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International Space Station Microgravity Analytical Model Correlation And Update

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ABSTRACT

The acceleration environment aboard the completed International Space Station (ISS) is a key resource for scientific and technological endeavors. Hardware verification activities and early measurements indicate that the ISS is well on the way of meeting these "Assembly Complete" "microgravity" provisions, however, the simulation models that compute these accelerations have, to date, lacked the high degree of empirical validation typical of standard aerospace industry practices. Assembly stage, on-orbit measurements are used to address this shortcoming and to develop higher confidence in the simulation models. The Phase 1 correlation results show the analyses to be consistently conservative, producing higher than measured levels. The 25 to 30% greater quasi-steady computations are deemed acceptable for verification. Updates are made to localized structural dynamic and vibroacoustic parameters that reduce responses in selected one-third octave bands by almost 50%. These models are then used for the Assembly Complete verification analysis which concludes that the ISS vehicle meets the ISS microgravity requirements with minor reservations. Two of the sixteen racks are marginally non-compliant in the quasi-steady regime, and operational constraints are needed on the U. S. Lab and ESA APM vacuum resource vents, and the Russian Resistive Exercise Device in the structural dynamic regime.

INTRODUCTION

The International Space Station (ISS) has been designed to insure that the extreme, low acceleration levels inherent in an object in orbit are preserved and exploited.[1] The design has been tailored to a set of microgravity requirements that apply to the final vehicle configuration, designated as Assembly Complete (AC) (Figure 1). At Assembly Complete, the ISS program begins a minimum of 10 years of mature operations during which the vehicle configuration and its microgravity environment will remain relatively stable. It is during this phase that most of the microgravity science research will be planned for and accomplished. Thus, the capability to confidently predict the acceleration environment for these periods is paramount to design to requirement convergence, operations support, and future mission planning.

One of the ISS microgravity challenges is the inability to conduct integrated structural ground test of the assembled vehicle for model correlation. This is simply a consequence of its size, flexibility, and execution costs. The AC ISS has a wingspan from one end of the central truss structure to the other of 356 feet, and the photovoltaic arrays span some 290 feet from tip to tip. It will weigh approximately 1 million pounds and contain some 43,000 cubic feet of pressurized volume with structural vibration modes starting below 0.10 Hz. So even with component ground tests, the ISS program has had to accept greater system model uncertainty than many classical aerospace programs due to the lack of system level model validation.

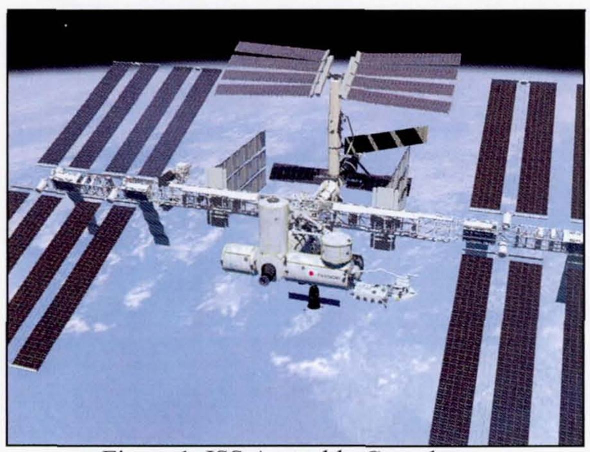

Figure 1: ISS Assembly Complete

Another challenge presented by the microgravity requirements is the breadth of the frequency range over which they apply. Spanning from 0 to 300 Hz, the design, analysis, and control of the microgravity environment necessitates a multi-disciplinary approach from vehicle attitude control to the acoustic emissions of fans.

Assembly stage ISS on-orbit data can be used to address these challenges by providing measurements from intermediate configurations that can lead to the development of high confidence, AC, microgravity simulation models and tools. This work began in 2001 following the delivery and initial outfitting of the U.S. Laboratory "Destiny" module, and was reported on at the 40th Aerospace Sciences Meeting in January 2002.[2] Additional work was performed in 2002, and are reported, herein. These efforts combined with the completion of the Active Rack Isolation System (ARIS) ISS Characterization Experiment (ICE) led to the final contractual verification analyses of the ISS AC microgravity requirements. These results are also presented and discussed.

At this time, the initial truss elements have already been assembled and "Destiny" has functioned as a research platform for over a year with continuous ISS habitation for over two years. Figure 2 contains a photograph of the current configuration taken by an STS-113 crewmember on board the Space Shuttle Endeavor following undocking from ISS on December 2, 2002. As seen in the imagery, ISS construction is well underway with primarily truss elements and International Partner modules to go. The module on top of the ISS stack, with the "dangling" Space Station robotic arm, is the U.S. laboratory module. It is here, within the 28.8 feet long, 14.6 feet diameter, "Destiny", that microgravity research will be focused and where the microgravity requirements apply.

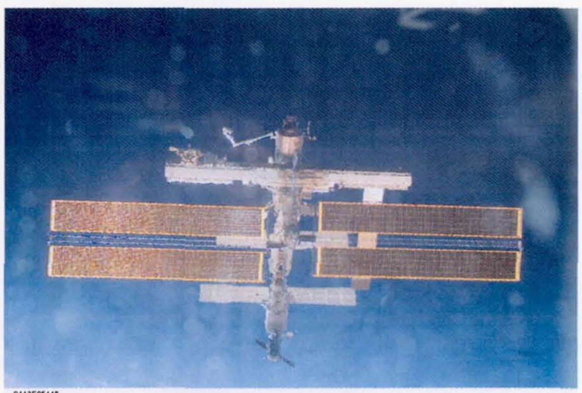

Figure 2: ISS Stage 11A

MODEL CORRELATION & UPDATE

The model correlation and update activities to date are based on measured acceleration data from the ISS Stage 7A configuration captured in the summer of 2001. Stage 7A is similar to Stage 11A less the three integrated truss segments, S1, S0, and P1. These can be seen in Figure 2 parallel to the large, "golden" solar arrays above the aft end of the "Destiny" module. The measurements were obtained with the Microgravity Acceleration Measurement System (MAMS) and the Space Acceleration Measurement System (SAMS) that are installed in the "Destiny" module and managed by the NASA Glenn Research Center (GRC) Principal Investigator Microgravity Services (PIMS) project. ARIS ICE sensors were also utilized and most of the data was collected in conjunction with ARIS ICE activities.

The capabilities of these measurement systems and their application to the suite of microgravity analysis simulations is detailed in reference 2 and will not be repeated here. The measurements are used in each of the simulation areas necessary to determine requirement compliance. These span three technical disciplines designated as: quasi-steady, structural dynamic, and vibroacoustic. The quasi-steady assessment is closely related to the Guidance, Navigation, and Control arena based on closed loop, multi-rigid body models determining the acceleration environment from 0 to 0.01 Hz. The structural dynamic assessment is associated with classical Loads and Dynamics tools based on structural dynamic finite element methods and address the 0.01 to 50 Hz range. Vibroacoustics may be considered a technical discipline in and of itself with relationships to both the structural dynamics and the acoustics fields. The vibroacoustic assessment is performed with statistical energy analysis methods and covers the 50 to 300 Hz regime.

Quasi-steady

MAMS data was acquired during a crew sleep period on October 17, 2001. This was compared with the baseline analytical results obtained with the Space Station Multi-Rigid Body Simulator (SSMRBS), and SSMRBS flight specific reconstructions using complimentary vehicle state vector information from the Operational Data Request Center (ODRC) and NOAA measured solar flux. The baseline case represents a set of conditions for requirement compliance assessments as defined in the ISS Microgravity Control Plan.[3] The flight specific reconstructions utilize available flight and environmental data for improved correlation with measurements.

Figure 3 shows approximately three orbits of acceleration magnitudes compared to the baseline analysis and flight specific reconstructions.[4] The baseline conditions results are conservative, as intended, with peaks ranging from 1.7 to 0.6 μg versus a much tighter measured range of 1.1 to 0.9 μg. The flight specific reconstructions show improved correlation with the "best" case peaks similar to the measured values. The "best" case results were obtained by iterating parameters associated with the drag coefficient and mass properties. These parameters are the key remaining variables with uncertainty that need to be quantified. It was found that with a 100% diffuse drag coefficient, rather than a 60/40 diffuse to spectral split, and a one foot offset in the MAMS location, the magnitude vector is within 1% of MAMS data. In addition, the predicted altitude degradation is within 2% of flight data.

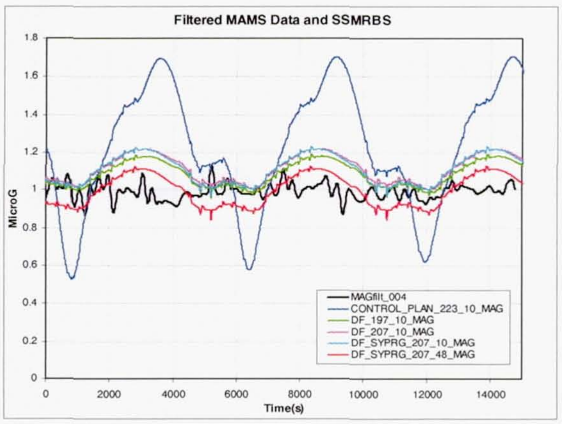

Figure 3: Quasi-steady Correlation

The quasi-steady model correlation and update work to date establishes confidence in the SSMRBS simulation tool and methods for downstream microgravity requirement verification and operational support. The results indicate that the verification mandated operational conditions produce acceleration magnitudes that are 30% greater than measured levels. This substantiates the conservative intentions of the verification prescription and suggests that a reasonable margin is so introduced.

This work will be repeated on additional assembly stages to assure its repeatability and to exercise models with ISS truss segments and discrete quasi-steady disturbances, such as experiment vacuum resource vents. Emphasis will be placed on improved SSMRBS drag correlation, and mass properties identification that can not only benefit the microgravity community, but also help the Guidance, Navigation, and Control and Mass Resources teams.

ARIS ICE

The structural dynamic and vibroacoustic correlation efforts utilized data generated as part of the ARIS ICE activity. These tests were conducted to determine the measured, on-orbit isolation capability of ARIS. The ARIS concept is to isolate the entire rack from the ISS acceleration environment to minimize loss of payload volume versus sub-rack approaches (Figure 4). The rack is isolated by effectively detaching it from the station structure and then holding it relatively motionless within a 0.50 inch sway space via an active control system. This "position" loop portion of the control system has a bandwidth from approximately 0 to 0.01 Hz. Umbilicals remain connected to the rack to support power, fluid, vacuum, and data communication transfer as required by the science payload. Any remaining undesirable forces transmitted from the station to the rack by these custom designed "low stiffness" umbilicals are canceled by the "acceleration" loop portion of the active control system. The "acceleration" loop is active from approximately 0.01 to 10 Hz. The active control system consists of electronics, inertial accelerometers mounted in the rack, voice coil type actuators with photodiode position sensors, and pushrods placed between the rack and the station as depicted in the Figure 5 schematic. Note that there are no visible ARIS components other than the corner "snubbers" in the Figure 4 implementation example.

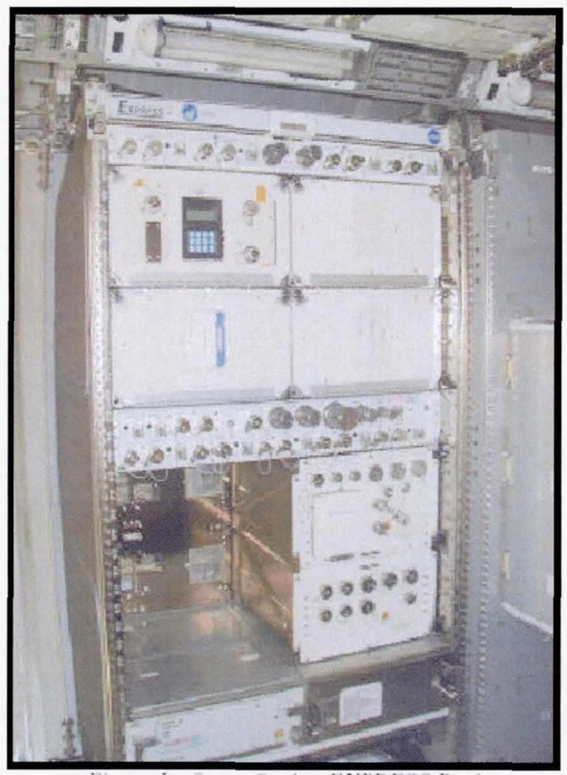

Figure 4: ARIS Isolated ISPR

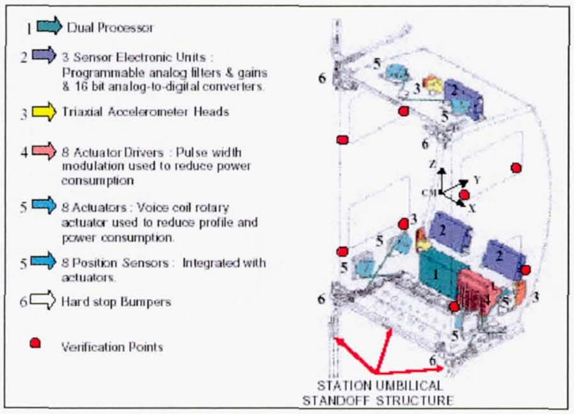

Figure 5: ARIS Components

Results from the ARIS ICE were reported at the World Space Congress in October of this year.[5] Figure 6 is an excerpt that compares the assembly stage station acceleration environment to the isolated acceleration environment on the rack against the ISS microgravity requirement level. It incorporates 5 hours of nominal crew awake data plus an additional 9 minute test in which a crew member excited the local standoff structure by tapping it with a small rubber tip hammer. The excitation was necessary to demonstrate the required isolation levels in the higher frequency regimes because the ambient station levels were not sufficient. The graph shows the max/min envelopes for both the station and rack accelerations over these times. The ARIS provides approximately –20 db of attenuation per decade (factor of 10 per decade) from approximately 0.01 through 1 Hz and then levels out due to umbilical and rack structural dynamics through the higher frequencies. The actual flight derived isolation levels were used to update the ARIS isolation requirements that were incorporated into the AC verification analyses.

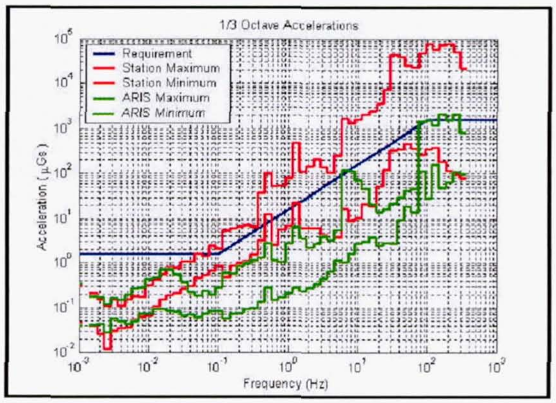

Figure 6: ARIS ICE Measured Acceleration Levels With Impact Hammer Excitation Above 5 Hz

Structural Dynamics

The structural dynamic correlation focused on the acceleration ratio between the rack "z-panels" of the ARIS outfitted rack and the adjacent rack in the ISS 7A.1 configuration rather than on the actual response levels due to the uncertainty of the input forces. The term "z-panel" applies to the umbilical pass through panel beneath each rack and describes its gross cross-sectional feature. It represents the predominant input source to the isolated rack via the umbilicals (see Figure 7).

Figure 7: "Z-Panel" With Umbilicals

The correlation effort utilized the ARIS ICE "hammer tap" and "shaker" tests. These "z-panel", "forced", ARIS tests were used to produce the necessary ISS acceleration levels above 5 Hz to establish isolation capabilities. Analytically, "hammer tap" forcing functions were generated based on the "tap" signature of the measured acceleration response at the driving point. Voltage levels were used to define the "shaker" forcing function based on ground calibrations. These were then applied to the 7A.1 configured finite element model and the one-third octave band response ratios between "z-panels" were compared to the measured case. The "hammer tap" and "shaker" tests allowed the use of a single forcing function in the analytical construction as these events resulted in a significant increase to the background levels in the measured data above 10 Hz. Figures 8 and 9 contain examples of the on-orbit measured "z-panel" acceleration response to the "hammer tap" and "shaker" respectively.

Figure 10 plots "hammer tap" test-to-analysis one-third octave band ratios in the 20 to 50 Hz frequency range. This range captures the primary "z-panel" modes within the structural dynamic domain. Values greater than one indicate that the analytical results are conservative with a smaller ratio between panels reflecting less structural attenuation. The average value of approximately 1.5 suggests reasonable and conservative correlation. Both modal damping and "z-panel" boundary conditions were adjusted to obtain the improved correlation levels associated with the "modified" model curve.

Unfortunately, the "shaker" test analytical results visually showed poor correlation with the measured data. This was attributable to the dwell time duration mismatch between the provided sweep profile and the on-orbit data at a number of frequency steps. Directional uncertainty complicated the "hammer tap" tests and close-up video was used to ascertain the "normalcy" of the strike. Despite these limitations, the correlation effort resulted in improved "z-panel" boundary conditions and provided valuable insight to the model validity in the mid-frequency range.

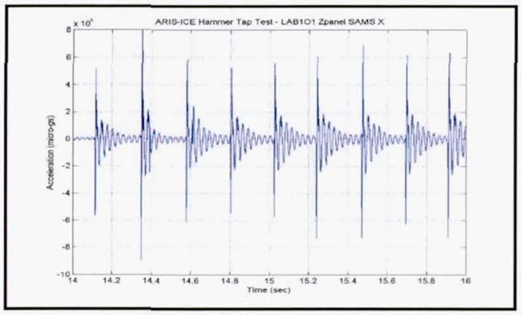

Figure 8: "Z-Panel" Hammer Tap Response

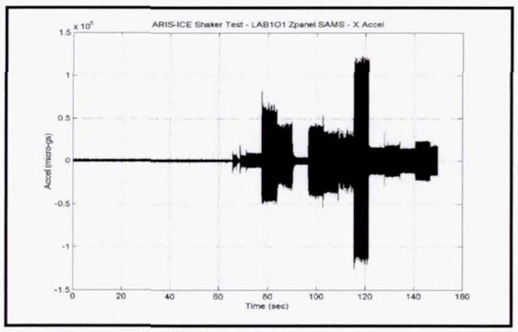

Figure 9: "Z-Panel" Shaker Response

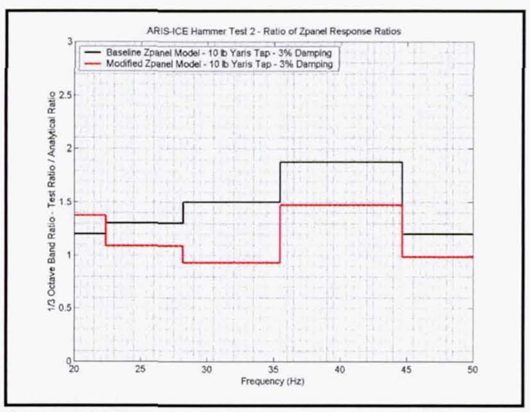

Figure 10: Structural Dynamic Adjacent "Z-Panel" Acceleration Response Ratio Correlation

Vibroacoustics

The vibroacoustic correlation effort is similar to the structural dynamic effort in that both used the ARIS ICE "hammer tap" data and the acceleration response ratios between adjacent "z-panels". As seen in Figure 11, the "hammer tap" response remains at least an order of magnitude above the background acceleration levels throughout the 50 to 300 Hz vibroacoustic regime offering a good correlation data set. However, unlike the structural dynamic effort, the statistical energy analysis (SEA) model was limited to the U.S. Laboratory rendition shown in Figure 12 rather than the integrated 7A.1 system simulated in the finite element model. Such an approach is justified for correlation at the "z panel" level given the propagation losses at the higher frequencies and the localized mode approach inherent in statistical energy methods.

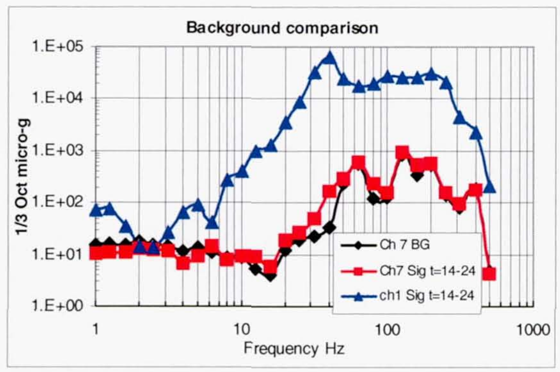

Figure 11: "Hammer Tap" Vs. Background Levels

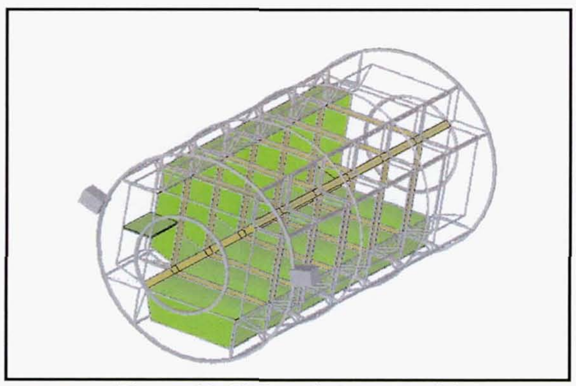

Figure 12: U.S. Lab SEA Model

Figure 13 presents the baseline results that shows the analysis ratios approximately an order of magnitude greater than the on-orbit data except in the 250 Hz one-third octave band. Increased damping levels derived from the test data (0.25% to 4%), updated "z-panel" modal density values obtained from detailed correlated finite element models, and increased mass loading (8 pounds) to account for attached umbilicals and hardware were implemented to improve the correlation results to the levels shown in Figure 14. The average ratio over the nine one-third octave bands encompassing the 50 to 300 Hz range was reduced by 40% while still maintaining reasonable margin.

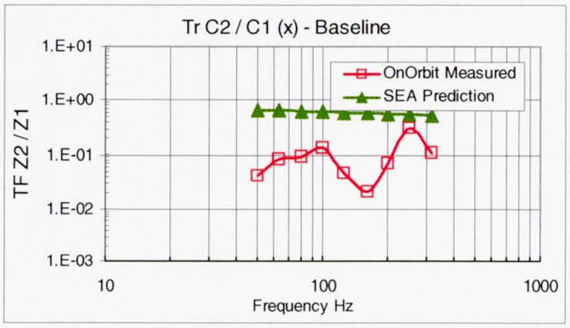

Figure 13: Vibroacoustic Adjacent "Z-Panel" Acceleration Response Ration Correlation With Baseline Model

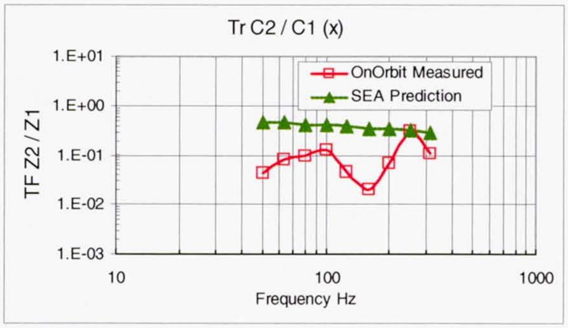

Figure 14: Vibroacoustic Adjacent "Z-Panel" Acceleration Response Ration Correlation With Modified Model

ASSEMBLY COMPLETE VERIFICATION ANALYSES

The model correlation work just described contributed to the microgravity AC verification analyses. Selected model updates identified from the correlation effort were incorporated into the AC configuration simulation models. Forcing functions from microgravity disturbance sources were then applied to these models and the acceleration responses at the ARIS rack to module interfaces were computed and compared to the ISS vibratory and transient microgravity requirements. For quasi-steady requirements, the rack geometric center is used. The model correlation work also increased confidence in the analytical methods and models by establishing that the analysis results compared reasonably well, albeit consistently conservatively, with the measured data.

The significant forcing functions were themselves subject to ground test. The actively isolated treadmill was suspended in a high bay and load sensors measured the interface forces (Figure 15).[6] The passively isolated ergometer was similarly tested but on an air bearing table. The rotary joints were exercised at ambient and at temperature conditions, at atmosphere and at vacuum pressures, from which enveloped torque inputs were ascertained.[7] Interface accelerations were obtained from the Russian Segment Service Module ground tests in which all major disturbance sources were operational and then used to "base drive" the finite element and vibroacoustic models.[8] The European Space Agency (ESA) developed forces at the component level from Columbus Attached Pressurized Module (APM) thermal control and environmental control sub-system tests.[9] ESA used test configuration measured transfer functions in conjunction with the operational acceleration responses to back out forces. The U.S. Laboratory module was also instrumented at Kennedy Space Center (KSC) and both acceleration response and transfer function testing performed.[10] Because of access limitations the transfer functions obtained at KSC did not originate at the disturbance sources so that forces could not be derived as in the ESA sub-system tests. However, these transfer functions, both mechanical and acoustic, and the operational acceleration responses did provide an early indicator of the validity of the analytical results and confidence in the program's capability of achieving microgravity compliance.

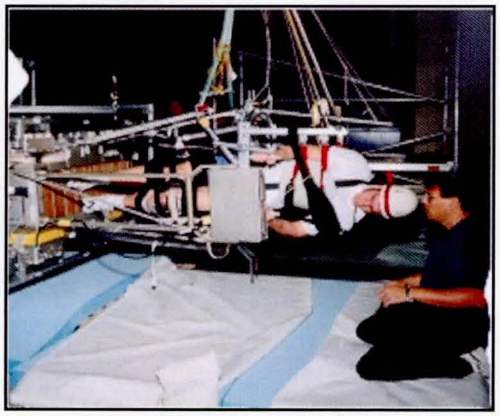

Figure 15: Isolated Treadmill Horizontal Test

Further support of achieving this goal is provided by the many hours of on-orbit measurements recorded by the PIMS SAMS and MAMS accelerometers and the ARIS ICE results. Figure 16 is a sample of SAMS data collected at the "z-panel" at the forward end U.S. Lab ceiling rack, the ARIS outfitted rack. The graph shows the max/min values as well as the

75th, 50th, and 25th percentile 100 second one-third octave band acceleration levels that occurred over a one hour time period. Note that much of the data is below the ISS vibratory microgravity requirement even without the isolation afforded by the ARIS. However, it is dangerous to arrive at a final conclusion on the AC microgravity environment based on this relatively early assembly stage, single rack location data.

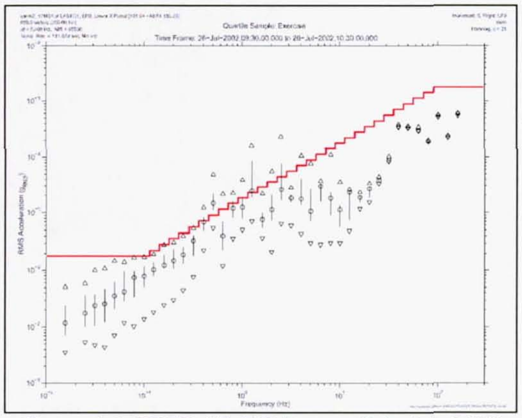
Figure 16: PIMS SAMS Data – July 26, 2002

The ARIS ICE demonstrated the systems mechanical and controller robustness to life on-orbit and established its isolation capability. The ISS isolation requirement was subsequently updated to these levels (Figure 17), and the AC verification analyses employ these isolation "transfer functions" to post process the non-isolated outputs from the standard simulations prior to requirement compliance assessments. It should be noted that above 30 Hz the influence of the rack structural dynamics is retained in the results preventing the second order roll-off characteristics of a passive isolator to continue.

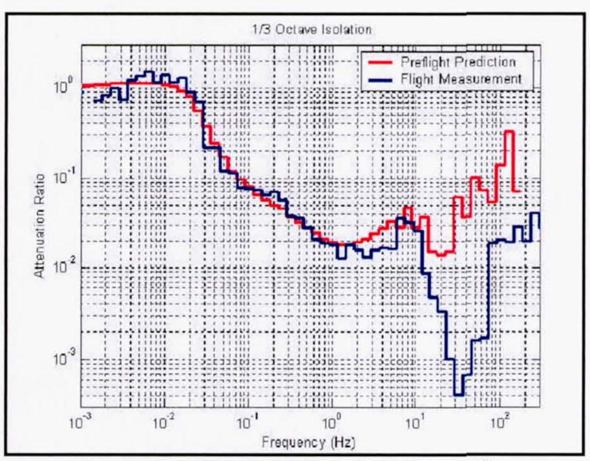

Figure 17: ARIS ICE Isolation Capability

Quasi-steady

The Assembly Complete quasi-steady verification analyses determined that 14 of the 32 payload rack locations are compliant with the 1 μg magnitude and 0.2 μg perpendicular component quasi-steady requirements.[11] While this is less than the required 50% or 16 racks, the non-compliances are minimal (15th rack at 1.11 μg and 16th rack at 1.17 μg) and are driven by configuration dependant gravity gradient accelerations. Figure 18 illustrates the situation with the ESA APM and NASDA JEM modules, extending to the left and right of the forward leading Node2, cut by the 1 μg contour lines. (The JEM module is identifiable by its external platform closest to the right border of the drawing.) The U.S. "Destiny" module contains 12 of the 14 compliant locations. Figure 19 demonstrates the gravity gradient/torque equilibrium attitude dependency as it shows a compilation of quasi-steady magnitude performance for various conditions at each payload rack location. A comparison of cases "BL" and "BL_NOAERO" shows no change in the number of compliant racks even when drag induced accelerations are eliminated, leaving only the gravity gradient dominant terms. The "BL" case represents the baseline verification results because it uses the verification ground rules set in the ISS Microgravity Control Plan. The "BL_Dist" case adds the response of six individual disturbance sources that have been identified as long duration, quasi-steady sources to the baseline case with no change to the number of compliant racks.

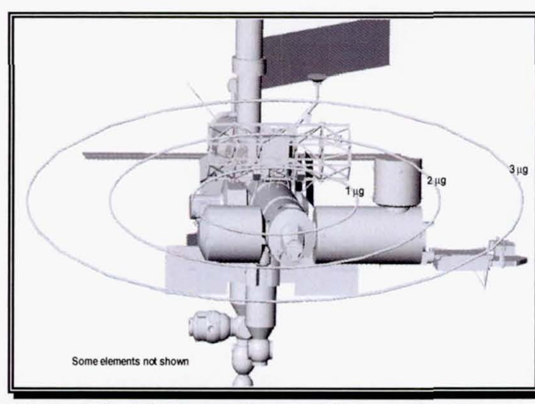

Figure 18: AC Quasi-Steady Magnitude Contours

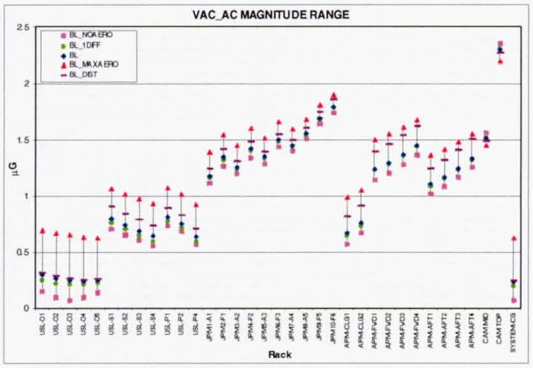

Figure 19: AC Quasi-Steady Magnitudes Vs. Assessment Conditions

Structural Dynamics

The Assembly Complete structural dynamic verification analyses determined that at least 50% of the payload racks, consistent with those that meet quasi-steady requirements, comply with the vibratory and transient microgravity requirements.[12] The vibratory requirement applies to the combined acceleration environment and is formulated as a 100 second, root-mean square limit per one-third octave band. The transient requirement applies to individual disturbance sources with 1000 µg peak and 10 µg-sec 10 second integrated limits per axis. Note that in order to achieve compliance, operational constraints have been placed on vacuum resource vents in the U.S. and ESA labs, and on the Russian Resistive Exercise Device or RRED. These constraints will be evaluated on-orbit for operational tuning.

The constraints arose primarily due to violations of the 10 µg-sec requirement. To meet this requirement, the vent pressure, vent volume, and RRED exercise frequency must be reduced. Figure 20 contains graphs of the non-constrained results (VAC_AC_ANTIBMP) and the constrained results (VAC_AC_25RRED_ADJVENTS_ANTIBMP). As can be noted the overall system level is greatly reduced in the low frequency range with these adjustments. An additional graph is included (VAC_AC_25RRED_ADJVENTS) to illustrate the contribution from the anti-bump accelerations discussed further on. Some constraints on the ESA vent and RRED currently exist. The ESA vent is already constrained to 14.7 Psi/100L versus 40 Psi/250 L conditions through GNC momentum requirements. The RRED is limited to MOD rowing (.33Hz) through flight rules generated in support of system loads. In Figure 20, the graph labeled, VAC_AC_ANTIBMP_NOMVENT_MODRRED, illustrates the environment using these existing constraints that are still slightly above those necessary for the 10 µg-sec compliance, but as can be seen are sufficient for vibratory compliance.

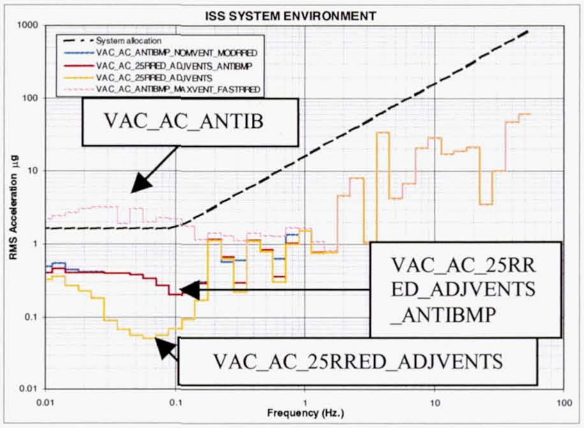

Figure 20: AC Structural Dynamic Vibratory Results

Figure 21 lists the percentage contribution of the disturbance categories to the verification results (VAC_AC_25RRED_ADJVENTS_ANTIBMP). Exercise devices, U.S. rotary joints, and the ARIS "anti-bump", found in the last column, dominate the fields. While the initial two categories are expected, the last item, ARIS "anti-bump" may be a surprise. In addition to its position control loop, the ARIS design includes an "anti-bump" algorithm. This "anti-bump" feature is invoked based on position and velocity knowledge to prevent "snubber" impact. Upon command, the ARIS accelerates the rack away from the stops with 5 µg pulses. Since this feature was invoked at times during the ARIS ICE, it was also considered in the verification environment. The "anti-bump" force commands were determined as the ARIS response to a conservative set of Assembly Complete disturbance conditions. Sway space incursion loss is most sensitive to low frequency, constant velocity disturbances just beyond the position control bandwidth. Such disturbance sources, three crew translations, two vacuum vents, and three exercise devices, were simultaneously applied to the AC model to generate the acceleration time history input to the ARIS closed loop simulation. The resulting "anti-bump" profile that prevented any impact was then added to the AC acceleration environment. Note, that while crew translation was included as part of the sway space evaluation, the microgravity requirements do not apply to crew activity nor payloads, and need only be met 180 days per year in 30 day increments or greater.

Center Freq	LAB_VNT	COF_VNT	RS_RT_JNTS	US_RT_JNTS	CMG/KU	RTAS	EXER	LAB	RS	NODE	JEM	COF	ANTI_BP
0.010	22%	21%	5%	1%	2%	0%	12%	0%	0%	0%	0%	0%	37%
0.013	23%	21%	4%	0%	2%	0%	12%	0%	0%	0%	0%	0%	37%
0.016	17%	13%	2%	0%	4%	0%	7%	0%	0%	0%	0%	0%	56%
0.020	14%	8%	0%	0%	2%	0%	6%	0%	0%	0%	0%	0%	70%
0.025	9%	5%	0%	0%	2%	0%	4%	0%	0%	0%	0%	0%	80%
0.032	2%	1%	0%	0%	0%	0%	2%	0%	0%	0%	0%	0%	95%
0.040	1%	0%	0%	0%	0%	0%	2%	0%	0%	0%	0%	0%	97%
0.050	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	98%
0.063	0%	0%	0%	0%	0%	0%	2%	0%	0%	0%	0%	0%	98%
0.080	1%	0%	0%	0%	0%	0%	3%	0%	0%	0%	0%	0%	95%
0.100	1%	0%	6%	0%	0%	0%	5%	0%	0%	0%	0%	0%	87%
0.125	2%	0%	3%	6%	0%	0%	9%	0%	0%	0%	0%	0%	80%
0.160	2%	0%	0%	6%	0%	1%	25%	0%	0%	0%	0%	0%	65%
0.200	0%	0%	0%	2%	0%	0%	96%	0%	0%	0%	0%	0%	2%
0.250	0%	0%	0%	8%	0%	0%	84%	0%	0%	0%	0%	0%	7%
0.315	0%	0%	0%	30%	0%	0%	25%	0%	0%	0%	0%	0%	44%
0.400	0%	0%	0%	95%	0%	0%	1%	0%	0%	0%	0%	0%	3%
0.500	0%	0%	0%	61%	0%	0%	30%	0%	0%	0%	0%	0%	9%
0.630	0%	0%	0%	69%	0%	0%	3%	0%	0%	0%	0%	0%	27%
0.800	0%	0%	0%	92%	0%	0%	4%	0%	0%	0%	0%	0%	5%
1.00	0%	0%	0%	80%	0%	0%	18%	0%	0%	0%	0%	0%	2%
1.25	0%	0%	1%	67%	0%	0%	26%	0%	0%	0%	0%	4%	2%
1.60	0%	0%	0%	67%	0%	0%	31%	0%	0%	0%	0%	0%	1%
2.00	0%	0%	0%	5%	0%	0%	95%	0%	0%	0%	0%	0%	0%
2.50	0%	0%	0%	3%	0%	0%	97%	0%	0%	0%	0%	0%	0%
3.15	0%	0%	0%	95%	0%	0%	1%	0%	0%	0%	1%	1%	0%
4.00	0%	0%	0%	2%	0%	0%	98%	0%	0%	0%	0%	0%	0%
5.00	0%	0%	0%	97%	1%	0%	0%	0%	0%	0%	0%	2%	0%
6.30	0%	0%	0%	93%	0%	0%	0%	2%	0%	0%	2%	1%	0%
8.00	0%	0%	0%	89%	0%	0%	1%	9%	0%	0%	0%	0%	0%
10.00	0%	0%	0%	80%	0%	0%	0%	1%	18%	0%	0%	0%	0%
12.50	0%	0%	0%	94%	0%	0%	0%	1%	3%	0%	0%	0%	0%
16.00	0%	0%	0%	49%	1%	0%	0%	1%	49%	0%	0%	0%	0%
20.00	0%	0%	0%	62%	1%	0%	1%	1%	27%	0%	0%	8%	0%
25.00	0%	0%	0%	27%	1%	0%	40%	3%	19%	1%	0%	8%	0%
31.50	0%	0%	0%	4%	0%	0%	93%	2%	0%	1%	0%	0%	0%
40.00	0%	0%	0%	4%	0%	0%	89%	1%	2%	4%	0%	0%	0%
50.00	0%	0%	0%	1%	1%	0%	4%	93%	1%	0%	0%	0%	0%

Figure 21: AC Structural Dynamic Percent Contribution To Vibratory Results

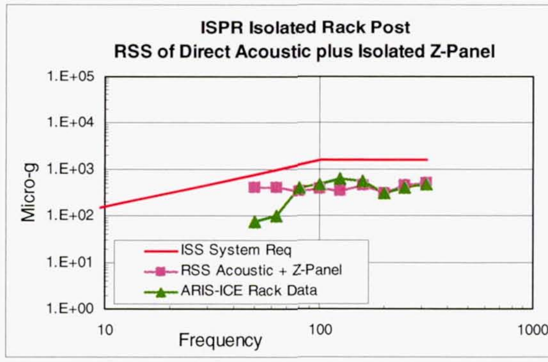

Figure 23: AC Vibroacoustic Vibratory Results

Vibroacoustics

The Assembly Complete vibroacoustic verification analyses determined that at least 50% of the payload racks, consistent with those that meet the quasi-steady and vibratory requirements, comply with the vibratory microgravity requirements in the 50 to 300 Hz range.[13] The beam subsystems of the AC statistical energy analysis model along with the input force locations are shown in Figure 22. Shell elements and pressurized volumes are excluded for clarity. Figure 23 contains the resulting vibratory environment co-ploted with ARIS ICE data. The analytical and on-orbit environments are similar. Note that at the higher frequencies where global modes do not have significant participation, assembly complete environments are not expected to differ considerably from assembly stage environments. The vibroacoustic results include the root-sum-square of the accelerations at the "z-panel" attenuated by the ARIS isolation factors and the un-attenuated rack post accelerations produced by direct impingement acoustics.

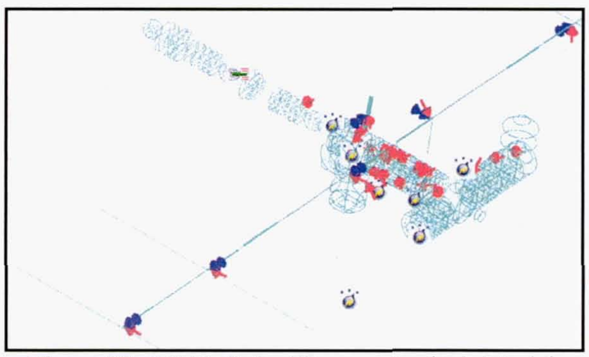

Figure 22: AC Statistical Energy Analysis Model

CONCLUSIONS

The initial phase of the ISS microgravity analytical model correlation and update effort is completed and has provided updated parameters for, and increased confidence in, the Assembly Complete verification analyses. Further efforts are recommended with later assembly stage configurations to address additional disturbance sources as they become operational, the low frequency structural dynamics with the expanded truss, and alternate measurement locations within the laboratories. These updates can help tune the models to reduce conservatism for operational and baseline change evaluations.

The Assembly Complete verification analyses has shown the ISS to comply with the microgravity requirements with minor reservations. 44% instead of 50% of the payload racks comply with the quasi-steady requirements with marginal violations of 1.11 and 1.17 μg of the 1 μg requirement. Otherwise, to meet the 10 μg-sec requirement, operational constraints are needed on U.S. Lab and ESA APM vacuum resource vents and the Russian Resistive Exercise Device (RRED). Other sub-systems have already placed constraints on these sources and the slight tightening needed for microgravity compliance is not expected to be a significant impact. In any case, once operational these constraints will be assessed and appropriate adjustments enacted. And so what appeared as an "impossible" requirement at its inception some 10 years ago has been successfully verified with refined analysis methods in conjunction with ground test and validated by on-orbit measurements.

However, vigilance must be maintained as much of the assembly remains and changes to the baseline will occur. Next generation exercise equipment are in development and will challenge their allocations. ESA is already considering an "enhancement" package with new disturbance sources. What the final Assembly Complete configuration will be is still to be determined as the International Partners discuss the issue over the next couple of years. Perhaps more importantly, the scope of this work has been limited to the "vehicle" requirements and disturbance sources. The payloads themselves, either on-board the isolated ARIS rack or attached to an external element will bear heavily on the final outcome.

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