Structural Design and Certification of the AMS-02 Magnet Strap Support System

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Lockheed Martin Space Operations
AMS-02 Critical Design Review
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Introduction

• Overview
• Strap Support System Design
• Strap Support System Verification Plan
  – Testing Plan
  – Analysis Plan
• Correlation Results to Date
• Future Work
Support System Responsibilities

• Straps designed and manufactured by Space Cryomagnetics, Ltd (SCL).
• Strap analysis and verification by Lockheed Martin and SCL.
• Strap testing at several sites
  – Crompton Technology Group (CTG)
  – Rutherford Appleton Laboratories (RAL)
  – Lockheed Martin
  – Johnson Space Center.
Overview

- Magnet strap support system is primary load path between magnet/He tank and flight support structure.
- Straps are nonlinear system which requires specialized analysis and testing.
- Strap stiffness and magnet/He tank mass defines the first few global AMS-02 modes.
Support System Design Goals

• Superfluid He tank must be maintained at ~1.8K for three-year design lifetime.
• Support system must have minimal parasitic heat load while still resisting launch and landing structural loads.
• System must fit in current Vacuum Case dimensions.
Magnet Support System Design

- AMS-02 cryomagnet and He tank suspended from Vacuum Case by 16 individual strap systems.
- Individual straps contain four composite bands.
- Overall strap system has a nonlinear force-displacement relationship.
Individual Strap Overview

• Individual straps consist of four composite bands.
  – On-orbit strap to support lower level loads.
  – Stiff launch/landing strap to support higher loads.
  – Carbon strap (cold end) and fiberglass bod (warm end)
    to help reduce heat transfer.
• Belleville washer stack at warm end.
• Two types of straps: C1W1 and C2W2.
Individual Strap Systems

Carbon Strap

Cold (Magnet) End

Launch/Landing Strap

Warm (VC) End

SECTION A-A

On-Orbit Strap
Strap Photos

Photo courtesy of CTG

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Strap “Wineglass” End Fitting
Wineglass Photo

Photo courtesy of C. Lauritzen
Disassembled End Photos
Strap Nonlinearity

• Straps have a generally bilinear or trilinear force-displacement relationship, based on temperature.
  – Lower region stiffness dominated by Belleville washer stack.
  – Upper region stiffnesses dominated by component band stiffness.

• Strap properties vary with temperature.
  – “Cold” set used when magnet/He tank cooled to cryogenic temperatures.
  – “Warm” set used when magnet/He tank at ambient temperatures.
C1W1 Warm Stiffness Curve

- Region I stiffness = 2,312 lb/in, Region II stiffness = 81,240 lb/in

<table>
<thead>
<tr>
<th>Tensile Load</th>
<th>Deflection from Preload Point</th>
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<tbody>
<tr>
<td>0 lb</td>
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<tr>
<td>1753 lb</td>
<td>0”</td>
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<tr>
<td>1989 lb</td>
<td>0.104”</td>
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<td>2157 lb</td>
<td>0.107”</td>
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<tr>
<td>26977 lb</td>
<td>0.360”</td>
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C1W1 Cold Stiffness Curve

- Region I stiffness = 2,262 lb/in, Region II stiffness = 46,238 lb/in, Region III stiffness = 87,207 lb/in.

<table>
<thead>
<tr>
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<tr>
<td>0 lb</td>
<td>-0.867”</td>
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<tr>
<td>1973 lb</td>
<td>0”</td>
</tr>
<tr>
<td>1989 lb</td>
<td>0.007”</td>
</tr>
<tr>
<td>4819 lb</td>
<td>0.061”</td>
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<tr>
<td>26977 lb</td>
<td>0.272”</td>
</tr>
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Strap Verification Plan

• Strap models will be correlated in multiple steps using five separate tests.
• Nonlinear models will be developed for internal project use.
• Linearized model developed and verified for use in the VLA.
  – Linearized model must be shown to envelope loads generated by the nonlinear model.
Strap Testing Plan

- Full straps will undergo six tests:
  - Fatigue Test (complete)
  - Static Test to 1.2x limit load (all flight and test units).
  - 1-D Dynamic Test (complete)
  - Warm Static Failure Test
  - Cold Static Failure Test
  - High-level Sine Sweep Test

- Component bands, Belleville washers, and wineglasses also extensively tested.
Component Band Tests

  - All units were pulled to 1.2x limit load without yielding.
  - Multiple units were then pulled to failure to determine ultimate strength. In each case, failure occurred above 2.0x limit load.
  - Component stiffnesses measured for use in model correlation.
Belleville Washer Tests

• Belleville washer static testing done in England in April/May 2002.
• Multiple washers statically loaded until fully closed to determine force-displacement relationship.
• Further static tests will be done on production washers to verify performance.
Strap Fatigue Test

- Two straps fatigue tested at CTG in August 2002.
- Fatigue spectrum includes all transport, testing, liftoff/landing, and on-orbit events. Details in SVP section 8.2.
- Both straps survived with no detrimental yielding.
Strap Static Tests

- Two strap static tests were performed at CTG in November 2002 and March 2003.
- Single straps were loaded to 20,225 lb (90 kN) and force-displacement characteristic recorded.
- Data used for strap model correlation and associated perturbation studies.
1-D Dynamic Tests

  - Wineglass fitting added after first test.
  - Wineglass fitting coated in Keronite after second test.
- Two straps connected coaxially to 500 lb mass resting on linear bearings.
- Two primary test goals
  - Validate nonlinear analysis methodology
  - Obtain frequency response data for correlation of individual straps.
1-D Dynamic Test Configuration

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1-D Dynamic Test Photos

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Warm Strap Static Failure Test

- Single strap will be pulled to failure.
- Primary goal is to determine actual strap ultimate load.
- Secondary goal is confirming force-displacement relationship for correlation purposes.
- If strap end clevises do not fail during the test, these will be tested individually.
Warm Strap Static Failure Test
Cold Strap Static Failure Test

- Strap will be attached to actuator and the cold end be cooled to cryogenic temperatures.
- Primary goal is verification of cold force-displacement characteristics and ultimate strength.
- Test still in early planning stages.
Sine Sweep Test

- Test article is STA vacuum case and straps with mass simulated magnet.
- System will be swept at flight-like load levels in each axis:
  - ~0.5g in x-axis
  - ~0.25g in y-axis
  - ~0.8g in z-axis.
- Primary goal is nonlinear response measurement at flight-like load levels.
Modal Test

- Standard modal test of entire AMS-02 structural system.
- Low level force input will minimize nonlinear effects.
- Primary goal is measurement of USS and VC modes.
- Nonlinear modes of global system will be correlated based on high-level sine sweep test.
Strap Analysis Plan

• Strap analysis includes all standard reports:
  – Fracture analysis.
  – Stress analysis to design loads.
  – Loads analysis to verify design loads.

• Certain elements require special analysis to address NASA concerns.
  – Creep analysis for composite components.
  – Linearized/nonlinearized loads comparison.
Strap Fracture Analysis

- Straps checked for fatigue using spectrum defined in AMS-02 SVP.
- Spectrum for flight unit includes:
  - 87 hours of truck and air transport.
  - Three liftoff/landing cycles.
  - Five-year on-orbit lifetime.
- NASGRO analysis of metallic parts with scatter factor of 4 shows no fracture issues for AMS-02.
Creep Analysis

• SCL performed a strap creep analysis in July 2001.
• Strap creep for three year on-orbit lifetime and one year of ground operations expected to be 16.8 µin.
• Preload loss is ~2 lb of an initial 1700 lb.
Strap Stress Analysis

- LMSO performed full stress analysis using design loads for strap pins and clevises.
- No negative margins found.
- Analysis being reviewed as component mass properties and math models are updated and design matures.
# Strap Minimum Margins

<table>
<thead>
<tr>
<th>Item</th>
<th>MoS (Ult)</th>
<th>MoS (Yield)</th>
<th>Failure Mode</th>
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<tr>
<td>Racetrack End Frame</td>
<td>+0.03</td>
<td>+0.45</td>
<td>Tension Load on Lug</td>
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<tr>
<td>Clevis</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Racetrack End Frame</td>
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<td>+0.05</td>
<td>Bending</td>
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<td>Pin</td>
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<td>Cold Link Central</td>
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<td>+0.23</td>
<td>Shear Bearing</td>
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<tr>
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<td>Cold Link Central Pin</td>
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<td>Warm Link Central</td>
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<td>+0.13</td>
<td>Shear bearing</td>
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<tr>
<td>Clevis</td>
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<td>Warm Link Bod Clevis</td>
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<tr>
<td>Glass Band</td>
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<tr>
<td>Glass Bod</td>
<td>+0.58</td>
<td>-</td>
<td>Tension</td>
</tr>
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</table>
Strap System Models

• Several AMS-02 math models being developed
  – Full nonlinear MSC/Nastran model for design loads and stress analysis.
  – Simplified nonlinear Excel/Matlab models to assist in sensitivity work, trade studies, and linearization work.
  – Linearized model for use in the Verification Loads Analysis.

• All nonlinear models will be correlated to test data as well as each other.

• Linear model will be shown to predict loads that envelope nonlinear results.
Nonlinear NASTRAN Models

• Nonlinear FEM developed using ICD strap curves.
• Straps modeled as CROD elements with exact strap force-displacement relationship using TABLES1.
• Current model has 360,000 degrees of freedom.
Polynomial Model

• Simplified polynomial models developed using method of multiple scales.
  – Method of multiple scales requires polynomial approximation of stiffness curve.
• First model created for 1-D dynamic test configuration.
• Next model will be six-DOF, 3-D full AMS-02 configuration.
1-D Dynamic Test Polynomial Model

• Curve for strap dynamic test analysis derived using modified least-squares approach.
  – Linear stiffness terms forced to match Region I stiffness properties. Nonlinear effects forced to be third-order or higher.
  – Curve forced to pass close to the knee point.
• 11th order polynomial provided first reasonable fit.
1-D Dynamic Test Polynomial

![Graph showing force vs. displacement for 1-D Dynamic Test Polynomial. The graph includes two curves, one labeled ICD and the other Polynomial, illustrating the relationship between force (lb) and displacement (in).]
Analytical FRF Predictions

- Frequency response functions predicted for test system for several excitation load levels.
- Three types of valid solutions
  - Region I linear solution (blue line)
  - Primary resonant nonlinear solution (red line)
  - Superharmonic and subharmonic nonlinear solutions (green lines)
FRF – 50 lb Excitation
FRF – 80 lb Excitation
FRF – 300 lb Excitation
Valid Solutions

• For a given excitation load level and excitation frequency, there are a variable number of valid solutions.
  – Region I linear solution only valid below knee point.
  – Primary resonant nonlinear solution and superharmonic/subharmonic solutions only valid above knee point.
Ueda Plots

- Ueda plots show number of valid solutions for any given load level and excitation frequency.
- Regional boundaries determined by where various solutions cross knee point.
- Verification of this plot for two-strap system was primary goal of 1-D dynamic test.
Ueda plot for two-strap, one-dimensional test system
FEM-Polynomial Comparisons

• Nonlinear transient analysis has been performed using MSC/NASTRAN to provide initial check on polynomial model.
• Comparisons of steady-state magnitudes quite good.
  – Region I linear solutions match within 0.40%.
  – Primary nonlinear resonant solutions match within 2.02%.
Test Results

• Three full strap tests completed to date:
  – Strap fatigue test (August 2002)
  – Strap static test (March 2003)
  – 1-D dynamic test (April 2003)

• All results being used to update analysis.

• Warm static failure test is next on schedule.
C1W1 Warm Static Curve Comparisons

Displacement (in) vs Force (lb)

- ICD
- Test Strap #4
- Test Strap #5
Frequency Response Comparisons

Preliminary Comparison of Pre-Test Predictions to Measured Results
FRF Accel #1 X-Axis - 40 lb. Sine Sweep

![Graph showing frequency response comparison](image)

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Damping Measurements

• Results from initial 1-D dynamic test show Region I damping of ~14%.
  – High damping most likely due to friction in Belleville washer stack.

• Nonlinear analysis using constant, conservative damping value equal to ~4.5% in Region I, 1% in Region II/III.

• Linearized model will use standard VLA damping schedule.
Future Work

- 1-D Dynamic Test Report to be released soon. Strap models will be correlated concurrently.
- Static Failure Test coming soon.
- STA strap construction and acceptance testing in 2003.
- Sine Sweep Test to determine nonlinear behavior of Vacuum Case.
- Modal Test of full AMS-02.
Support System Documentation

- CTG-SCL-130802 – Fatigue Test Report for Strap #2
- CTG-SCL-290802 – Fatigue Test Report for Strap #3
- LMSEAT 33848, 1-D Dynamic Test Plan
- LMSEAT 33892, 1-D Dynamic Test Pre-Test Analysis
- LMSEAT 34044, 1-D Dynamic Test Report
- CTG-SCL-240303C – Strap Static Test Report
- LMSEAT 33847, Warm Static Failure Test Plan
- Stress Analysis Report
- Fracture Analysis Report
Strap System Points of Contact

- Design, Manufacturing, and Assembly
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