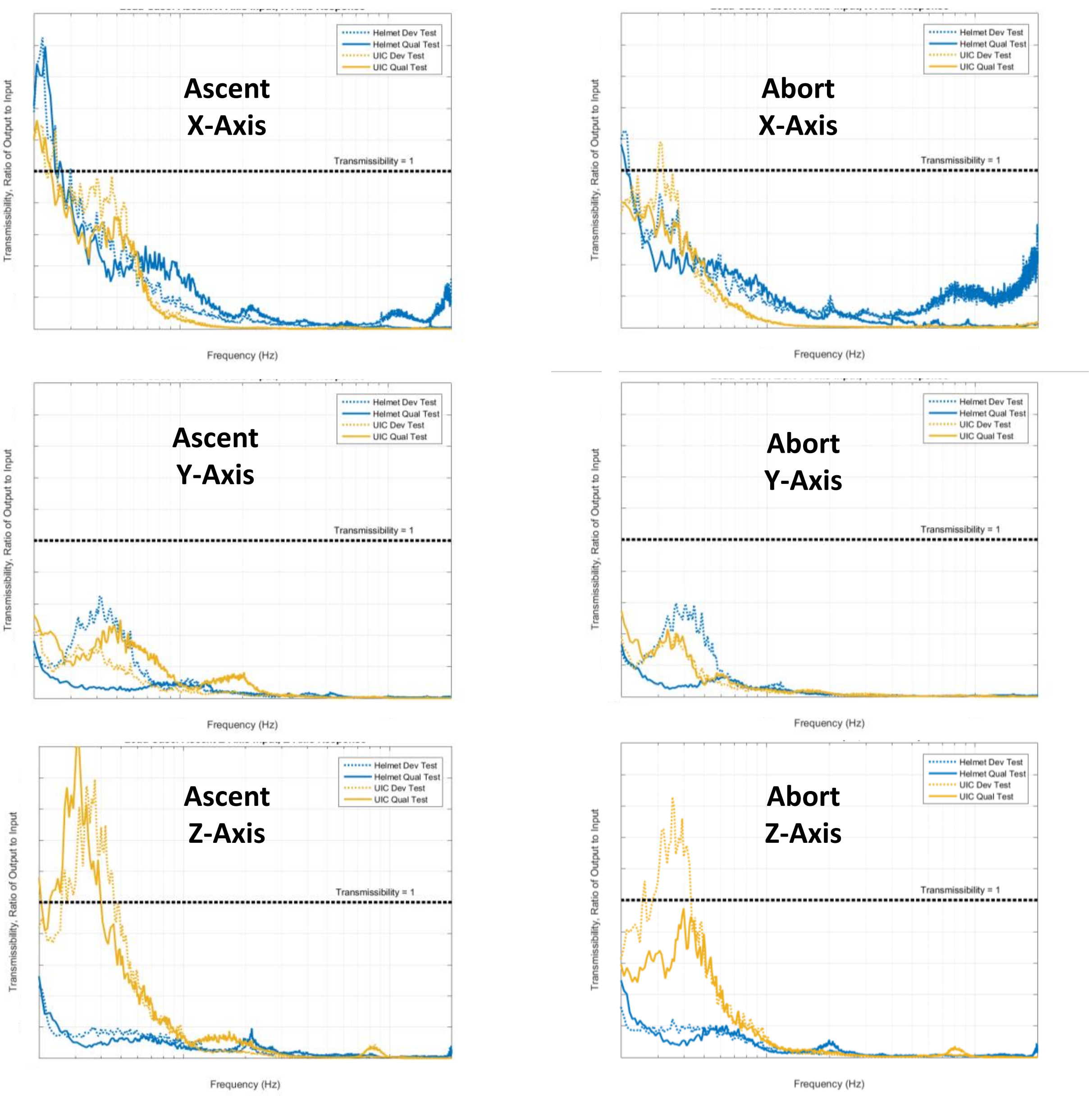


Figure 6. Development and Qualification Test On-Axis Transmissibility for Repeated Instrumented Suit Components (Helmet and UIC), X, Y, and Z Test Axes and Ascent and Abort Input Profiles.

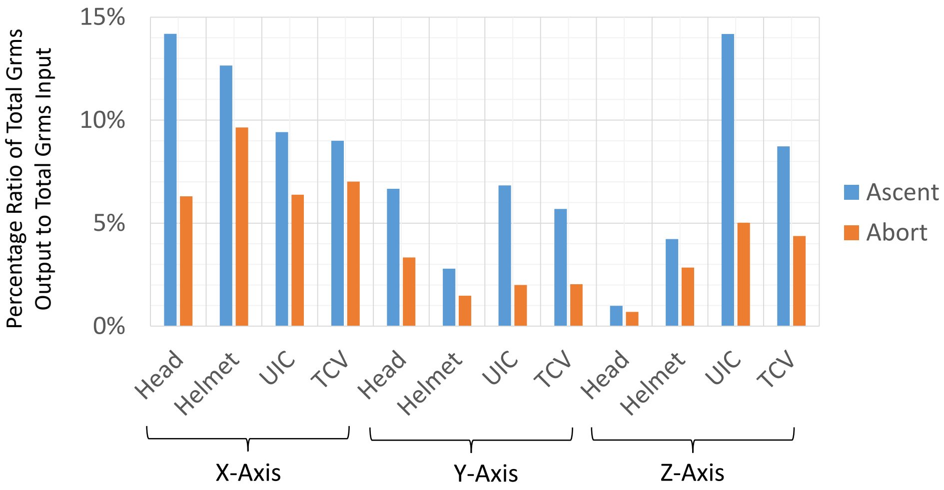


Figure 7. Ascent and Abort Case Component On-Axis Responses from Qualification Tests, as a Ratio of Total Grms Output to Input.

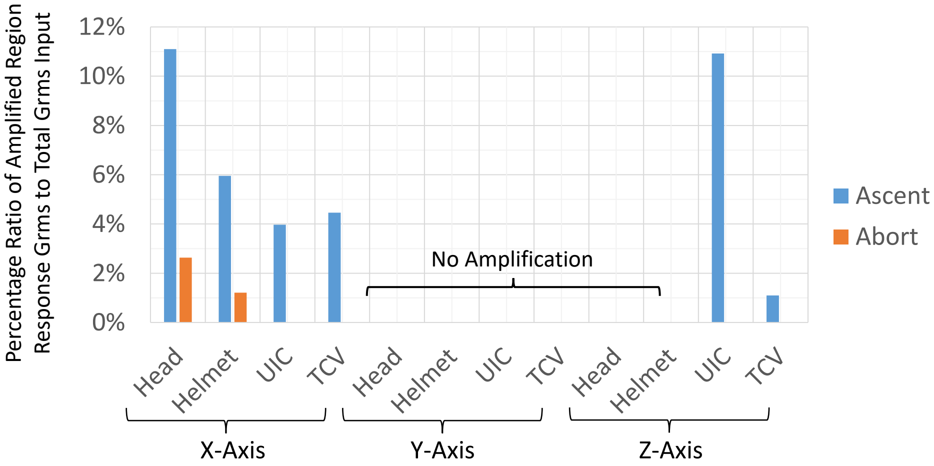


Figure 8. Ascent and Abort Case Component On-Axis Responses of Amplified Regions from Qualification Tests, as Ratio of Amplified Region Response Grms to Total Grms Input.

Table 3. Summary of Components with Regions of Off-Axis Amplification.

Input Profile	Input Axis	Output Axis	Response Accelerometer Location	Full Frequency Range Ratio (Grms output / Grms input)	Amplified Region Ratio (Amplified Grms output / Grms input)
				[%]	[%]
Ascent	X	Z	UIC	9.0%	1.1%
Ascent	Z	X	Helmet	19.2%	1.1%
Abort	Z	X	Helmet	9.7%	0.4%

V. Discussion

Based on review of the transmissibility plots, the OCSS Suit components showed amplification in the lower frequency range. Generally, more amplification was seen in ascent than abort, attributing to the nonlinearity of the system. Comparing the Helmet and UIC, which were both instrumented the same way in the Development and Qualification Tests, the responses compared well for ascent cases in amplitude and frequency content, but the abort cases showed some differences in amplitude. The expected contributing difference in the tests causing more energy to reach the suit components was the use of a medium manikin in the abort Development Test and a large manikin in the abort Qualification Test. The additional mass likely increased the attenuation of the system. While some variation in the transmissibility plots shows differences in the amount of attenuation and amplification, the overall conclusion of mostly attenuated energy holds. This was further evidenced by the overall percentage of attenuation, with less than 15% of the energy input into the system reaching the suit components. For on-axis response, the amplified region response Grms varied, but accounted for under 12% and under 3% of the total input Grms, for ascent and abort, respectively. Three off-axis response cases, for two suit components (UIC and Helmet), showed amplification with output to input ratio of Grms as high as 19.2%. These cases can be explained by the cantilevered nature of the two components allowing energy from the input axis to drive the perpendicular response of the output axis.

VI. Conclusions

The plot comparisons between the Helmet and UIC show similar behavior across the frequency ranges for X, Y, and Z, ascent and abort Cases. No major trend differences or magnitude differences were seen across the tested frequency ranges between tests for these on-axis comparisons. Total response Grms was less than 15% of the total input Grms for all cases, and on-axis amplified response regions all remained under 12% of the input Grms, so most of the energy input to the system is attenuated before reaching the Suit component level. Additionally, off-axis ratios of response output to input ranged from 9% up to 19.2%, but were found to be non-detrimental to the hardware.

For the plots with all of the Development Test and Qualification Test responses plotted, all of the responses at the suit level measured in the Qualification Test were considered to fall within the family of the Development Test responses. Qualification Test trends and magnitudes look similar or are lower than the Development Test. Variations are expected in this data due to the variations in setup, and the nature of softgoods in general. In addition, while the suited components were very similar across tests, the seat used in the Development test was a development level seat that had been used in several tests before including many rounds of dynamic impact testing, while the Qualification seat was new and had some design differences. For ascent cases, the manikin was the same in Development and Qualification Tests, but for the abort cases, the Development Test used the medium manikin and the Qualification Test used the larger manikin. Since similar trends were seen in frequency range and attenuation of the suited components with similar and differing underlying manikins and hardware, it was concluded that the trends in attenuation seen in the suit components is likely driven mostly by the soft mounting and less by the differences in manikin mass and size. Each future Artemis crew member will be unique and have varying anthropometry, so it will be beneficial that the attenuation trends of the suit components are expected to occur in all actual flight cases despite variations.

Considering the nonlinear nature of this entire tested system, some variations between the plots were expected but the similarities showing consistency are 1) seeing similar trends in the frequency regions that are attenuated, 2) seeing similar trends in the frequency regions that are amplified, 3) seeing similar magnitudes of amplification and attenuation. While a unique spaceflight system and set of environments was tested, the general trends are likely to be consistent with similar flight systems and Suits and potentially allow for reduced scope and cost of testing. Overall, while test limitations exist, testing with the use of max enveloping environments, test factors on the input environments, and full duration in successive environments showed the OCSS Suit hardware is capable of withstanding expected flight conditions.

VII. Forward Work

With random vibration testing completed for the OCCS suit, the additional upcoming work relates to the continued development and testing of the OCSS suit and components. Following this series of tests, the Qualification program continues with additional tests to fully stress the hardware beyond expected environments. Additionally, these suits will undergo impact testing with manikin and human subjects to assess occupant protection metrics and fit/comfort. Further work could be performed to correlate this tested response data of suited manikins with human vibration analysis models that are currently used to integrate with structural finite element models. There is also a potential to study acute human injury related to low frequency amplification of components mounted to the body, as was seen across some of the components in this set of test cases.

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References

[1] NASA Columbia Crew Survival Investigation Report, NASA/SP-2008-565, 2008.

[2] NASA Columbia Accident Investigation Board Report, Volume 1, 2003.

[3] J. Somers, J. Melvin, A. Tabiei, C. Lawrence, R. Ploutz-Snyder, B. Granderson, et al., "Development of Head Injury Assessment Reference Values Based on NASA Injury Modeling," Stapp Car Crash Journal, vol. 55, pp. 49-74, 2011.

[4] K. D. Klinich, "NHTSA Child Injury Protection Team. Techniques for Developing Child Dummy Protection Reference Values. NHTSA Docket No. 74-14, Notice 97, Item 069.," National Highway Traffic Safety Administration, Washington, DC, 1996.

[5] M. Kleinberger, E. Sun, R. Eppinger, S. Kuppa, and R. Saul, "Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems," National Highway Traffic Safety Administration, Washington, DC, 1998.

[6] R. Eppinger, E. Sun, F. Bandak, M. Haffner, N. Khaewpong, M. Maltese, et al., "Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems - II," National Highway Traffic Safety Administration, Washington, DC, 1999.

[7] R. Eppinger, E. Sun, S. Kuppa, and R. Saul, "Supplement: Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems - II," National Highway Traffic Safety Administration, 2000.

[8] J. Suhey, D. Gohmert, S. Jacobs, M. Baldwin, "Development of a Novel Helmet Support Assembly for NASA Orion Crew Survival Suit," 49th International Conference on Environmental Systems, Boston, MA, July 2019.