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Acoustic Emissions Verification Testing of International Space Station Experiment Racks at the NASA Glenn Research Center Acoustical Testing Laboratory

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1. INTRODUCTION

The Acoustical Testing Laboratory (ATL) at the National Aeronautics and Space Administration (NASA) John H. Glenn Research Center (GRC) in Cleveland, Ohio, provides acoustic emission testing and noise control engineering services for a variety of customers, particularly developers of equipment and science experiments manifested for NASA's manned space missions. The ATL provides a comprehensive array of acoustical testing services, including sound pressure level testing per ISO 11201[1] and sound power level testing per ISO 3744[2]. The ATL is accredited by the National Voluntary Laboratory Accreditation Program (NVLAP code 200557-0) for both of these standards.

During the past five years the ATL has tested a variety of space payloads for the International Space Station (ISS), with its primary customer being the Fluids and Combustion Facility (FCF), a two-rack microgravity research facility being developed at GRC for the USA Laboratory Module of the ISS [3,4,5]. FCF will accommodate the unique challenges associated with investigating the behavior of fluids and combustion processes in microgravity and will provide services and capabilities comparable to those found in traditional Earth-based laboratories. The Fluids Integrated Rack (FIR) will house a succession of fluid physics experiments, and the Combustion Integrated Rack (CIR) will support combustion experiments.

ISS space experiment payloads, which include the FCF racks, are required to meet the acoustic emission requirements set forth in NASA SSP 57000[6], which support goals related to crew safety, speech communication, and hearing conservation. An acoustic emission verification test is required to show compliance with NASA's acoustic emission requirements. In 1999, NASA made the decision to support the challenging low-noise design process facing FCF by establishing a full-service acoustic emissions testing laboratory at Glenn Research Center. Since its construction in 2000, ATL has conducted acoustic emission testing of components, subassemblies, and partially-populated FCF engineering model racks. The culmination of this effort has been the acoustic emission verification tests on the CIR and FIR in early 2005.

NASA's acoustic emission requirements for ISS payloads include meeting an NC-like maximum sound pressure level criterion measured at a distance of 0.6 meters from the surface of the space experiment payload that projects into the habitable volume of the space station. For the FCF racks, this means that the sound pressure level measured at a distance of 0.6 meters from the noisiest location on the front of the rack must meet the criterion. ATL selected ISO 11201 as the overarching method for sound pressure level determination because it standardizes many of the elements of NASA SSP 57000 that are either not standardized or otherwise not well defined.

This paper will provide an overview of the test methodology, hardware, software, and test procedure that were developed to perform the acoustic emission verification tests on FCF's Combustion Integrated Rack (CIR) and Fluids Integrated Rack (CIR), per NASA SSP 57000 and in accordance with ISO 11201. It will also discuss the lessons learned from these verification tests.

2. ATL FCF TESTING OVERVIEW

The acoustic emissions verification tests are the culmination of the low noise design work on the FCF Racks, during which ATL tested components, subassemblies, and partially populated Engineering Model (EM) Racks. Tests of these components and subassemblies typically were performed utilizing six microphones arranged in a rectilinear configuration with each microphone 0.6 meters from the center of each side of the test article.

Acoustic emissions testing of two CIR and two FIR Engineering Model (EM) Racks at the ATL, which are shown in Figure 1, provided insight into the expected acoustic emission characteristics of the CIR and FIR Flight Racks. During the first CIR EM Rack test, a very spatially dense microphone grid pattern of 0.1 meters (4 inches) x 0.1 meters (4 inches) was used to measure the sound pressure levels on the front of the rack for a single selected test condition. This microphone grid was implemented using a 10-position microphone array that required repositioning 36 times and took approximately 2 hours to complete. Figure 1 shows this 10-position microphone array in front of the CIR EM Rack, configured to measure the lower half. For all FIR EM Rack tests and all other CIR EM Rack tests, a less spatially dense microphone grid pattern was used on the front (typically a total of 9 microphones arranged in a 3 x 3 rectilinear grid pattern). A single microphone was located 0.6 meters (≈ 24 inches) from the center of each of the other sides and top.

The primary objective of the CIR and FIR Flight Rack acoustic emissions verification tests was to determine the acoustic emissions of the racks for purposes of comparison with the limits specified in NASA SSP 57000 for both continuous and intermittent acoustical noise. The secondary objective of these tests was to provide data to support test-correlated analytical acoustic models of the CIR and FIR Flight Racks, which may be used to accurately predict the acoustic emissions of future (e.g., modified on-orbit) CIR and FIR Flight Rack configurations for compliance with the limits specified in NASA SSP 57000.

3. TEST METHODOLOGY

The principal challenge of acoustic emissions verification testing in accordance with NASA SSP 57000 is that the requirements document provides little guidance in the way of measurement methodology or measurement uncertainty. In particular, NASA SSP 57000 does not discuss how to locate the noisiest location (highest A-weighted sound level), nor does it address how to measure impulsive or transient noise sources or how to make ambient background corrections.

ATL adopted the ISO 11201 procedures and uncertainty estimates as the overarching method for sound pressure level testing of the FCF Flight Racks. This included the implementation of two stationary microphone arrays. A more spatially dense microphone array was used to measure the sound pressure levels on the front, and a less spatially dense microphone array was used to measure the sound pressure levels on the sides, back, and top.

The use of these two separate microphone arrays represents the optimum accommodation of the maximum number of microphones and data channels available, the desired level of measurement accuracy, and the total amount of testing time available. The geometry of these arrays was based upon the acoustic emission characteristics of the CIR EM and FIR EM Racks.

The Front microphone array incorporates a stationary 21-position microphone array of 3 vertical columns of 7 microphones each. Since the measurements on the sides, back, and top are for informational purposes only, a less spatially dense microphone grid pattern was chosen. The Side-Back-Top microphone array was a stationary 22-position microphone array with 6 microphones on the left, right, and back sides and 4 microphones on top.

For the CIR Flight Rack, all measurements with the Front microphone array were made first, then the microphones were transitioned from the Front to the Side-Back-Top microphone array, and finally all measurements with the Side-Back-Top microphone array were made. The order of measurements for the FIR Flight Rack was complicated by the need to install a sub-rack hardware component, the Light Microscopy Module (LMM), into the rack part way through the test, in order to acquire data with and without the LMM. This resulted in measurements being made first with the Front microphone array with LMM not installed, then with the Side-Back-Top microphone array with and without the LMM installed, and finally with the Front microphone array with the LMM installed.

During each acquisition of acoustic data, 60 second Leq averaged 1/3rd octave band sound pressure level data were acquired first and then post processed into equivalent 1/1 octave band sound pressure level data. If, for data acquired with the Front microphone array, the A-weighted sound level spread was greater than or equal to 10.5 dBA, and then a manual scan with a hand-held sound level meter at predetermined intermediate grid locations was performed. The Compliance Verification Point (CVP) microphone, a "roving" microphone, was then positioned at the loudest location found during the scan and the measurement was repeated. In addition, if the impulsive indicator for any of the microphones was greater than or equal to 3.0 dBA, then data were also acquired using a slow exponential time weighting with a max hold function.

4. MICROPHONE ARRAY FIXTURES

The design criteria for these microphone array fixtures were, in order of priority: personnel safety, test article safety, measurement accuracy, and operational ease of use. These microphone array fixtures are the culmination of several design iterations. The final Front and Side-Back-Top microphone array fixtures are self-standing and consist of aluminum base plates with leveling feet. Predrilled vertical posts mount to these base plates, and their tops are tied together with lightweight aluminum tubing. Threaded aluminum rods are secured to the predrilled vertical posts with nylon wing nuts. A ball head microphone clip attaches to the end of each threaded aluminum rod. Figure 3 shows the Front and Side-Back-Top microphone array fixtures as they are positioned around the FIR Flight Rack.

It was observed during repeatability testing that the Front microphone array (bare aluminum tubing) was vibrating and artificially inflating the measured sound pressure levels in the 250 Hz 1/3rd octave band. Several types of damping treatment were tested. In the end, a layer of heavy silicone sheeting was glued to the top of all base plates, and magnetic strip tape was added to the sides of all vertical posts. In addition, the vertical posts were filled with hardening expanding foam. While this foam did not increase the structural damping in the vertical posts, it did prevent them from becoming acoustic resonators.

5. PROFICIENCY/REPEATABILITY TESTING

Leading up to the acoustic emissions verification test, a series of repeatability tests were performed using a B&K Reference Sound Source (RSS) and a JBL Eon loudspeaker driven with a multi-tonal signal[7]. These repeatability tests helped the ATL staff gain experience assembling and setting up the microphone array fixtures and were invaluable in refining the test methodology and procedures. As noted above these repeatability tests were also helpful in identifying problems well before the rack verification tests so they could be resolved.

The data from these repeatability tests was used to construct control charts for the 1/3rd octave band sound pressure levels at each microphone position as well as the average overall A-weighted sound level and overall sound pressure level. This information was also used in estimating the overall measurement uncertainty. Figure 4 shows the Front microphone array setup during repeatability testing with the B&K RSS and JBL Eon loud speaker.

As part of the test method, proficiency tests were performed with both the Front and Side-Back-Top microphone arrays using the B&K RSS before and after each acoustic emissions verification test.

6. TESTING SPACE FLIGHT HARDWARE.

Because the CIR and FIR Flight Racks were actual space *flight* hardware, additional challenges were imposed that impacted testing procedures and schedule. The physical environment of the ATL test chamber had to be controlled and monitored so that its temperature and relative humidity stayed within certain limits as dictated by contamination and electrostatic discharge (ESD) sensitivity concerns. While temperature was not an issue, maintaining the relative humidity inside the test chamber was critical. For the FCF Flight Racks the relative humidity needed to be maintained between 30% and 50%. The lower limit is driven by ESD sensitivity concerns, while the upper limit is driven by contamination (e.g., mildew) concerns. The host building in which the ATL resides does not have humidity control, and during the late fall, winter, and early spring, the relative humidity inside the building can fall below 20%. Since the FIR Flight Rack was tested in January, 2005, and the CIR Flight Rack was tested in April, 2005, the test chamber needed to be humidified. Humidification was accomplished using two humidifiers in the test chamber that were turned off and covered with melamine foam during data acquisition. In addition, the temperature and relative humidity inside the test chamber was recorded at a sampling rate of once per minute for the duration of both tests.

All personnel entering the test chamber wore smocks, hairnets, beard covers (if needed), and gloves. In addition, all personnel who were going to come within three feet of the racks needed to wear a grounding wrist strap attached to a grounding strip. Repeated donning and doffing of these extra garments increased the time needed for setup and testing.

The FCF Flight Racks are housed in an International Standard Payload Rack (ISPR), which is supported with a Rack Handling Adapter (RHA) during ground operations. The combined weight of an FCF Flight Rack and RHA is approximately 3000 lb. The overall dimensions of the FCF Flight Racks is 1.1 meters (42 inches) wide, 2 meters (78 inches) tall, and 0.9 meters (37 inches) deep. The RHA holds the bottom of the FCF Flight Racks approximately 0.6 m (24 inches) above the floor. The overall dimensions of an FCF Flight Rack and RHA are 1.1 meters (42 inches) wide, 2.8 meters (111 inches) tall, and 1.9 meters (75 inches) deep. Because of the size and weight of the combined FCF Flight Rack and RHA, testing had to be performed in hemi-anechoic mode with the RHA sitting directly on the hard floor of the test chamber. Because the underside surfaces of the FCF Flight Racks were only 0.6 m above the floor, the lower microphones on the front, right, left and back sides were influenced by acoustic reflections off the floor. To reduce some of these acoustic reflections, melamine foam padding was placed directly under the FCF Flight Racks, between the legs of the RHA. Also, the RHA is comprised of an open ended tubular structure, which could become an acoustic resonator. To prevent this, foam was stuffed into the open ends of the RHA.

7. DATA ACQUISITION CAPABILITIES

The ATL's PC-based data acquisition system uses National Instruments' Sound Power System software (SPS) with Multi-Channel Enhancement software (MCE) written by Nelson Acoustical Engineering. The data acquisition system has six NI-4552 boards (4 input channels each) and one NI-4551 board (2 input channels and 2 output channels) housed in a Magma PCI expansion chassis that is connected to a workstation computer[8]. The data acquisition system provides up to 26 channels of simultaneous data acquisition with real-time 1/1 octave band, 1/3rd octave band analysis, and narrowband FFT analysis.

The SPS with MCE data acquisition window has two displays when acquiring 1/3rd octave band data. The upper display plots the sound pressure level spectrum of a user-selected data channel as well as giving the overall sound pressure level (dB OASPL) and A-weighted sound level (dBA) for that data channel. The data channel selected in this upper display can be changed at any time during the data acquisition process, allowing detailed inspection of individual data channels. The lower display plots either a color contour plot of the sound pressure level spectra of all the data channels (color coded to magnitude) or the A-weighted sound level at user-selected channels. This provides the user a way to easily monitor all data channels and indicates data channels that may not be functioning properly. Figure 2 shows screen shots of the SPS with MCE display during 1/3rd octave band and narrowband FFT acquisition. Finally, the software also has a noise intrusion alarm that signals when the noise level within the host building, measured with a reference microphone on top of the ATL test support enclosure, is producing a noise level inside the test chamber that exceeds a user defined limit at any of the microphone positions.

The SPS with MCE software automatically generates a multi-worksheet Microsoft Excel workbook that thoroughly documents the test and provides for fast and efficient turn-around of data to the customer. For these tests, the Excel workbooks were customized so that the 1/3rd octave band data that were automatically output were converted into equivalent 1/1 octave band data. Worksheets were coded to automatically highlight the loudest microphone location, estimate the NC criteria at this location, and plot the sound pressure level and overall A-weighted sound level at this location against the NASA SSP 57000 continuous and intermittent noise limits, respectively. This customized Excel workbook facilitated real-time decision making, which allowed the matrix of test conditions to be altered during the test, thus facilitating maximum testing efficiency.

8. TEST DOCUMENTATION

Checklists were used by the Test Conductor and ATL Facility Engineer to ensure that all aspects of the test were successfully completed. These checklists were used to verify and document the configuration of the FCF Racks and test chamber, and to ensure that data had been correctly acquired and stored before giving the go-ahead to move onto the next test condition. These checklists became part of the official documentation of the test. Test notebooks with separate sections created for each test run were created at the beginning of each test and were filled in as the test proceeded. Each section contained a Test Run Summary Form that briefly described the configuration of the microphone array and FCF Rack; Test Conductor's and Test Facility checklists; and summary data sheets.

9. LESSONS LEARNED

The CIR and FIR Flight Racks were tested with approximately twenty-five test conditions each. The test methodology, procedures, and microphone arrays, which were developed by the ATL, were important contributors to successful testing and to meeting scheduling constraints. If a test method that used a manual scan to locate the loudest location had been implemented instead, either the matrix of test conditions would have had to be drastically reduced, or the testing schedule significantly lengthened. Finally, the success of the FCF low-noise design process was in part a result of the frequent acoustic emissions testing that was a key element of the overall design strategy. The NASA Glenn Research Center's Acoustical Testing Laboratory was originally designed and constructed to provide a highly accurate in-house source of frequent and easily accessible acoustic emissions testing for the FCF project from component through full-rack levels. The iterative design/test process enabled the FCF acoustics team to understand and continually track the acoustic emissions of components and subassemblies as they were successively incorporated into larger and larger assemblies. These historical data and the techniques by which they were acquired became an important tool in detecting and diagnosing damage and/or failure in components, in addition to serving their intended purpose in the low-noise design process.

ACKNOWLEDGEMENTS

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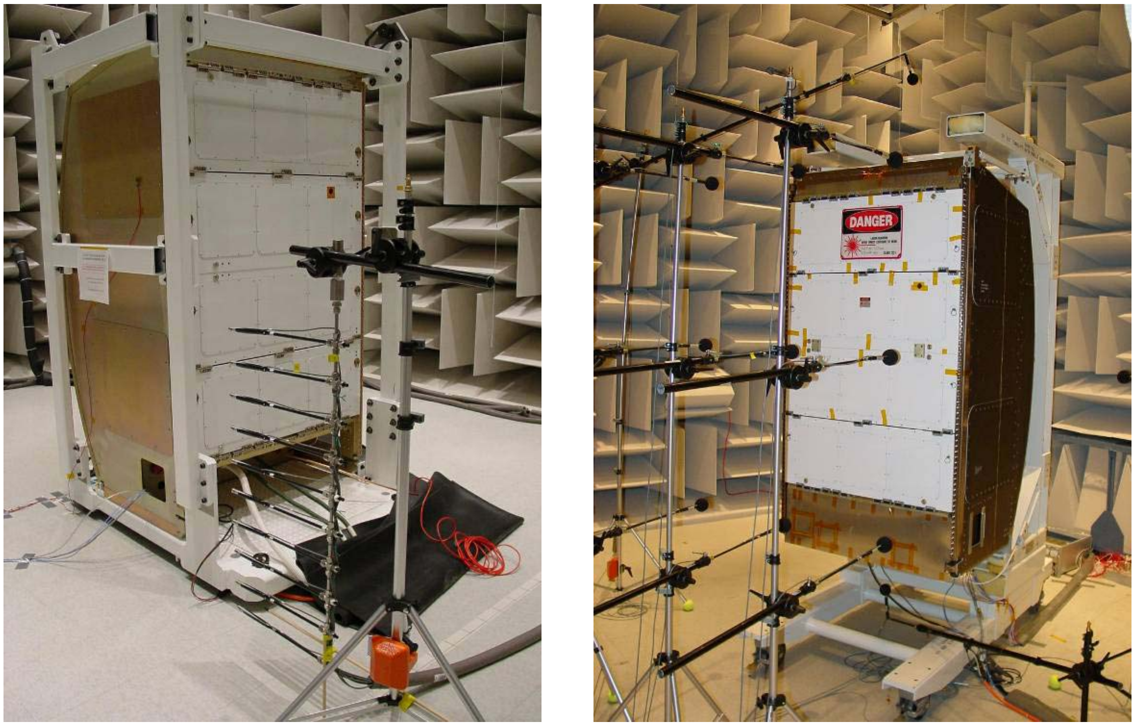

Figure 1. CIR EM Rack (l) and FIR EM Rack (r).

Position 25

10 dB Safety

Cursor Value: 42.0 dB @ 200 Hz
Linear: 59.0 dB A: 52.2 dBA A Imp.: 52.7 dBA 0.5

Color Min. 25

Channels to Display
Pos. 1
Pos. 10
Pos. 18
Pos. 19
Pos. 24
Pos. 25

Status 2: Complete
Analysis: Magnitude
Window: Flat Top
Number of Averages: 60
% Overlap: 50
Reference Value (Pa): 2.00E-5
Mode: RMS
Linear
Cursor 0 5832.0 -3.4
Start Span (Hz): 0.0
Stop Span (Hz): 12800.0
delta-f (Hz): 1.00

Figure 2. ATL data acquisition window for 1/3rd octave band data (l) and narrowband data (r) acquisition.

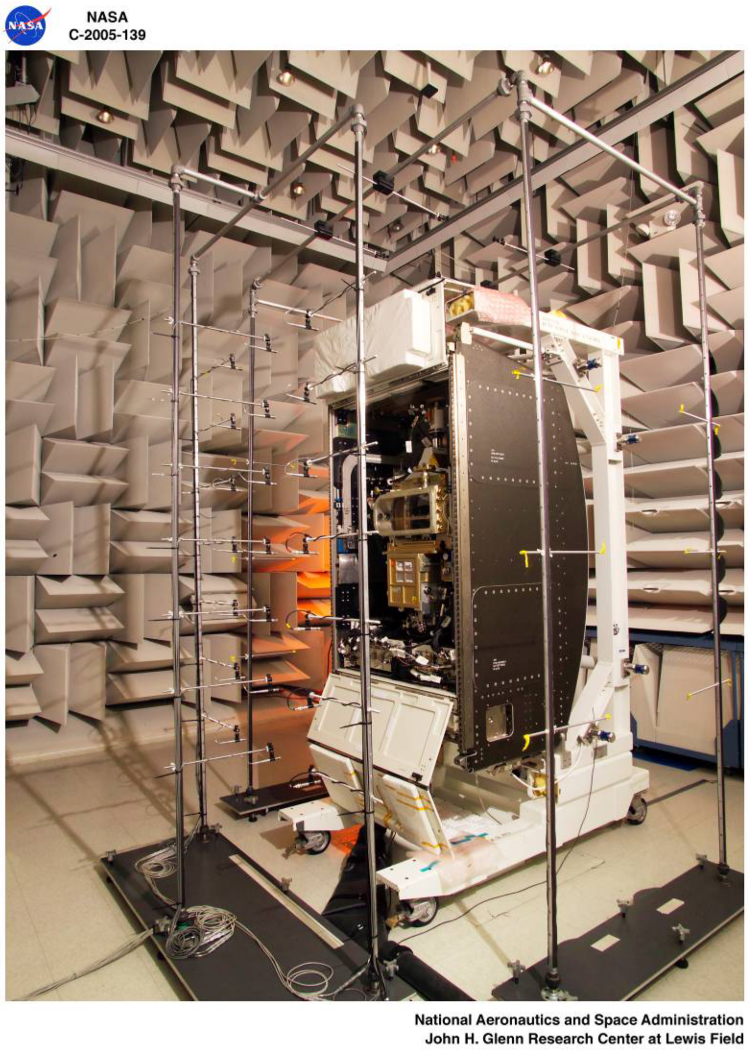

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Figure 3. FIR Flight Rack with microphone arrays.

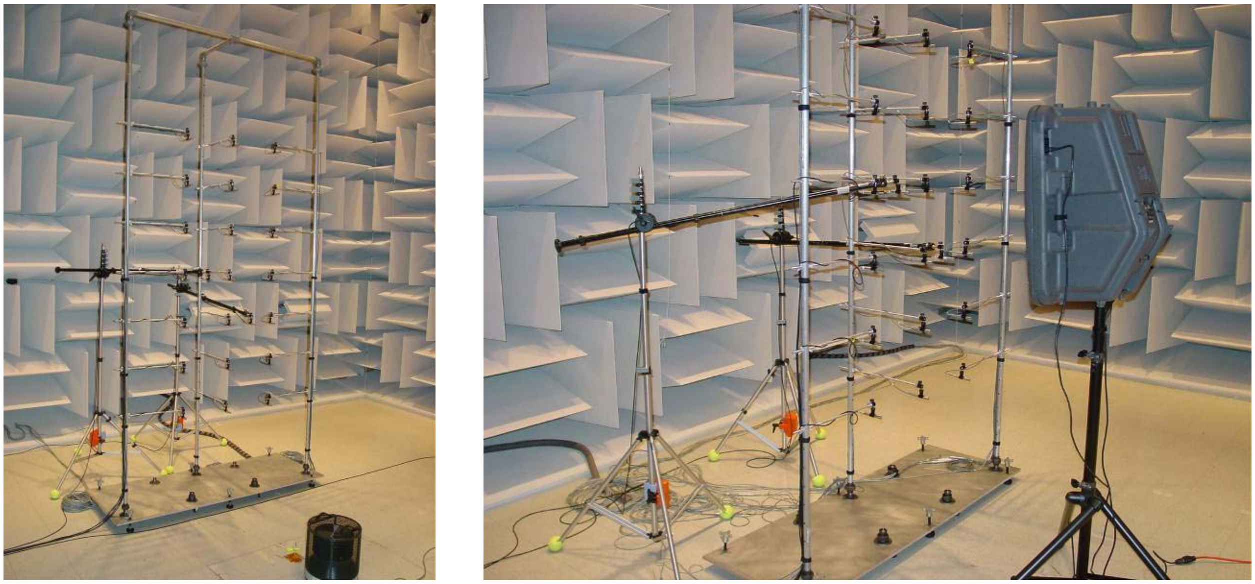

Figure 4. Proficiency/repeatability testing with RSS (l) and loud speaker (r).