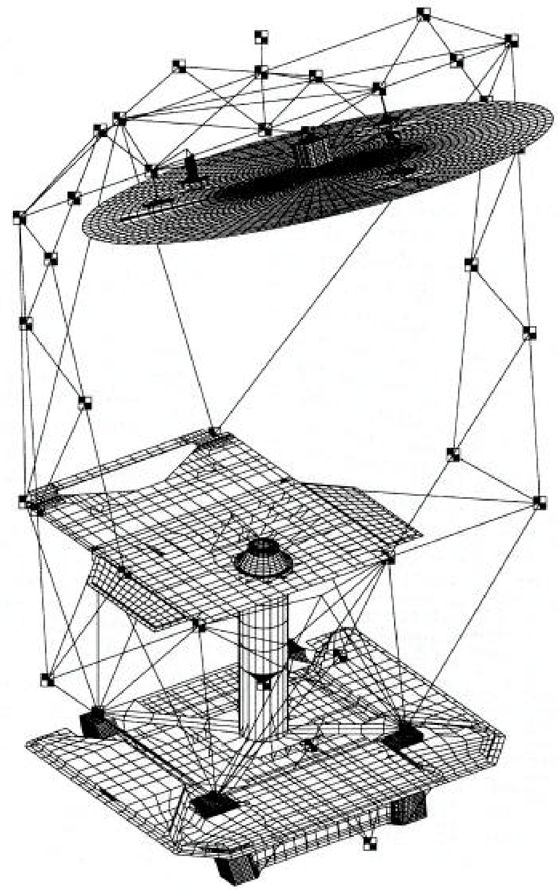
Structural Qualification Testing of the WindSat Payload Using Sine Bursts Near Structural Resonance



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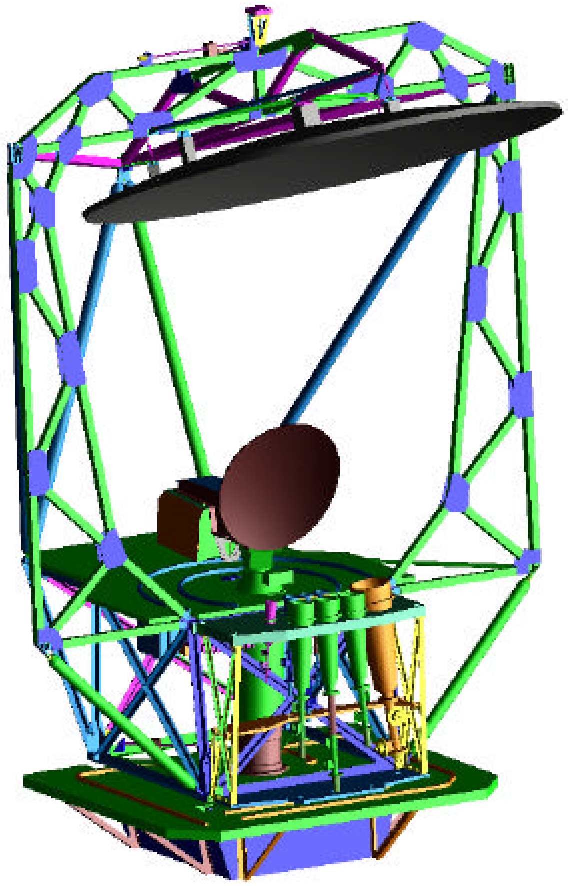
SWALES AEROSPACE



Outline

- Introduction
- Objectives
- Analytical approach
- Experimental approach
- Testing
- Conclusions

Introduction

- WindSat Payload:
  - ~700 lb, 10.5’ GR/EP, Ti, and Al radiometer, 6’ reflector
  - Spins ~ 30 rpm, canister frame w/preloaded deck & launch locks for deployed clearance
  - Acceleration gradient nearly 4:1 up the stack
  - Due to size & lightweight composite bonded reflector support structure construction, static pull testing to qualify all composites and bonded joints in the upper structure would result in large, expensive, and extensive test fixturing.
- Typical sine burst testing
  - Driving frequency vs. first resonant mode
  - Common scenario for large structures (and WindSat):
    - Qualification of lower parts of the structure only, or
    - Over- test of lower structure to achieve qualification of upper structure
    - Using larger mass sims result in exceeding shaker displacement limitations

Introduction

- Sine burst testing near the first two structural resonant modes was performed on the WindSat payload to achieve the correct load factor distribution up the stack for structural qualification.

- This presentation discusses how FEM sine burst predictions were used in conjunction with low level random and sine burst tests to achieve correct qualification test load factor distributions on the WindSat payload.

- Also presented is the risk mitigation approach for using the uncorrelated FEM in this procedure.

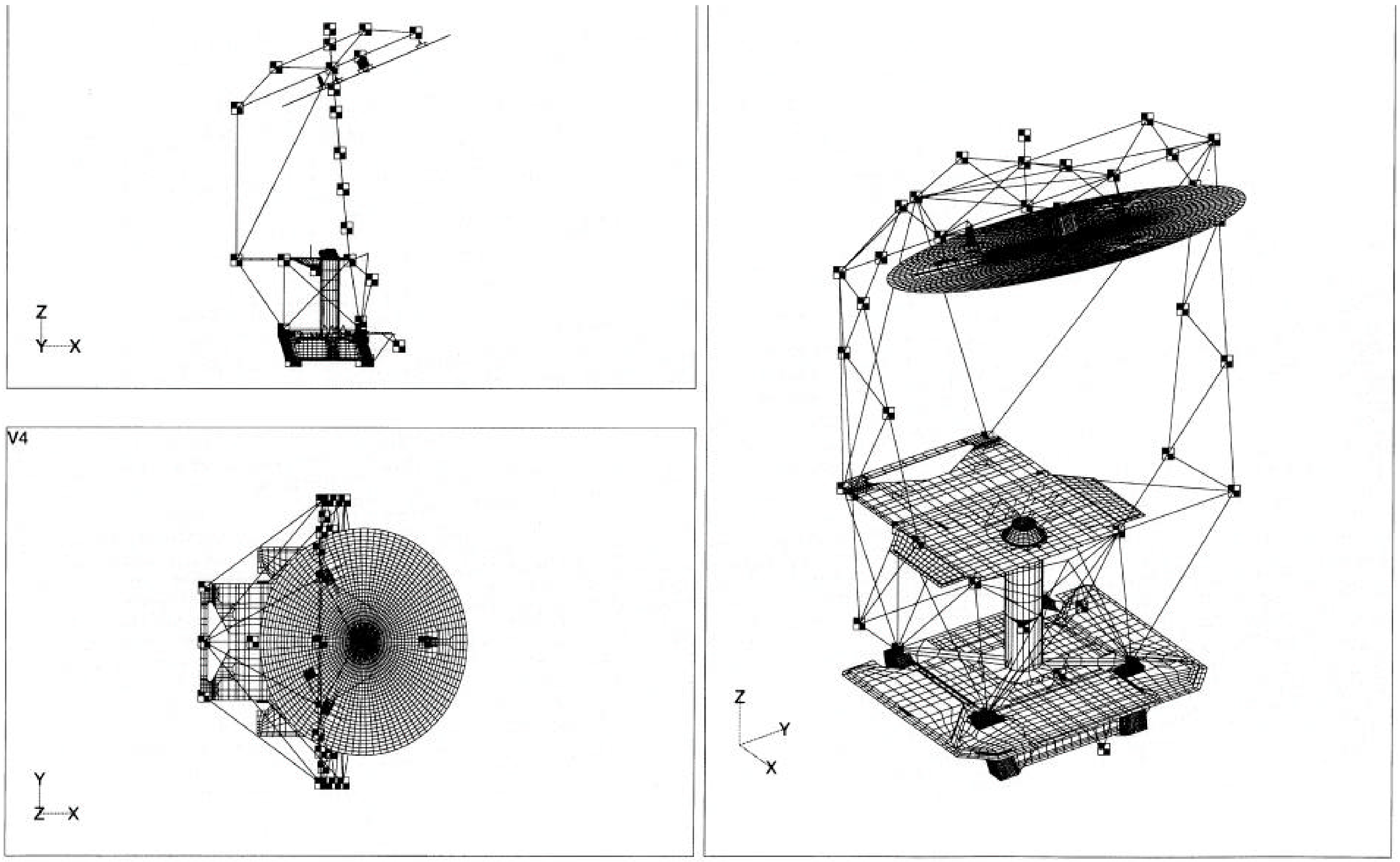
Objectives

- Qualify WindSat critical structural elements with near-resonance sine burst testing
- Proof load composite elements and bonded joints in WindSat structure
- Prove rotating to stationary deployed structural clearances do not change after dynamic load application
- Complete testing quickly and inexpensively

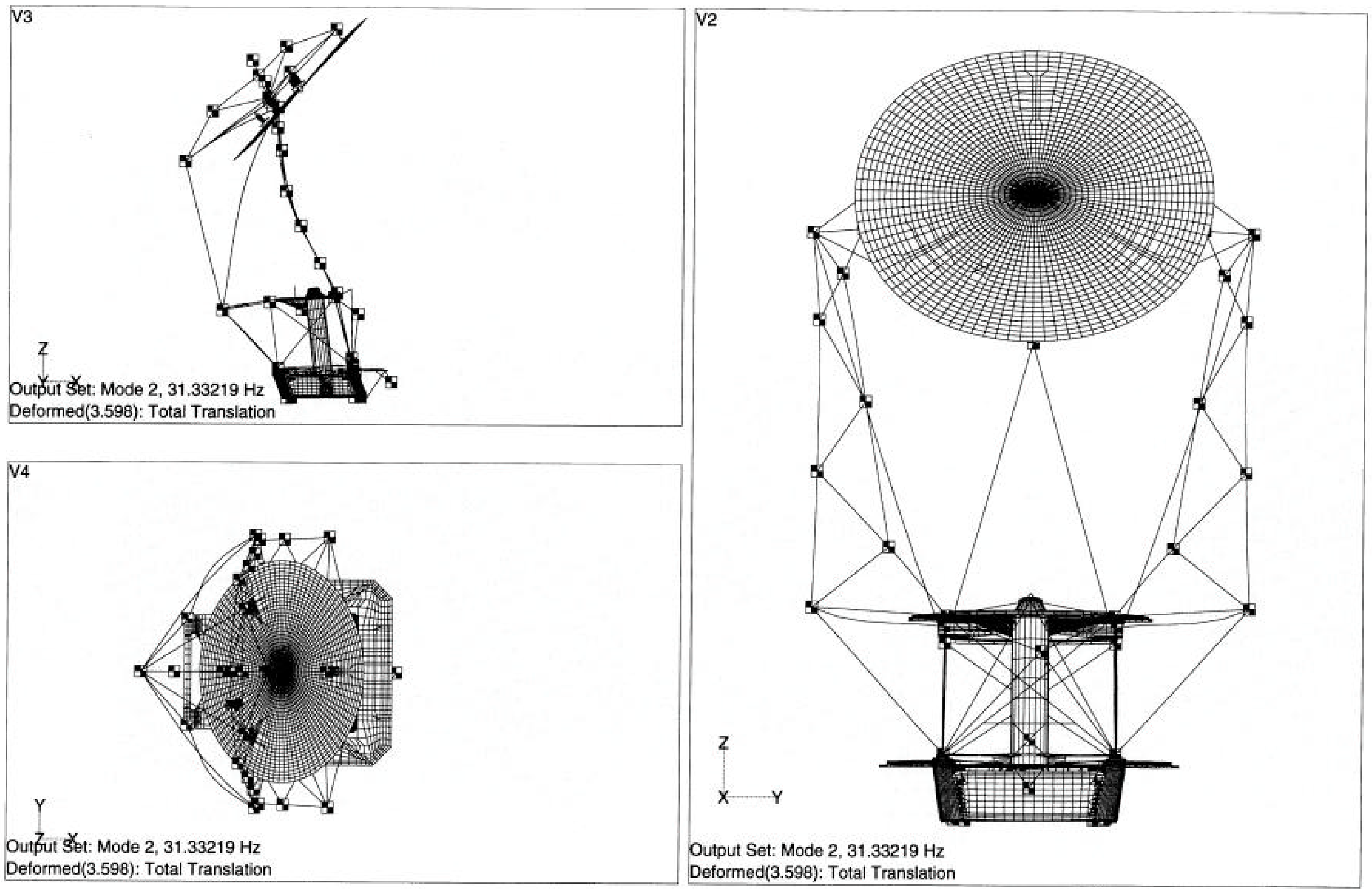
Analytical Approach

- Determine critical components by checking M.S. with no-test factors of safety
  - Screens out non-composite structure that can be qualified by analysis
- Analytically simulate the sine burst test (uncorrelated FEM)
  - Track accelerations at center of reflector and feed bench upper deck
  - Recover internal loads in critical components and compare with critical DLL
  - Estimate test parameters (**frequency**, input acceleration and direction) to qualify critical components by tracking **ratio of reflector-to-feed bench acceleration**
- NASTRAN FEM created using FEMAP
  - ~22,000 nodes, ~110,000 DOFs, standard element types
  - Transient analyses completed on Craig-Bampton model using FLAME
    - 1g X & Y input in 1Hz increments, 5 cycle ramps, 5 cycle hold
    - Plot responses and pick frequency that gives desired accelerations
      - $f_{\text{analytical input x}}$ = 21 Hz (f_2 = 31.3 Hz), $a_{\text{reflector}}$ = 12.0 g, R_x = 1.83
      - $f_{\text{analytical input y}}$ = 18 Hz (f_1 = 24.3 Hz), $a_{\text{reflector}}$ = 17.8 g, R_y = 2.31

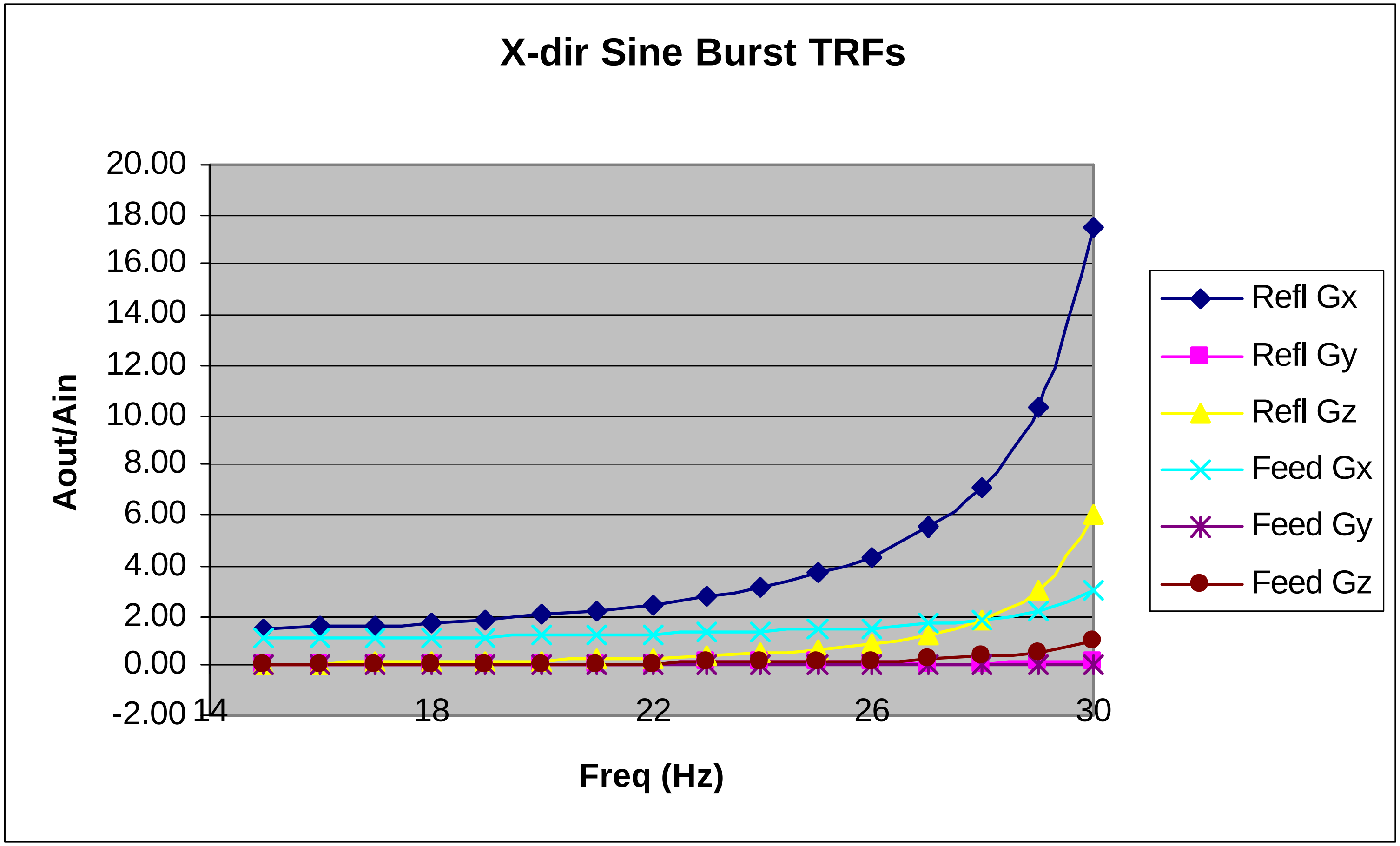
Analytical Approach



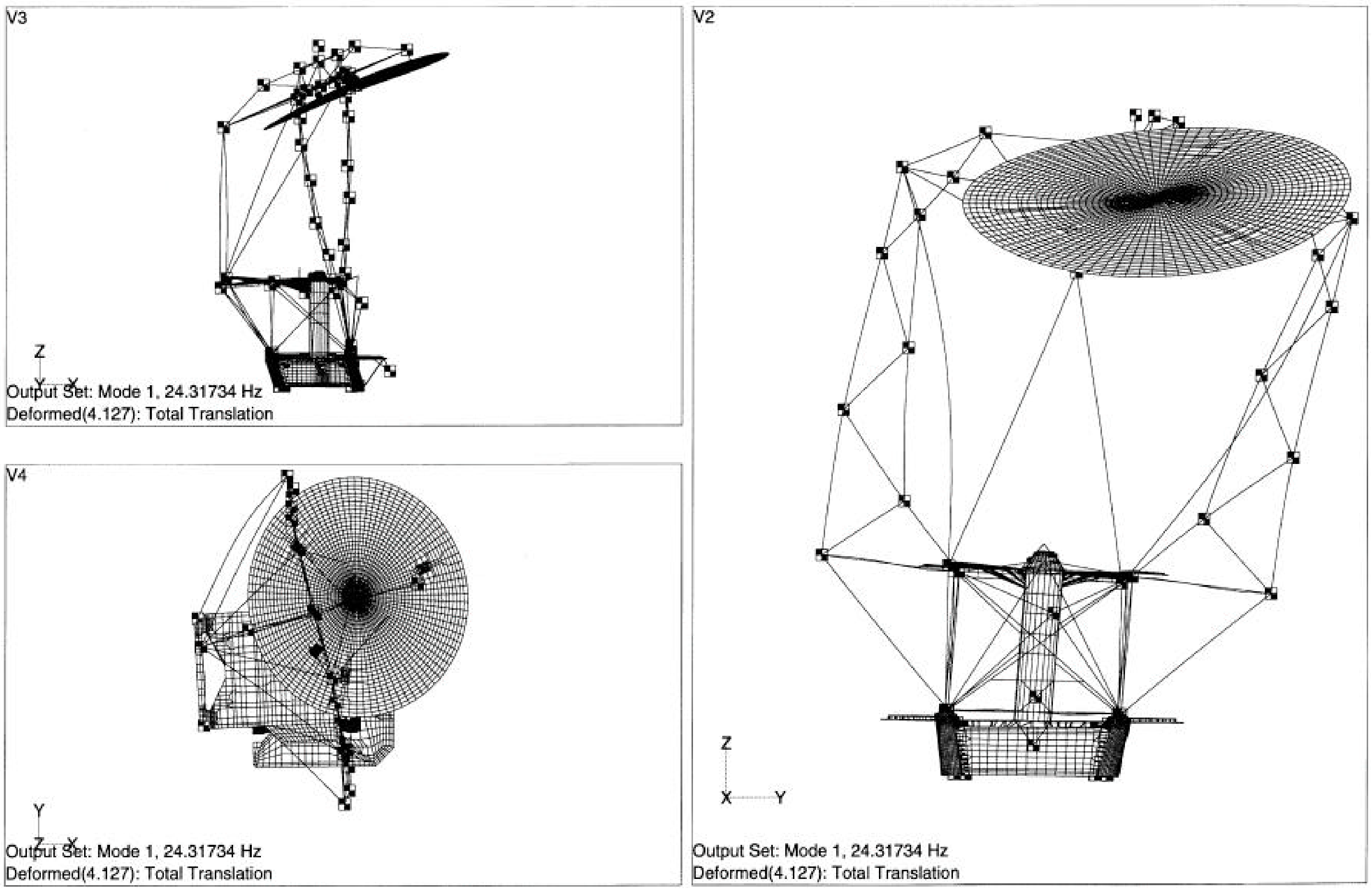
Analytical Approach



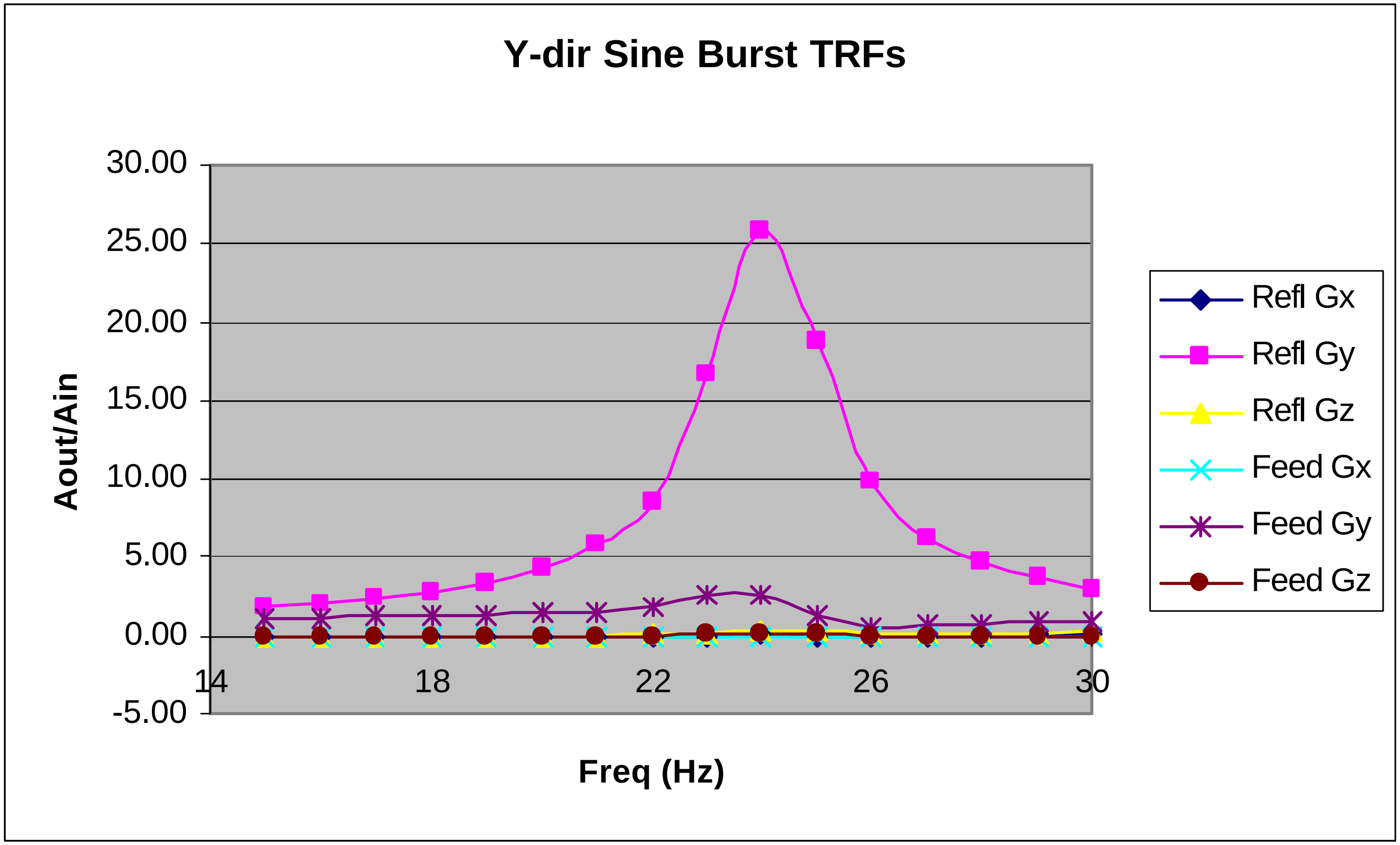
Analytical Approach



Analytical Approach



Analytical Approach



Experimental Approach

- Perform modal survey of WindSat in test configuration
  - Quick comparison of analytic vs. test frequencies
- Develop MATLAB script to track internal loads from strain readings and write M.S. using the same analytical expressions used during the design phase
  - Uses time consistent data
- Perform shaker test to 150% of full analytically-predicted test levels without WindSat on the table
- Run X-dir qualification test first, then Y (Y-dir a bit more exciting!)
- Generate pre-test low level random signature (1.0 G_{rms})

Experimental Approach

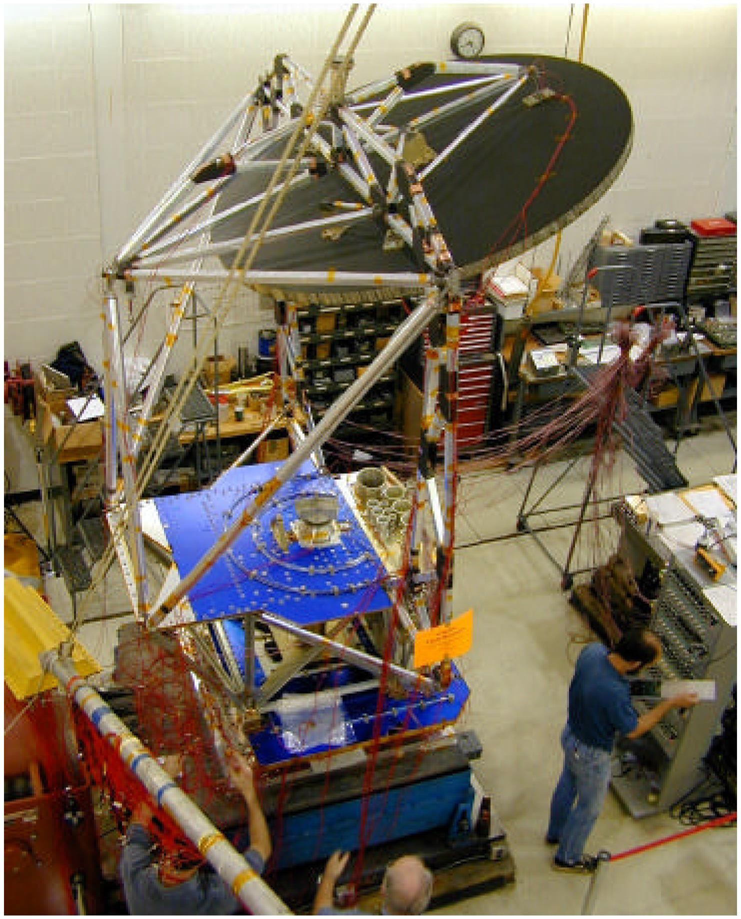
- Use low level random FRFs to find Qs at the center of the reflector and feed bench upper deck, and subsequently determine sine burst input frequency and level
  - Calculate ratio of reflector-to-feed bench acceleration for various frequencies
  - Compare analytical and test ratios at analytically-predicted frequency and modify input parameters accordingly
- Perform low level sine burst tests at -18 dB, -10dB, and -6 dB
  - Monitor M.S., compare actual internal loads with analytically-predicted values, track linearity
  - Determine reflector-to-feed bench accel ratio and verify it remains constant
  - Extrapolate next load increase and full level accels
  - Make full level M.S. predicts via MATLAB script

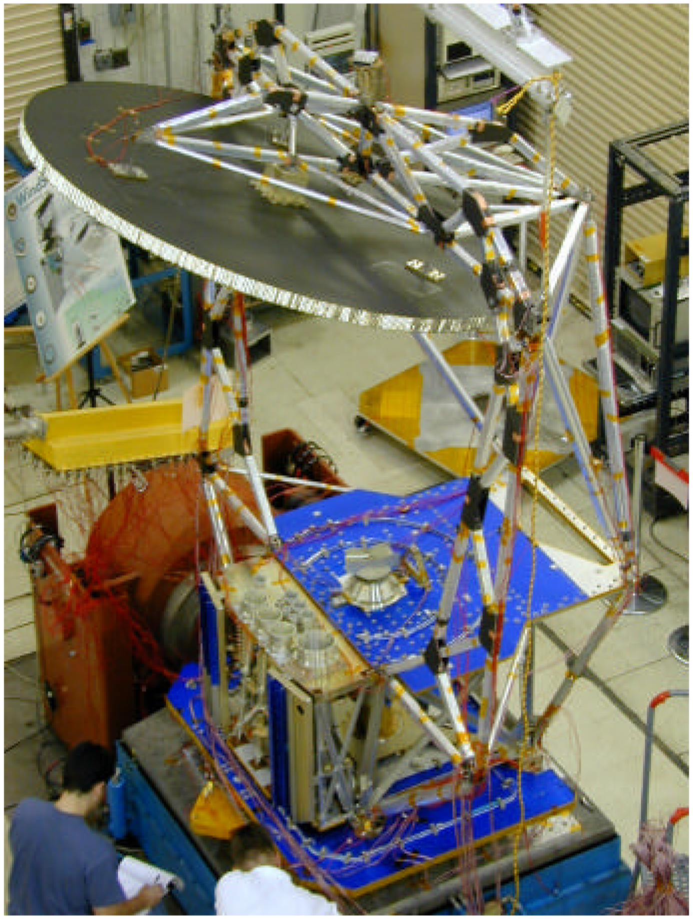
Experimental Approach

- Shift input frequency up or down to get correct ratio of reflector to feed bench acceleration if needed
- Repeat low level sine bursts until “zero-ed” in on input frequency
- Perform next level sine burst test, -3 dB
  - Monitor M.S., compare actual internal loads with analytically-predicted values, track linearity
  - Verify ratio doesn’t change at higher input levels
  - Extrapolate to next load increase, then compare with test
  - Make full level M.S. predicts via MATLAB script
  - Modify full level input as required to get 100% +/- 3% TLL
- Increase to -1 dB, repeat checks, then to qualification level
- Perform low level random and overlay with pre-test FRFs

Testing

SWALES AEROSPACE





Testing

- Instrumentation
  - 128 accel, 50 strain channels
- Performed modal survey
  - First 4 FEM modes were within 5% of test modes
    - Quality, detailed model
    - Efficient structural design
    - Excellent manufacturing workmanship
- Performed low level random on slip table for X-dir
  - Reflector and feed bench FRFs from low level random were used to calculate reflector to feed bench acceleration ratio and to compare with analytical ratio
    - No adjustment to initial sine burst frequency (21 Hz) made for X-dir test

Testing

- Ran low level sine burst tests (-18 dB, -10 dB, and -6 dB) for X-dir
  - Verified system is responding linearly
    - Acceleration ratio was constant (1.67, 1.60, 1.62)
    - Internal loads, moments increased linearly
  - Verified no coupling/cross-talk
  - Monitored M.S. and made full level predictions
  - Both FEM predicts and low level random FRFs indicated that a 2 Hz increase in input frequency was needed to get to accel ratio of 1.88 (goal was 1.83)
- Shifted sine burst test input frequency to 23 Hz for X-dir
  - Repeated -10 dB and -6 dB tests
  - New acceleration ratio was constant (1.90, 1.88)

Testing

- Performed next level sine burst tests, -3 dB and -1 dB
  - Monitored M.S., compared actual internal loads with analytically-predicted values, tracked linearity
  - Verified ratio didn't change (R= 1.86)
  - Extrapolated next load increase, then compared with test
  - Made full level M.S. predictions via MATLAB script
- Determined qualification level would be reached at -0.5 dB
- Performed qualification level sine burst test at -0.5 dB

	Frequency (Hz)	Feed bench accel (g's)	Reflector accel (g's)	Accel Ratio
FEM	21.0	6.56	12.00	1.83
Test	23.0	6.56	12.46	1.90

Testing

- Ran post-test low level random for X-dir
  - Compared pre- and post- test FRF overlays for frequency shifts
    - Virtually identical
  - Reviewed all accelerometer channels
- Successful qualification for X-dir

- Performed low level random on slip table for Y-dir
  - Reflector and feed bench FRFs from low level random were used to calculate reflector to feed bench acceleration ratio and to compare with analytical ratio
    - 2 Hz increase (from 18 Hz to 20 Hz) made to initial frequency for Y-dir test
      - FEM showed R = 2.31 at 18 Hz
      - Test showed R = 2.38 at 20 Hz

Testing

- Ran low level sine burst tests (-18 dB, -10 dB, and -6 dB) for Y-dir
  - Verified system is responding linearly
    - Acceleration ratio was constant (2.61, 2.59, 2.60)
    - Internal loads, moments increased linearly
  - Verified no coupling/cross-talk
  - Monitored M.S. and made full level predictions
  - Both FEM predicts and low level random FRFs indicated that a 1 Hz decrease in input frequency was needed to get to accel ratio of ~2.25 (goal was 2.31)
- Shifted sine burst test input frequency to 19 Hz for Y-dir
  - Repeated -10 dB and -6 dB tests
  - New acceleration ratio was constant (2.27, 2.27)

Testing

- Performed next level sine burst tests, -3 dB and -1 dB
  - Monitored M.S., compared actual internal loads with analytically-predicted values, tracked linearity
  - Verified ratio didn't change (R= 2.28)
  - Extrapolated next load increase, then compared with test
  - Made full level M.S. predictions via MATLAB script
- Determined qualification level would be reached at -0.5 dB
- Performed qualification level sine burst test at -0.5 dB

	Frequency (Hz)	Feed bench accel (g's)	Reflector accel (g's)	Accel Ratio
FEM	18.0	7.69	17.80	2.31
Test	19.0	7.68	17.50	2.28

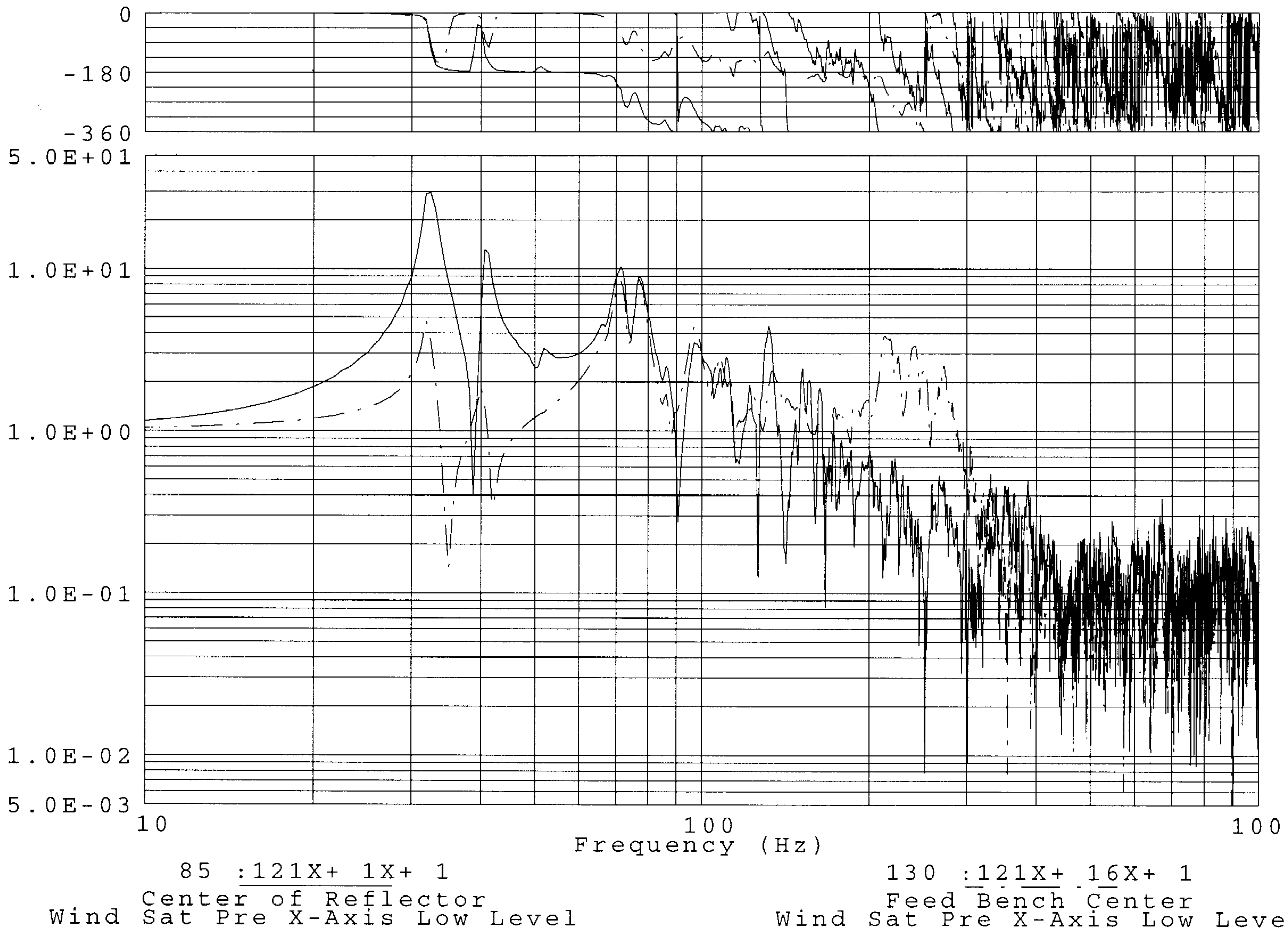
Testing

- Ran post-test low level random for Y-dir
  - Compared pre- and post- test FRF overlays for frequency shifts
    - Virtually identical
  - Reviewed all accelerometer channels
- Successful qualification for Y-dir

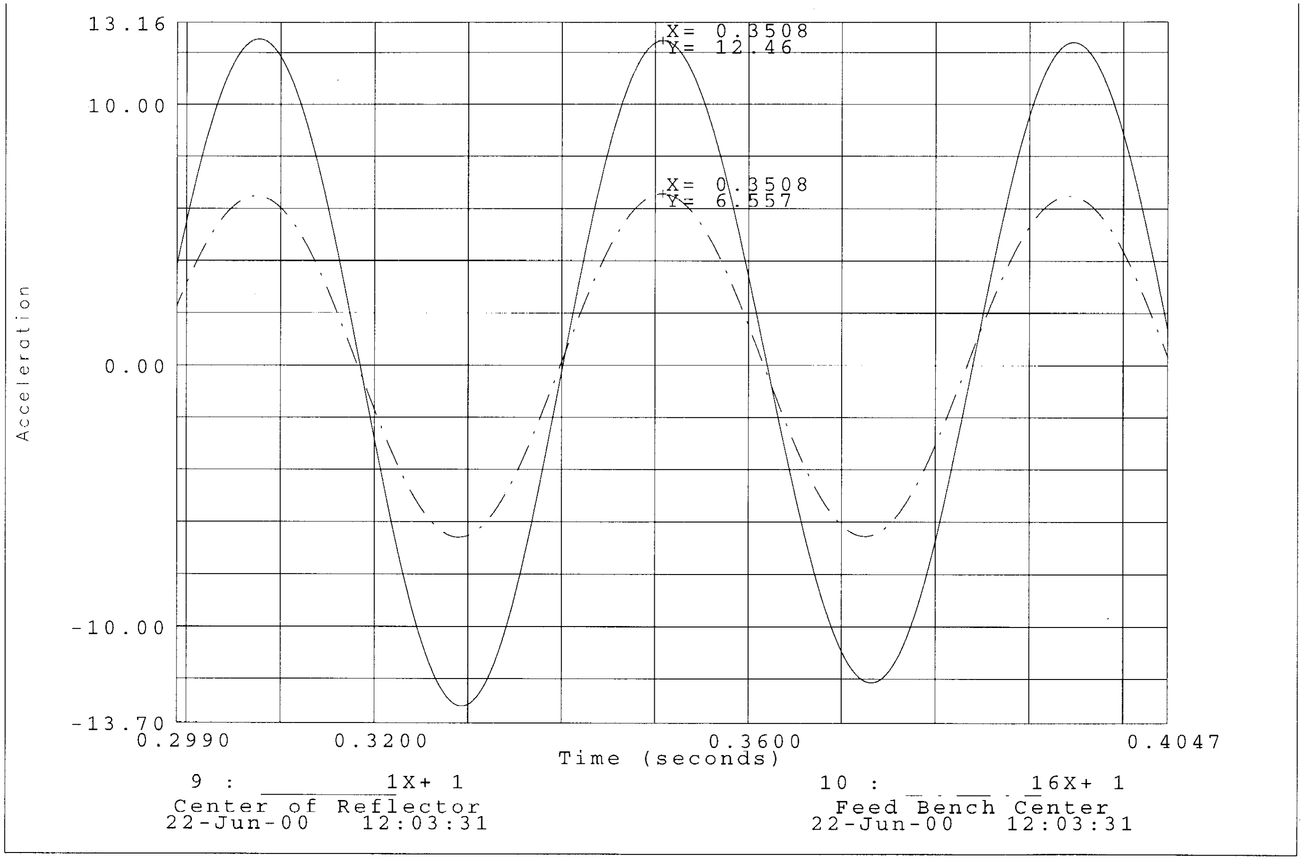
- Deployed rotating canister launch locks
  - Measured clearances between stationary and deployed halves of launch locks
  - Gaps changed less than 0.001” (0.100” nominal)

- Successful qualification of WindSat structure

Testing

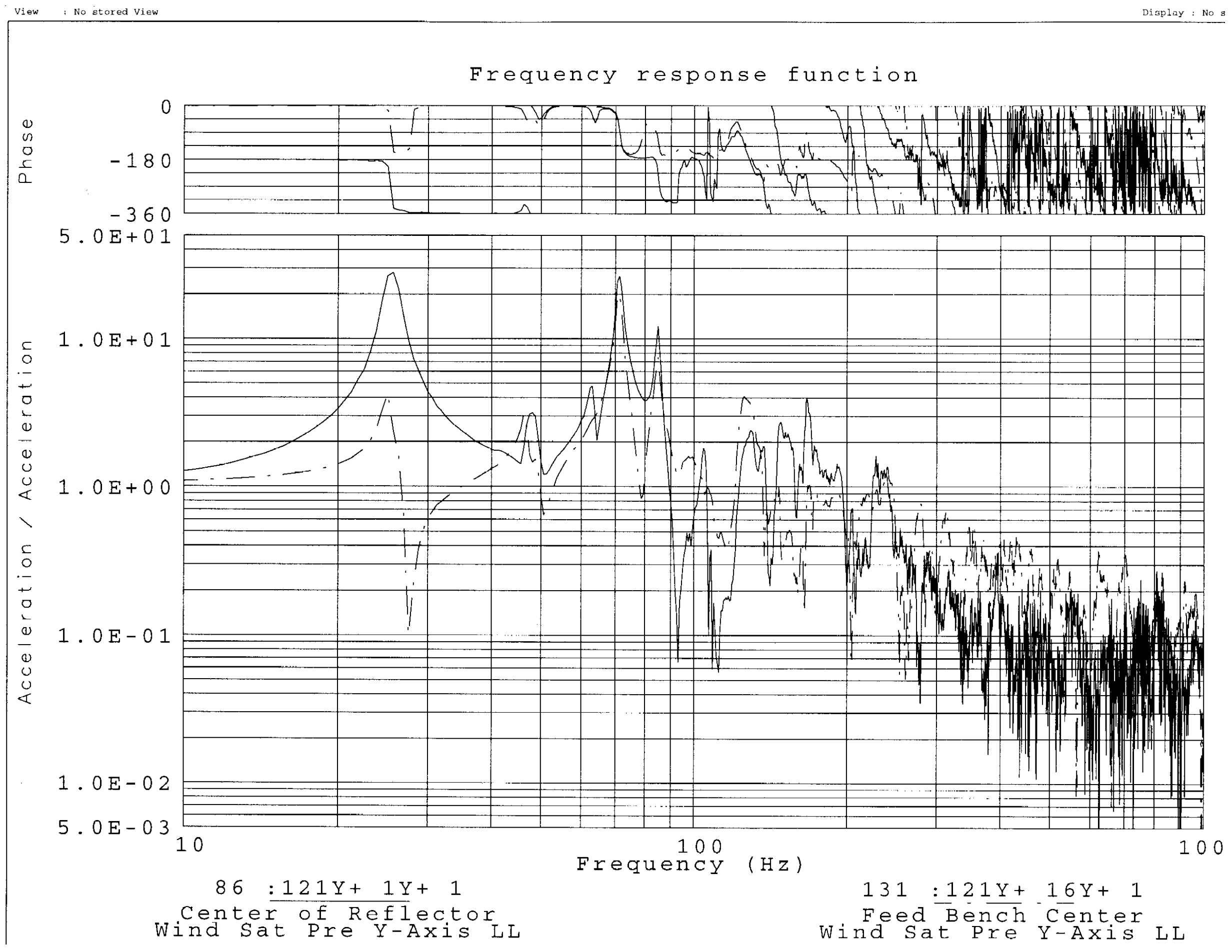

0
-180
-360
5.0E+01
1.0E+01
1.0E+00
1.0E-01
1.0E-02
5.0E-03
10
100
100
Frequency (Hz)
85 :121X+ 1X+ 1
Center of Reflector
Wind Sat Pre X-Axis Low Level
130 :121X+ 16X+ 1
Feed Bench Center
Wind Sat Pre X-Axis Low Leve

Testing

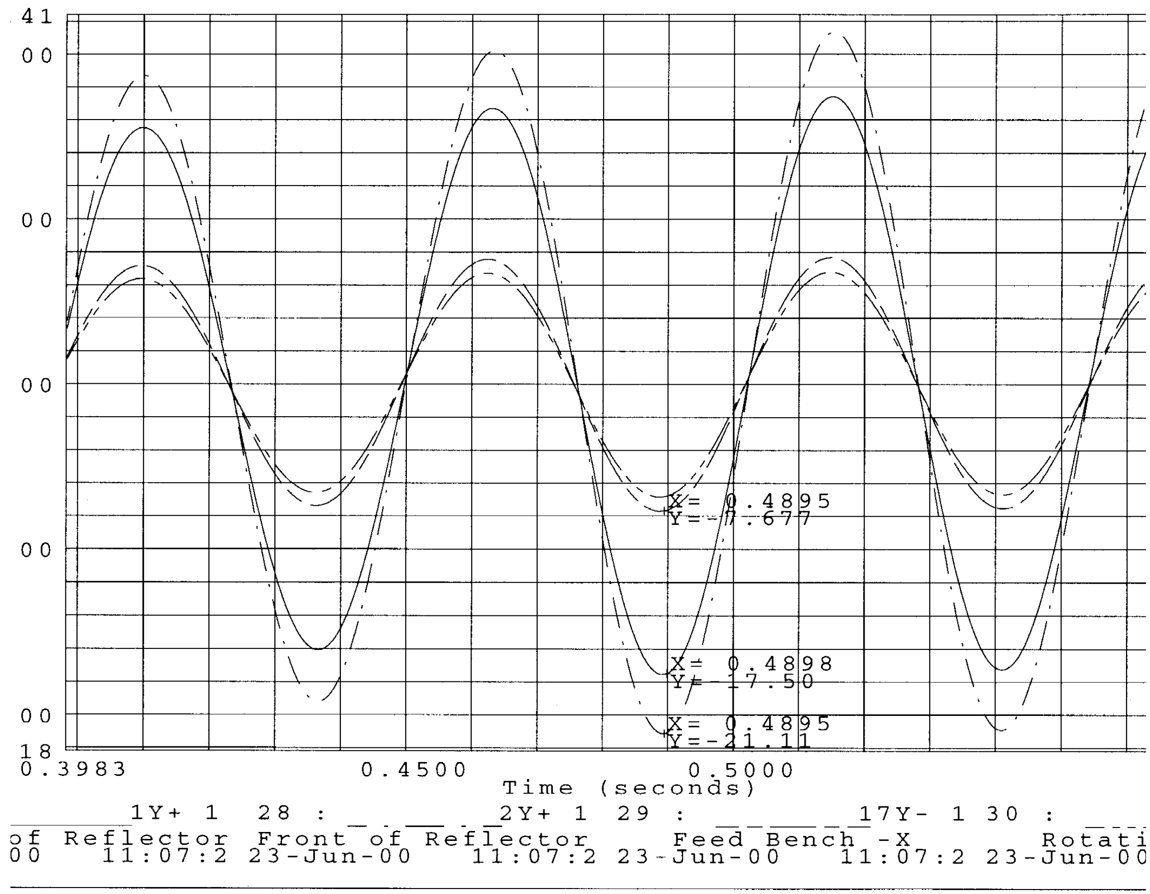


FULL QUAL LEVEL (-0.5 dB)

Testing

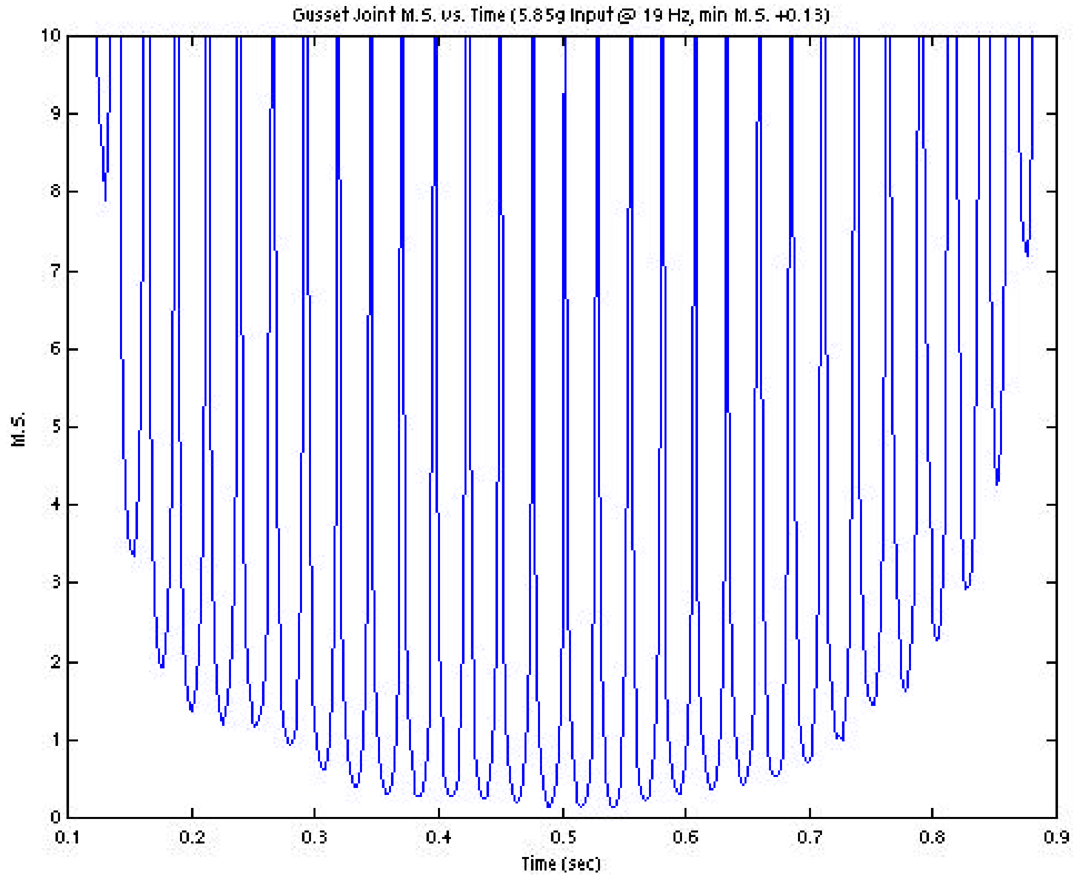

View : No stored View
Display : No s
Frequency response function
Phase
0
-180
-360
Acceleration / Acceleration
5.0E+01
1.0E+01
1.0E+00
1.0E-01
1.0E-02
5.0E-03
10
100
100
Frequency (Hz)
86 :121Y+ 1Y+ 1
Center of Reflector
Wind Sat Pre Y-Axis LL
131 :121Y+ 16Y+ 1
Feed Bench Center
Wind Sat Pre Y-Axis LL

Testing



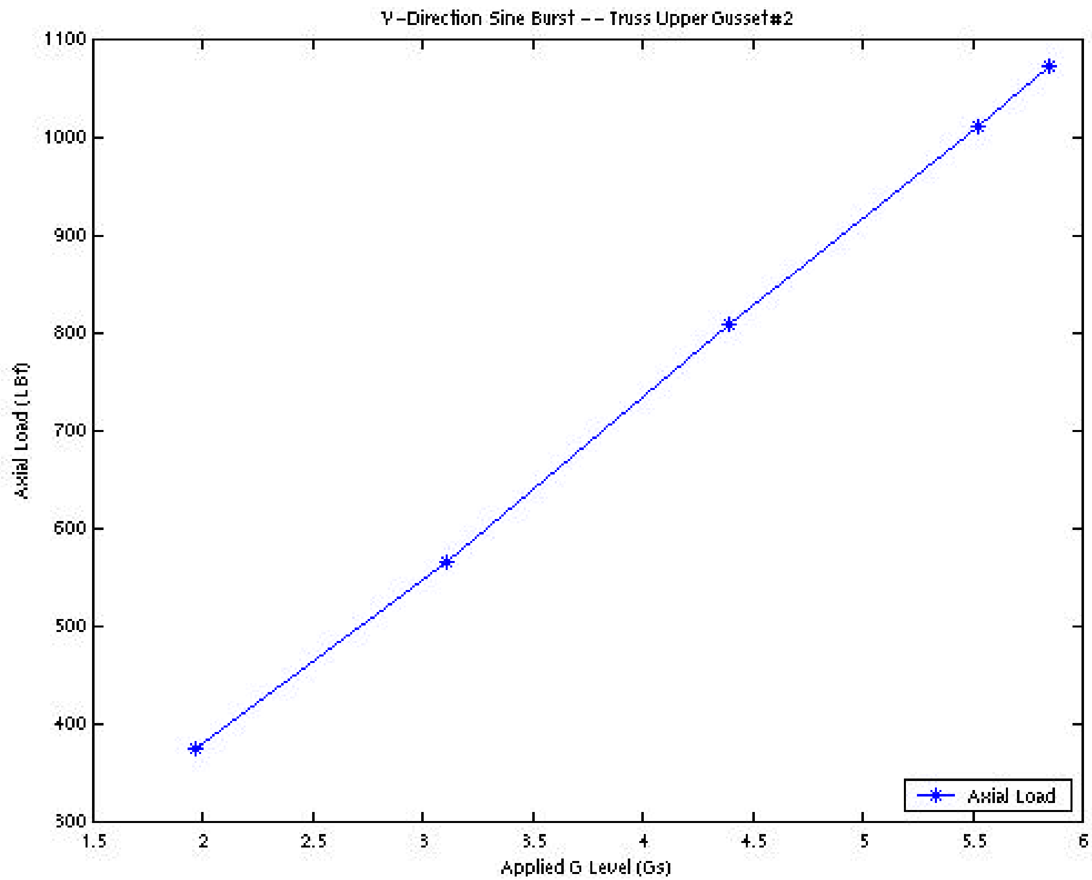
~0,5 dB

Testing



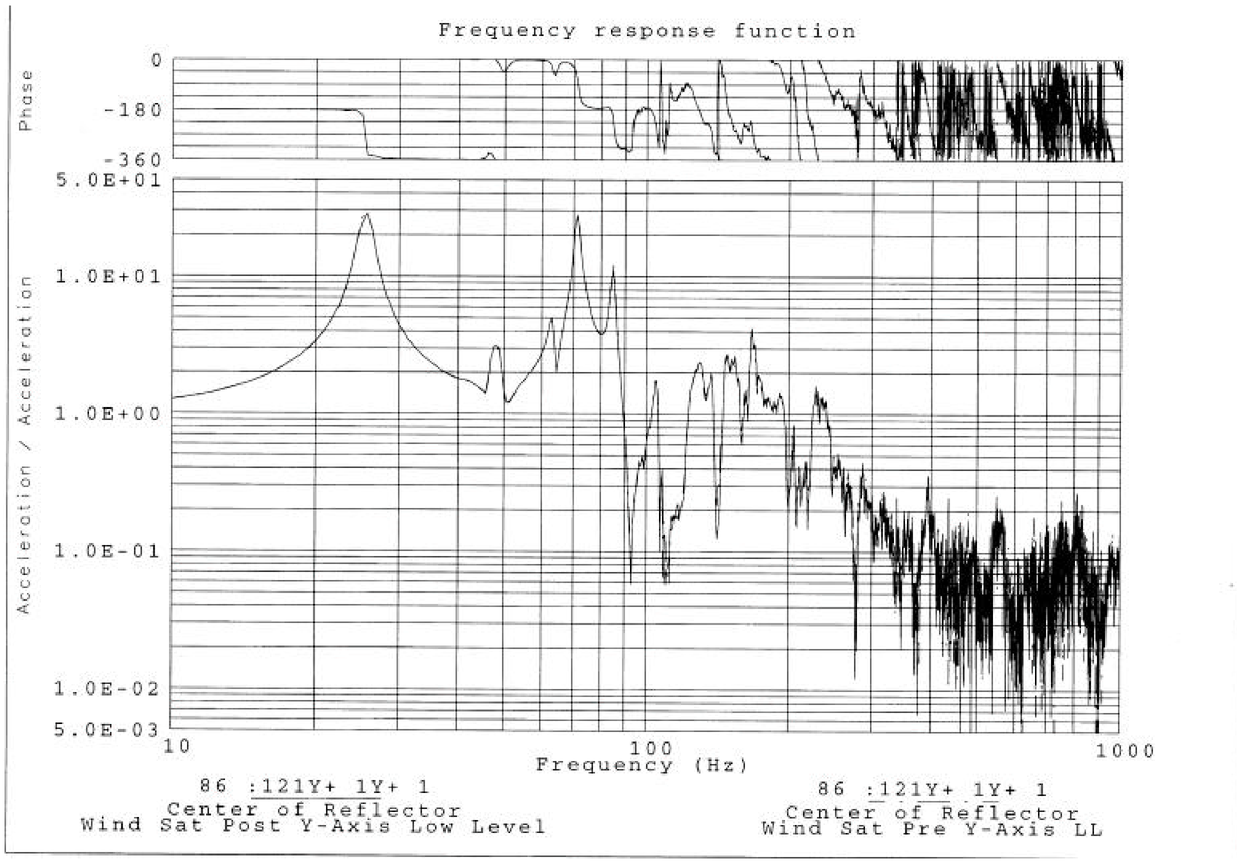
Gusset Joint M.S. vs. Time (5.85g Input @ 19 Hz, min M.S. +0.13)
M.S.
Time (sec)
0
1
2
3
4
5
6
7
8
9
10
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Testing



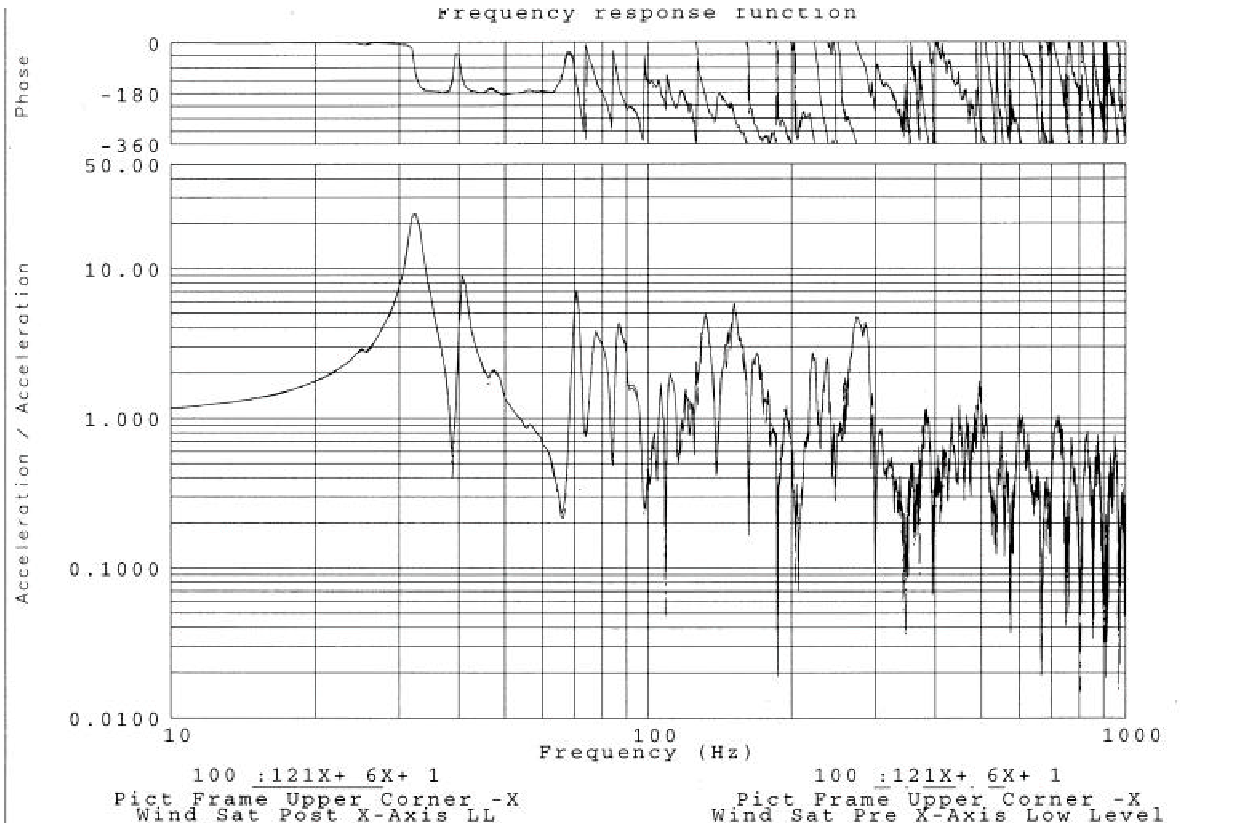
Y-Direction Sine Burst -- Truss Upper Gusset#2
Axial Load (LBf)
Applied G Level (Gs)
Axial Load
1100
1000
900
800
700
600
500
400
300
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6

Testing



Frequency response function
Phase
0
-180
-360
Acceleration / Acceleration
5.0E+01
1.0E+01
1.0E+00
1.0E-01
1.0E-02
5.0E-03
10
100
1000
Frequency (Hz)
86 :121Y+ 1Y+ 1
Center of Reflector
Wind Sat Post Y-Axis Low Level
86 :121Y+ 1Y+ 1
Center of Reflector
Wind Sat Pre Y-Axis LL

Testing



Frequency response function
Phase
0
-180
-360
Acceleration / Acceleration
50.00
10.00
1.000
0.1000
0.0100
10
100
1000
Frequency (Hz)
100 :121X+ 6X+ 1
Pict Frame Upper Corner -X
Wind Sat Post X-Axis LL
100 :121X+ 6X+ 1
Pict Frame Upper Corner -X
Wind Sat Pre X-Axis Low Level

Conclusions

- Successfully qualified WindSat structure
  - Achieved correct load factor distribution up the stack
  - No shifts in any frequencies
  - No change in performance of rotating/stationary structural deployment
- Finite element analytical simulation of sine burst test used successfully to prove test feasibility and reduce test time (frequency searching)
  - Less risk if correlated FEM is available (program schedule issue)
- "Real time" assessment of sine burst test is invaluable (M.S., internal loads, full level predictions)
- Total time on shaker table was five (5) days (6/19/00 – 6/23/00)