Technical Aspects of Acoustical Engineering for the ISS

The 4th Meeting of the MidSouth Chapter of the Acoustical Society of America

The University of Central Arkansas
Conway, AR 72034

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Outline

- ISS Overview
- Controlling Acoustical Noise
- Examples
  - Service Module
  - US Segment Ventilation
  - Crew Quarters
Nodes 1, 2, and 3
What Makes Noise on ISS?

- **Hardware**
- Air conditioning, fans, water cooling pumps, refrigerators, experiments, exercise equipment, computers, cameras, hundreds of pieces of equipment (vacuum cleaner, hair trimmer)
- **Modules are reverberant** ($T_{60}$ approx. 0.5s)
Controlling Acoustical Noise

- Sound levels in space vehicles must be controlled
  - Hearing conservation
  - Protect communications
  - Alarms audibility
  - Habitability
- Requirements and verification requirements
  - Allocated requirement depending on system level
- Hardware design and reviews (SRR, PDR, CDR)
  - Acoustic Noise Control Plan (ANCP)
- System-level analysis
- Remedial actions and noise control
- Certification of Flight Readiness (CoFR)
- On-orbit acoustical monitoring
Continuous Noise Requirements

Octave Band Sound Pressure Level, dB (re 20 µPa)

Octave Band Center Frequency, Hz

- Resultant Vehicle + Payload Req. (NC48 + NC-50, approx NC-52)
- Vehicle/Module Spec. (NC-50)
- Payload Complement Spec. (NC-48)
- Payload Rack and Non-Int GFE Spec. (NC-40)
- Aisle-Mounted Payload Spec. (NC-34), Effective UF-3
- EXPRESS sub-rack alloc. (modified NC-32)
Acoustic Noise Control Plan

- Indicate allocation and integrator
- Sub-allocations for components
  - Identify noise makers
  - Select quiet components
  - Design in noise controls – isolators, absorption
- Operational Scenarios
- Account for changes throughout lifetime of h/w
  - Rack with changing sub-rack payloads
  - Orbital Replacement Units (ORUs)
- Documentation
  - Specify limits and verification requirements for components
  - Specify limits, verification requirements and process for ORUs
- Testing and Verification Plan
  - Determine insertion losses and other transfer functions
  - Test-correlated analytical model
- Recovery Plan
Verification

- **Test**
  - Preferred method
  - Most hardware
  - Worst-case nominal operating conditions

- **Test-correlated analytical model**
  - Used for payload rack facilities which are designed to support multiple experiments
  - Experiment hardware not yet available
  - Testing used to determine:
    - Base facility noise
    - Insertion losses/transfer functions
    - Sub-rack payload/experiment noise when available
  - Model describes how to combine the test data to predict integrated rack noise
  - Model documented in Acoustic Noise Control Plan (ANCP)
  - Worst-case nominal operating conditions
Module Verified by Ground Test

- Includes Integrated GFE
- Some analysis may be used under certain circumstances
Integrated Rack Verification

- Two feet from Rack
  - All sides of rack
  - Bottom measurements
- Payloads not changed-out
- Payloads changed out
  - Rack system noise
  - Insertion losses/transfer functions
- Inputs to model
- All operational scenarios
- Throughout lifetime
Sub-Rack Payload Verification
Rack Verification from Model

Octave Band Sound Pressure Level, dB (re 20 \( \mu \)Pa)

Octave Band Center Frequency, Hz

- **NC-40**
- **EXPRESS Requirement**
Rack Verification from Model

Octave Band Sound Pressure Level, dB (re 20 μPa)

Octave Band Center Frequency, Hz

- ADVASC-GC1
- ADVASC-SS
- MAMS
- CGBA1
- PCG-STES9
- CPCG-H1
- PCG-STES8
- SAMS-RTS1
- SAMS-RTS2
- NC-40
- EXPRESS Requirement
Rack Verification from Model

Octave Band Sound Pressure Level, dB (re 20 μPa)

Octave Band Center Frequency, Hz

- AAA Fan
- ADVASC-GC1
- ADVASC-SS
- MAMS
- CGBA1
- PCG-STES8
- SAMS-RTS1
- SAMS-RTS2
- PCG-STES9
- CPCG-H1
- NC-40
- EXPRESS Requirement
Rack Verification from Model

Octave Band Sound Pressure Level, dB (re 20 μPa) vs. Octave Band Center Frequency, Hz

- AAA Fan
- ADVASC-GC1
- ADVASC-SS
- MAMS
- CGBA1
- PCG-STES9
- CPCG-H1
- PCG-STES8
- SAMS-RTS1
- SAMS-RTS2
- Integrated Rack
- NC-40
- EXPRESS Requirement
Typical US Lab Topology

- LAB1O6
- LAB1O5
- ZSR
- MELFI
- LAB1O4
- LAB1O3
- LAB1O2
- LAB1O1
- LAB1P6
- LAB1P5
- LAB1P4
- LAB1P3
- LAB1P2
- LAB1P1
- LAB1D6
- LAB1D5
- LAB1D4
- LAB1D3
- LAB1D2
- LAB1D1
- LAB1S6
- LAB1S5
- LAB1S4
- LAB1S3
- LAB1S2
- LAB1S1
- CHeCS
- HRF#2
- TeSS
- LAB1S6
- LAB1S5
- LAB1S4
- LAB1S3
- LAB1S2
- LAB1S1
- CHeCS
- HRF#2
- TeSS
- systems
- payloads
- stowage

overhead
port
deck
starboard
System Level Noise Prediction

- **RAYNOISE Software**
  - based on enhanced geometrical ray-tracing algorithm
  - computes sound levels in any closed or open volume
  - sound reflection at a wall is specular, or can also be diffuse
  - sound is partially absorbed at a wall depending on the wall absorption coefficient
  - contribution of many rays at a point determines the sound level

- **Inputs**
  - geometry of acoustic space
  - “receiver surface” geometry
  - absorptive properties of room boundaries
  - sound power levels and directivity information for noise sources

- **Outputs**
  - Sound Pressure Level on “receiver surface”
System Level Continuous Noise

Octave Band Sound Pressure Level, dB (re 20 \( \mu \)Pa)

Octave Band Center Frequency, Hz

- NC-48
- NC-50
- NC-48 + NC-50
- UF-2 (P/L Pred)
- Module with GFE
- UF-2 (Tot Pred)
On-Orbit Measurement Comparison

Octave Band Sound Pressure Level, dB (re 20 µPa)
Octave Band Center Frequency, Hz

- NC-48
- NC-50
- NC-48 + NC-50
- UF-2 (P/L Pred)
- Module with GFE
- UF-2 (Tot Pred)
- On-Orbit Measurement, U. S. Lab Center, UF-2

Payload Complement Prediction by Ed O'Keefe
Module Prediction by Sam Denham
Service Module Ventilation
Subsystem Noise Control
Indicated Fans - vibration isolation
- acoustic lined duct
Ventilation Subsystem

Installation of soundproofing device on ВПО12
**Ventilation Subsystem**

Installation of soundproofing device on ВПО10, ВПО11, ВСЭП1
Ventilation Subsystem

Installation of fan ВПΦ1 on vibration isolation.
Installation of soundproofing device on ВПΦ1 and dust collector
Ventilation Subsystem

Installation of fans on vibration isolation
SM Acoustic Contract Status
Quiet Fan Development

[Graph showing acoustic levels across different frequencies]

 levels in 1/3-octave bands, dB

MO-2-5008
17KC.53Ю5009-0
17KC.53Ю5014-0
US Intermodule Ventilation (IMV) Fan
The IMV Fan Assembly consists of a cast aluminum fan housing, a brushless DC motor, an axial flow impeller, flow straightener, a motor controller, vibration isolating resilient mounts, and acoustic insulation. Acoustic wraps cover the exterior of the IMV Fan Assembly to attenuate case radiated noise emissions. Further attenuation of case radiated noise is provided by the aluminum honeycomb closeout panels.
IMV Fans – Ductborne Noise

- **Treatment - Muffler**
  - IMV muffler the "football" muffler
  - Made of “Feltmetal” and Melamine foam
Node 3 Ventilation System
Crew Quarters

- Noise allocation and ANCP
- Wooden mockup
- Fan selection
- Blanket design
- Mid-fidelity mockup
- Ground verification
- Resonance and fan speed control
- On-orbit levels
CQ Ventilation System Wooden Mockup

Acoustic Emissions of CQ Ventilation System Mockup, SPL @ 95th Percentile Male Ear, CQV
Inlet Fan Speed Medium (20 VDC, Chamber Ventilation Fan Off, 8/25/06, 8/28/06

![Graph showing sound pressure level (SPL) at 95th percentile male ear under different conditions. The graph plots octave-band center frequency (Hz) on the x-axis and sound pressure level (dB, re 20 μPa) on the y-axis. Different lines represent various conditions: NC-37 Baseline, Bare Ceptum, Foamed End Zones, Lined Ceptum, Foamed Terminator, Lined Duct, and All w/ Inlet Ramp.]
Materials Development (Absorption)

- Need to replace Melamine
- Need covering to contain particulates
- Assess layups
- Used new materials in CQ
  - duct-borne noise absorption
  - interior absorption

Absorption Coefficient

Impedance Tube Test Per ASTM E1050-98 and ISO 10534-2, NASA JSC Acoustic Office, 11:30:05
Materials Development (Transmission Loss)

- Test to determine blocking benefits
- BISCO, Radiation Panels, Closeouts
- Used in CQ development

<table>
<thead>
<tr>
<th>Frequency (Hz, Oct-band Center)</th>
<th>Insertion Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>10</td>
</tr>
<tr>
<td>125</td>
<td>15</td>
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<tr>
<td>250</td>
<td>20</td>
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<tr>
<td>500</td>
<td>25</td>
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<tr>
<td>1000</td>
<td>30</td>
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<tr>
<td>2000</td>
<td>35</td>
</tr>
<tr>
<td>4000</td>
<td>40</td>
</tr>
<tr>
<td>8000</td>
<td>45</td>
</tr>
</tbody>
</table>

- Bisco 0.25 psf, not stitched
- Bisco 0.25 psf, stitched 2"x2"
- Bisco 0.5 psf, fiberglass backed, stitched 2"x2"
Comparison of Engineering Mock-up, Initial Mid-Fidelity Mock-up, and Final Mid Fidelity Mock-up Levels
Ventilation at Low Speed
Overview: Inlet Blade Pass Frequency

- **Problem:**
  - Intake fan blade pass frequency (BPF) remains the primary acoustic exceedance root cause.
    - Same issue as with the Mid Fidelity Mockup before decoupling and moving the inlet fan.
    - The levels of the intake fan BPF are over 10 dB greater than any other narrow-band signal in the vicinity of the 250 Hz octave for the low and medium speed ventilation modes.
  
  - This was also the case with the mid-fidelity mock-up, however the levels were significantly reduced due to inlet fan decoupling measures (which were integrated into the flight design).

- **Flight Unit vs. Mid-Fidelity Mockup**
  - Significant difference between the mid-fidelity unit and the flight unit is the fan speed and resulting BPF at low speed ventilation.

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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Intake Fan Rotation Speed (Hz)</td>
<td>40</td>
<td>44</td>
<td>54</td>
<td>56</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>Intake Fan BPF (Hz)</td>
<td>201</td>
<td>220</td>
<td>268</td>
<td>281</td>
<td>320</td>
<td>322</td>
</tr>
<tr>
<td>Exhaust Fan Rotation Speed (Hz)</td>
<td>47</td>
<td>48</td>
<td>59</td>
<td>60</td>
<td>69</td>
<td>68</td>
</tr>
<tr>
<td>Exhaust Fan BPF (Hz)</td>
<td>233</td>
<td>238</td>
<td>296</td>
<td>300</td>
<td>344</td>
<td>340</td>
</tr>
</tbody>
</table>

- **Conclusion:** Assuming that the interior dimensional differences between the flight unit and the mid-fidelity unit are minimal, then the difference in frequency of the BPF coupled with the acoustical characteristics of the interior could be the source of the increase in levels of the 250 Hz octave (and also the solution for reducing the flight unit levels).
Method of Analysis

It is important to characterize both the source (intake fan BPF), and the path (structural and airborne paths to occupant), in order to understand the sound levels at the receiver (occupant ear location).

Source
- The narrow band measurement of the interior levels in the vicinity of the 250 Hz octave were analyzed.
  - The blade pass frequencies of the intake and exhaust fans are recorded as well as the other rotation orders of the fans.

(Airborne) Path
- The interaction of the crew quarters interior volume is examined by measurement of the acoustical transfer function between the diffuser and the occupant head location.
  - The transfer function acts as an “amplifier” (multiplier) between the intake fan BPF (source) and the occupant ear (receiver).

A comparison of the flight unit intake BPF and the mid-fidelity BPF and their interaction with the room response of the crew quarters interior volume is made in order to understand the difference in acoustic performance.
**Source – Path – Receiver Acoustical Model**

- **Source**: Inlet Fan
- **Path**: Interior Volume Of Enclosure (CQ)
- **Receiver**: Microphone
- **Narrow Band Spectrum**: Transfer Function (Frequency Response Function)
- **Measured Response**: Measured Response
Intake Measured Transfer Function to Occupant Head Location

Diffuser to Head Transfer Function

- Low Speed Inlet BPF – Flight Unit
- Low Speed Inlet BPF – Mid-Fid. Unit
- Med Speed Inlet BPF – Flight Unit
- Med Speed Inlet BPF – Mid-Fid. Unit
- High Speed Inlet BPF Flight & Mid Fid. Unit

Cursor values
X: 201.000 Hz
Y: -12.054 dB/1 Pa/Pa
CQ Interior Volume Acoustic Mode

Acoustic Finite Element Modal Analysis of CQ Interior Cavity Mode Frequency: 194 Hz

What this Means: SPL due to blade pass frequency at 201 Hz should decrease as the measurement location moves towards the center of the CQ interior volume (see next slide).
Variation of Octave Levels with Location in CQ Volume

Low Speed Ventilation - After Reassembly

Note 250 Hz Octave Levels Correlate with levels in previous modal shape slide

<table>
<thead>
<tr>
<th>Octave (Hz)</th>
<th>SPL (dB re 20e-6 Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>53.6</td>
</tr>
<tr>
<td>125</td>
<td>53.8</td>
</tr>
<tr>
<td>250</td>
<td>58.2</td>
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<tr>
<td>500</td>
<td>39.4</td>
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<tr>
<td>1000</td>
<td>34.3</td>
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<td>2000</td>
<td>24.4</td>
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<tr>
<td>4000</td>
<td>15.8</td>
</tr>
<tr>
<td>8000</td>
<td>15.2</td>
</tr>
<tr>
<td>A column:</td>
<td>48.4</td>
</tr>
</tbody>
</table>

Mic 1 (Head) 53.6 53.8 58.2 39.4 34.3 24.4 15.8 15.2 48.4
Mic 2 52.1 50.9 52.9 45.5 35.5 23.0 18.0 15.1 45.9
Mic 3 54.3 54.6 54.4 39.1 36.0 22.6 15.9 14.8 45.9
Mic 4 52.2 50.8 47.0 43.2 34.9 26.2 18.0 14.9 43.0
NC-40 64 56 50 45 41 39 38 37 49

SPL (dB re 20e-6 P)
Backup
Profile Cross-Section of Service Module

Kayuta Inlet Fan

Kayuta air register
Kayuta Acoustic Treatments
Ventilation Subsystem
Installation of mufflers and shock absorbers on BB1PO
Ventilation Subsystem
Installation of acoustic screens and soft air ducts on fans BKO1 (BKO2)
Service Module Control Points 7 & 9 vs time

Graph 500

Kayuta Sleep Stations

× KT7 Kayuta (starboard)
○ KT9 Kayuta (port)

Sound Pressure Level (Wideband) [dBA]

time [days]

data from SM Chronology 22Jan07.xls
[DenhamSServiceModule]Graph500.top

Sam Denham
Jan. 25, 2007
Vozdukh System
Vozdukh System

Results of installing soundproof cover on БОА fan onboard the ISS SM

- Complete installation of cover on board the ISS SM unsuccessful
- Space between vacuum pipeline and bar near fan insufficient to install the upper half of the cover.
Vozdukh System
Results of installing soundproof cover on БОА fan

- Adapter, shock absorber, and soft soundproof cover installed

- Upon crew initiative, additional soundproofing device installed for БОА unit components behind panel 425
Vozdukh System Microcompressor Noise
13–14 June 2006

Noise 50 cm from БОА fan before and after installation of cover 4315 and mats

<table>
<thead>
<tr>
<th>Frequency, Hz</th>
<th>Noise level, dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>90.0</td>
</tr>
<tr>
<td>23</td>
<td>85.0</td>
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<tr>
<td>31.5</td>
<td>85.0</td>
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<tr>
<td>40</td>
<td>80.0</td>
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<tr>
<td>10000</td>
<td>60.0</td>
</tr>
<tr>
<td>12500</td>
<td>55.0</td>
</tr>
</tbody>
</table>

- Initial БОА noise, 06/13/06, 80% flow, fans off
- Reduced БОА noise with cover components
- Reduced БОА noise next to closed panel 425
- Max. allowable level, work
- Initial БОА noise, 06/14/06, 60% flow, all fans on
- Reduced БОА noise with supplemental mat
Vozdukh System

Results of installing soundproof cover on БОА fan

Findings:

- In the SM, noise from БОА was reduced by ≈ 9 dBA
- Installation of metal box was not possible
- Noise level reduction value obtained is close to that measured during ground tests with the box (≈ 11 dBA)
Air Conditioning System [CKB]
Integrated interior panel 204+205 installed on board the ISS RS SM
Air Conditioning System [CKB]

Soundproofing devices 17KC.52Ю 9081A-0

- For [CKB]2 – all soundproofing items installed on 07/19/06
- For [CKB]1 – only the cover on [BP] was installed; all else planned for installation before ETA changeout in June 2007.
Findings:

- Due to installation of integrated panel 204+205, noise level near [CKB] fell by at least 5 dBA (to 65.8 – 66.3 dBA)
- Due to installation of soundproofing devices on [CKB]2, vibration isolation for [BT]2 and a shock absorber for [BTK]2 (per noise measurement data on 07/19/06), the following noise levels were achieved:
  - ≈ 64.5 dBA - near central post
  - ≈ 66 dBA - near Vozdukh system
  - ≈ 68.5 dBA - near [CKB] (point [KT]2)
- In August 2006, an unexplained increase in noise occurred near [CKB]2, up to 71-73 dBA (this made it difficult to determine the effectiveness of installing the shock absorber for fan [BTK]1 of [CKB]1)