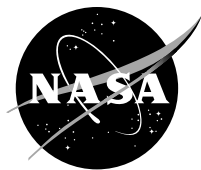


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Structural Dynamic Assessment of the GN2 Piping System for NASA's New and Powerful Reverberant Acoustic Test Facility

*Mark E. McNelis, Lucas D. Staab, James C. Akers, William O. Hughes,
Li C. Chang, Aron D. Hozman, and Michael W. Henry
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Abstract

The National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) has led the design and build of the new world-class vibroacoustic test capabilities at the NASA GRC's Plum Brook Station in Sandusky, Ohio, USA from 2007 to 2011. SAIC-Benham has completed construction of a new reverberant acoustic test facility to support the future testing needs of NASA's space exploration program and commercial customers.

The large Reverberant Acoustic Test Facility (RATF) is approximately 101,000 ft³ in volume and was designed to operate at a maximum empty chamber acoustic overall sound pressure level (OASPL) of 163 dB. This combination of size and acoustic power is unprecedented amongst the world's known active reverberant acoustic test facilities.

Initial checkout acoustic testing was performed on March 2011 by SAIC-Benham at test levels up to 161 dB OASPL. During testing, several branches of the gaseous nitrogen (GN2) piping system, which supply the fluid to the noise generating acoustic modulators, failed at their "T-junctions" connecting the 12 in. supply line to their respective 4 in. branch lines. The problem was initially detected when the oxygen sensors in the horn room indicated a lower than expected oxygen level from which was inferred GN2 leaks in the piping system. In subsequent follow up inspections, cracks were identified in the failed "T-junction" connections through non-destructive evaluation testing.

Through structural dynamic modeling of the piping system, the root cause of the "T-junction" connection failures was determined. The structural dynamic assessment identified several possible corrective design improvements to the horn room piping system. The effectiveness of the chosen design repairs were subsequently evaluated in September 2011 during acoustic verification testing to 161 dB OASPL.

Introduction

The NASA Space Environmental Test (SET) Project developed new environmental test facilities to support NASA's developing space exploration program. The Space Power Facility (SPF) at the NASA Glenn Research Center's (GRC) Plum Brook Station in Sandusky, Ohio, USA is already the home of the world's largest thermal vacuum chamber (Fig. 1). In order to provide one-stop testing for the suite of space environmental testing, the SPF has been augmented with a new reverberant acoustic (Ref. 1), mechanical vibration (Ref. 2), and fixed base modal floor (Ref. 2) test facilities, which are located in the Vibro-Acoustic Highbay of the SPF.

In August 2007, SAIC-Benham, located in Oklahoma City, Oklahoma, USA, won the NASA prime contract to design and construct these new test facilities, as well as to provide the high speed data acquisition system to support them. SAIC-Benham contracted with Aiolos Engineering Corporation (Aiolos), located in Toronto, Ontario, Canada to provide the acoustic design of the Reverberant Acoustic Test Facility (RATF).

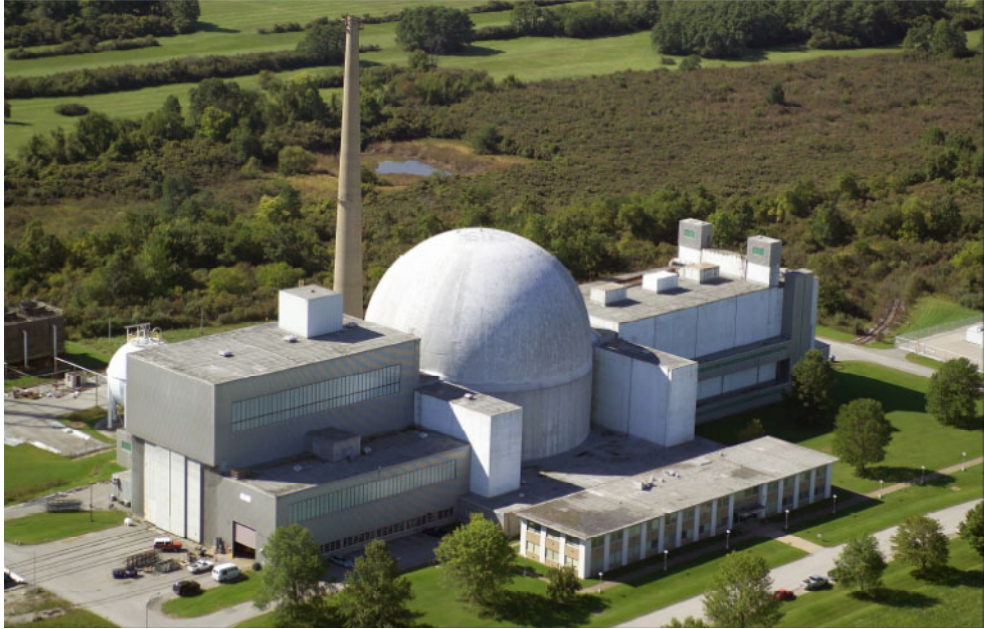


Figure 1.—NASA GRC's Plum Brook Station is home of the Space Power Facility.

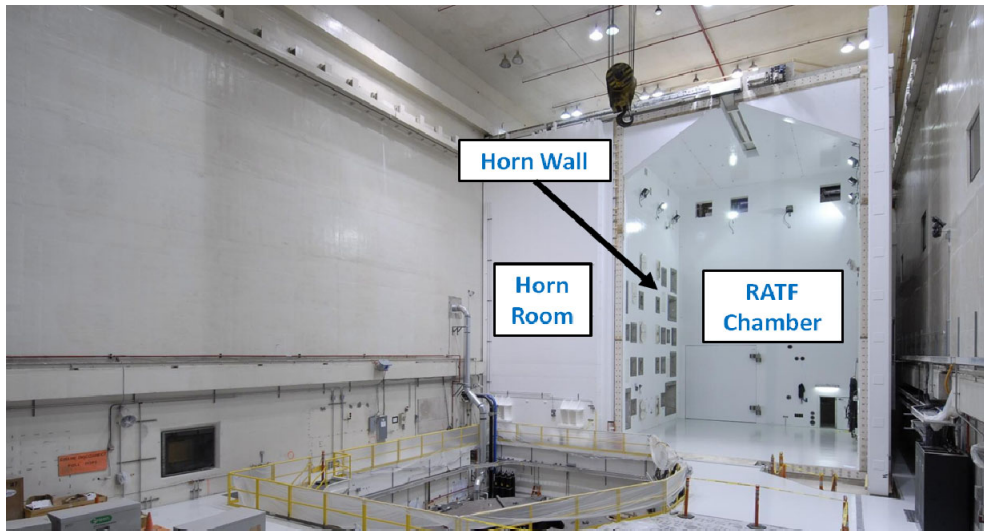


Figure 2.—RATF chamber and horn room in the vibro-acoustic highbay.

The RATF is a unique acoustic test facility (Fig. 2) due to its combination of very large chamber test volume and extremely high acoustic sound levels. The RATF's combination of size and acoustic power was necessary to meet NASA's requirements to test the next generation of large space exploration vehicles whose acoustic environments have been predicted to be on the order of 163 dB OASPL or even higher. This paper addresses the structural failure of the RATF's horn room gaseous nitrogen piping system during acoustic checkout testing, the subsequent structural dynamic assessment, repair, and verification testing of the piping system.

RATF Acoustic Design and Horn Room Piping System

The RATF acoustic noise generating system utilizes a combination of low frequency TEAM modulators (designated as MK-VI and MK-VII modulators) and high frequency Wyle modulators (designated as WAS 5000 modulators). Each of these modulators are connected to a dedicated horn designed with a cutoff frequency in a specific 1/3 octave frequency band. There are a total of 36 horns/modulators that produce the acoustic power to meet the RATF acoustic test spectra requirements. The RATF design has eleven (11) MK-VII modulators distributed on the 25, 35, 50, and 80 Hz horns, twelve (12) MK-VI modulators distributed on the 100 and 160 Hz horns, and thirteen (13) WAS 5000 modulators on the 250 Hz horns.

The RATF was acoustically designed to achieve a broad spectrum of acoustic test spectra; the design requirements (C1 to C8 acoustic test spectra) are shown in Figure 3. The C2 test spectrum is unique because it has the largest low frequency acoustic test levels (between 150 and 155 dB below the 100 Hz 1/3 octave frequency band), which dynamically couples to the RATF structure. The chamber walls, ceiling and foundation were designed and built to withstand up to 166 dB OASPL. The RATF acoustic design features are illustrated in Figure 4.

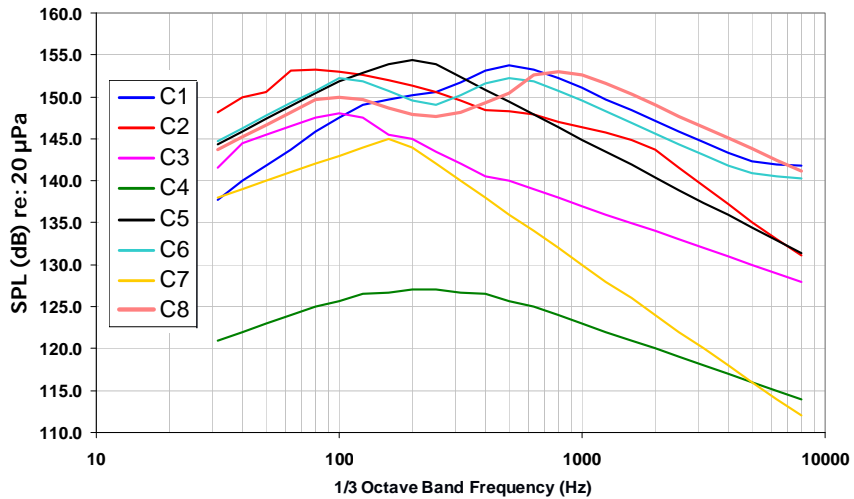


Figure 3.—RATF acoustic design test spectra requirements.

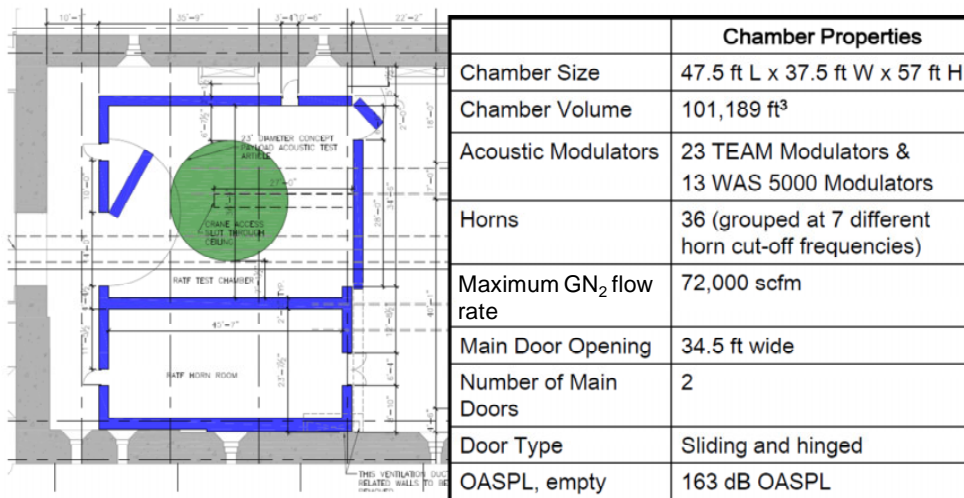


Figure 4.—RATF's acoustic design and features.

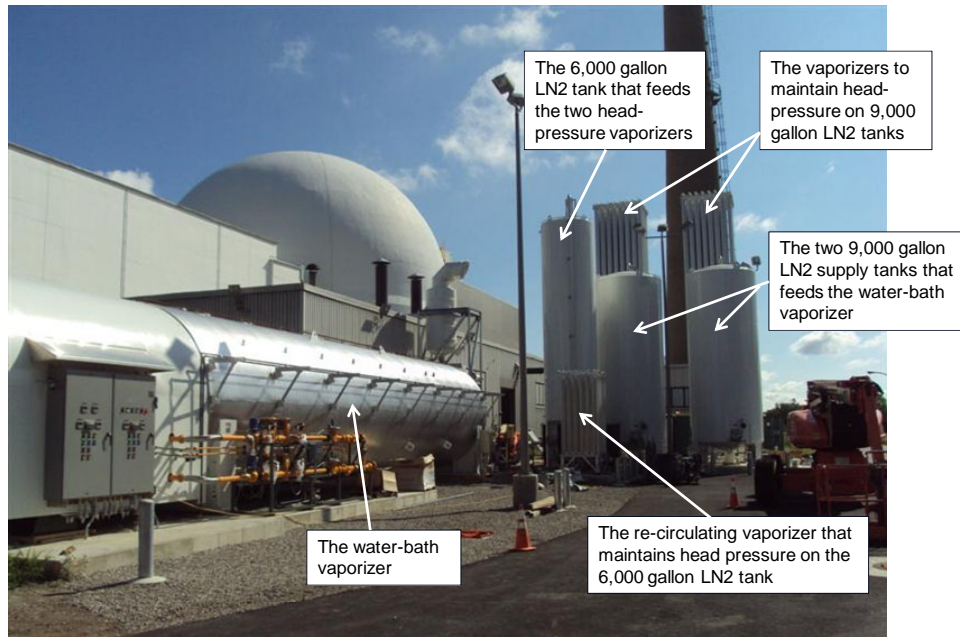


Figure 5.—RATF nitrogen generation system including the water-bath vaporizer and the liquid nitrogen tanks and vaporizers.

Gaseous nitrogen is used as the working fluid for reverberant acoustic testing because of its inherent cleanliness, low humidity and low acoustic absorption at high frequencies relative to air. In order to meet the gaseous nitrogen (GN₂) flow rate needs for the 36 modulators, a nitrogen generation system (Fig. 5) consisting of a water-bath vaporizer (GN₂ flow rate of 72,000 SCFM - standard cubic feet per minute) will be used in conjunction with a 6,000 gallon liquid nitrogen (LN₂) pusher tank and two (2) 9,000 gallon LN₂ high pressure storage tanks.

The distribution of the GN₂ to each of the five levels of the horn room (Fig. 6) is accomplished through a piping system comprised of an accumulator to maintain steady gas flow, a 12 in. main supply line (250 psi regulated GN₂ delivered to the TEAM modulators) and a 10 in. main supply line (30 psi regulated GN₂ delivered to the Wyle modulators). The modulators are connected via 4 in. pipe branches from the 12 and 10 in. main piping system. The piping system (Fig. 7) was originally constructed of Schedule 10 stainless steel (Schedule 40 piping was later added at the highly stressed elbows of the 4 in. branch). The 12 and 10 in. main supply lines are structurally supported off of the horn room wall with stainless steel stand-off brackets. The 4 in. branch lines are structurally supported off of the horn room wall and catwalk structures.

SAIC-Benham designed the piping system using CAESAR, a commercial software piping code which accounts for the pipe stiffness and fluid loading on the piping system to determine pipe stress. In addition, a BOSFluids analysis code was used by SAIC-Benham to assess dynamic gas flow in the pipe. Unfortunately, these analytical tools did not capture the effects of the very large, self-generated, dynamic environment within the RATF horn room or the structural dynamic coupling of the piping system's dynamic modes with the dynamic modes of the horn room itself.

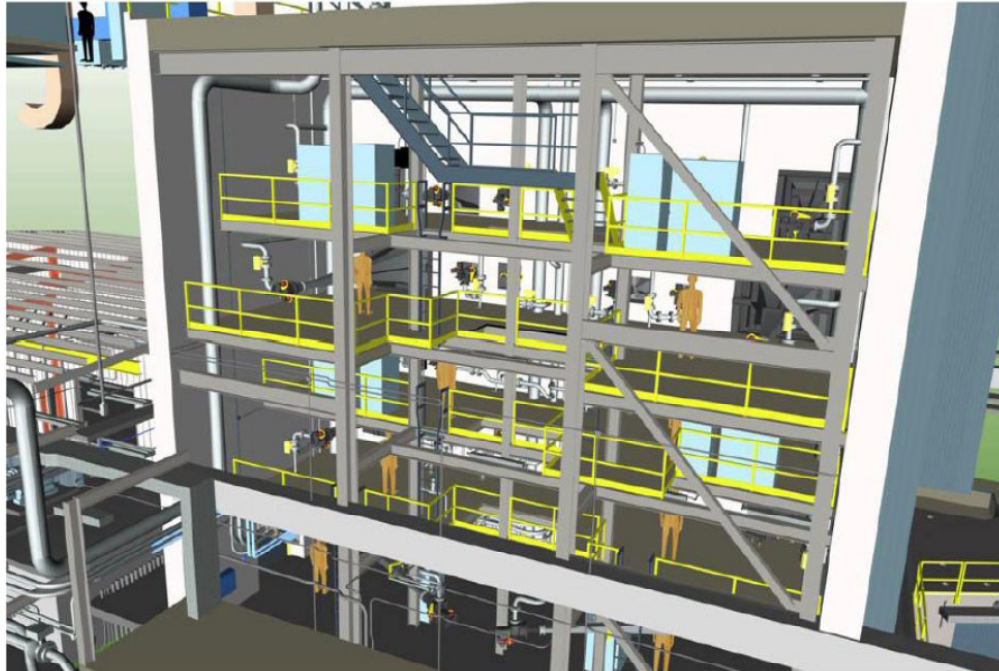


Figure 6.—Cutaway illustration of the 5 levels of the horn room (elevation view looking North).

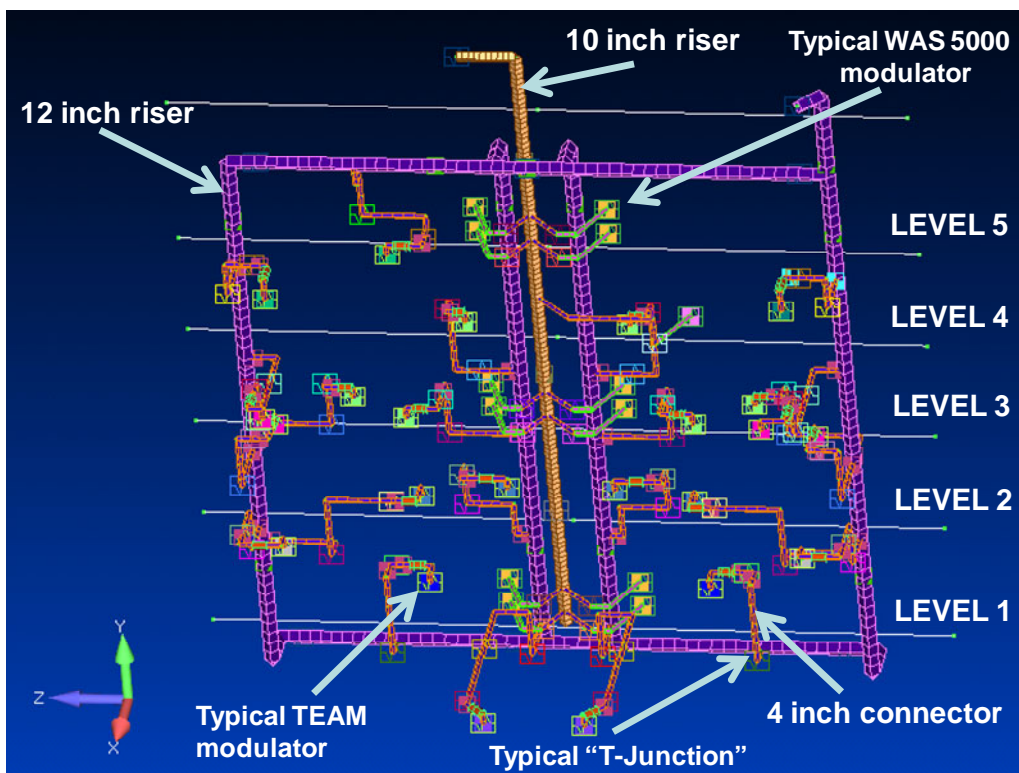


Figure 7.—Horn room piping system finite element model (elevation view looking North).

Piping System “T-Junction” Failures

In March 2011, during initial checkout acoustic testing performed by SAIC-Benham at 161 dB OASPL (on the way to stepping up to the full C2 and C8 acoustic levels of 163 dB OASPL), several branches of the GN2 piping system failed at the “T-junction” connecting the 12 in. supply line to the 4 in. branches. The initial problem was detected by a significant decrease in the oxygen level measured in the horn room, indicating a GN2 leak from the piping system. The checkout acoustic testing was aborted and an investigation commenced looking for the source of the GN2 leaks.

The initial inspection discovered a failed connection at the “T-junction” for the 4 in. branch supplying GN2 to the TEAM modulator and its 35 Hz horn on the fourth floor of the horn room (Figs. 8 and 9). In subsequent follow up inspections, crack failures were identified in 16 of the 23 “T-junction” connections (Fig. 10) through non-destructive evaluation testing using Red Dye Penetrant Technique, ASME Sec 5, Procedure 100-PT-001. The failed “T-junctions” required structural repair.

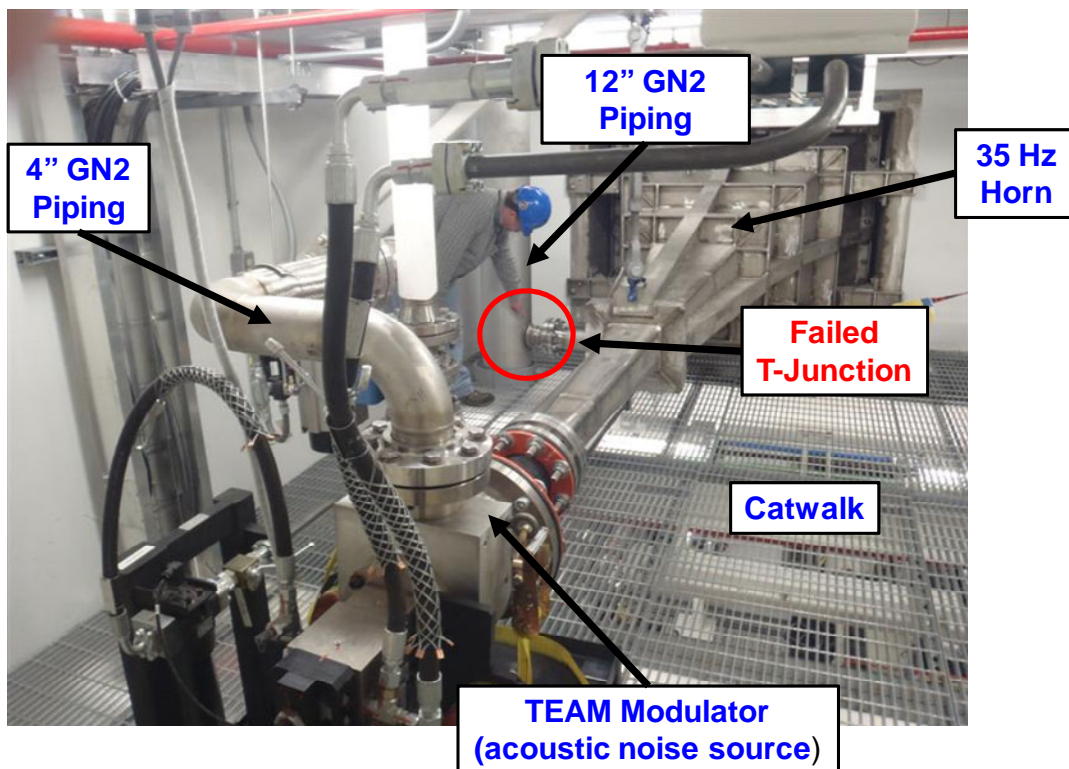


Figure 8.—Horn room “T-junction” failure on 4th floor of horn room near the TEAM modulator and 35 Hz horn.

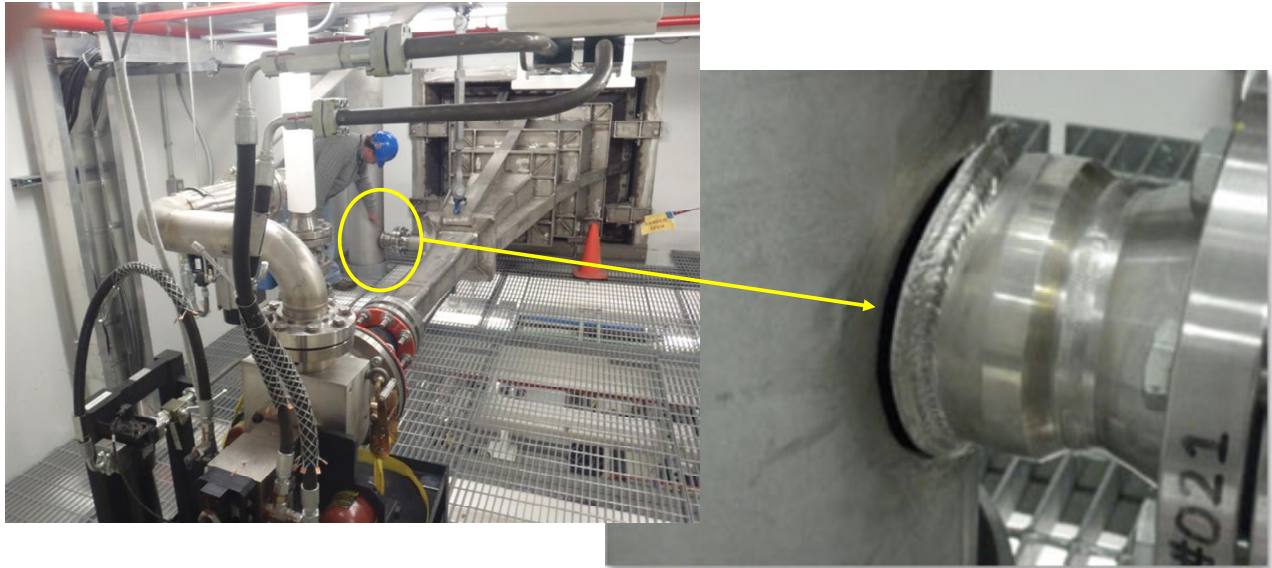


Figure 9.—Close-up view of “T-junction” failure on 4th floor of horn room near the TEAM modulator and 35 Hz horn.

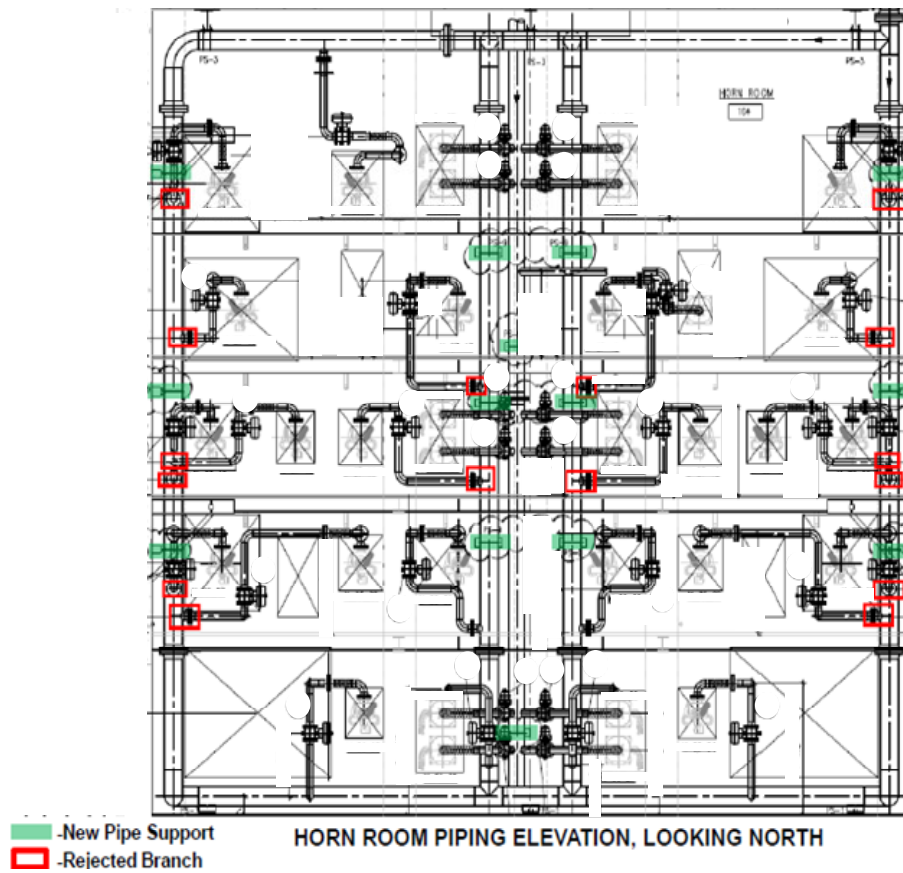


Figure 10.—“T-junction” failures (identified in red) during checkout acoustic testing.

Structural Dynamic Modeling of the Piping System

In order to determine viable structural repairs to the piping system, NASA GRC held technical information meetings with SAIC-Benham, the design build contractor, to determine the cause of the “T-junction” failures. It was determined that the initial structural design of the piping system did not account for:

- The structural dynamic coupling of the piping system’s structural modes with the RATF building and horn room catwalk structural modes.
- The thrust loading created by the operation of the TEAM modulators, generating mechanical vibration in the piping system.

NASA GRC performed an independent structural dynamic analysis to characterize the piping system structural modes and to determine how they dynamically couple to the RATF building (<20 Hz; Ref. 3) and catwalk (<17 Hz; Ref. 4) structure modes. A detailed finite element model (FEM) of the piping system was developed to ascertain the dynamic response of the piping system using MSC NASTRAN version 2010.1.3. NASA GRC made recommendations to SAIC-Benham how to decouple the piping system/modulator modes from the RATF building and catwalk modes.

The FEM (Fig. 7) consisted primarily of “CBEAM” and “lumped mass” elements representing the mass and stiffness of the piping system and incorporated the piping nodal coordinates from the CAESAR model (Ref. 5). The piping system configuration was based on the RATF as-built record drawings.

The entities modeled with “CBEAM” elements were:

- Schedule 10 pipe 12 in. risers and runners
- Schedule 10 pipe 10 in. risers
- Schedule 10 pipe 4 in. connection piping to the modulators
- 4 in. Mason braided flex hose to TEAM modulators
- 4 in. Gamma-Flex Red Tank hose to WAS 5000 modulators

The entities modeled with “lumped mass” elements were:

- TEAM modulator and cart mass
- WAS 5000 modulator mass

Typical pipe support configurations installed in the horn room are shown in the photographs of Appendix A. The boundary conditions for the piping system model are translational constraints at each of the pipe support locations (Fig. 11). The pipe supports were modelled individually with an explicit shell model representation. Unit loads were applied to each pipe support model to obtain displacements defining translational spring constraint stiffness. The pipe support constraints were implemented in the piping system by using the standard modelling technique of applying translational springs (“CBUSH” elements) between coincident nodes. One of the coincident nodes is the existing node in the piping system model representing the pipe support interface. The other coincident node is fixed in translation and rotation (Figure 11; The black arrow triads indicate the locations of where the translations and rotations have been fixed).

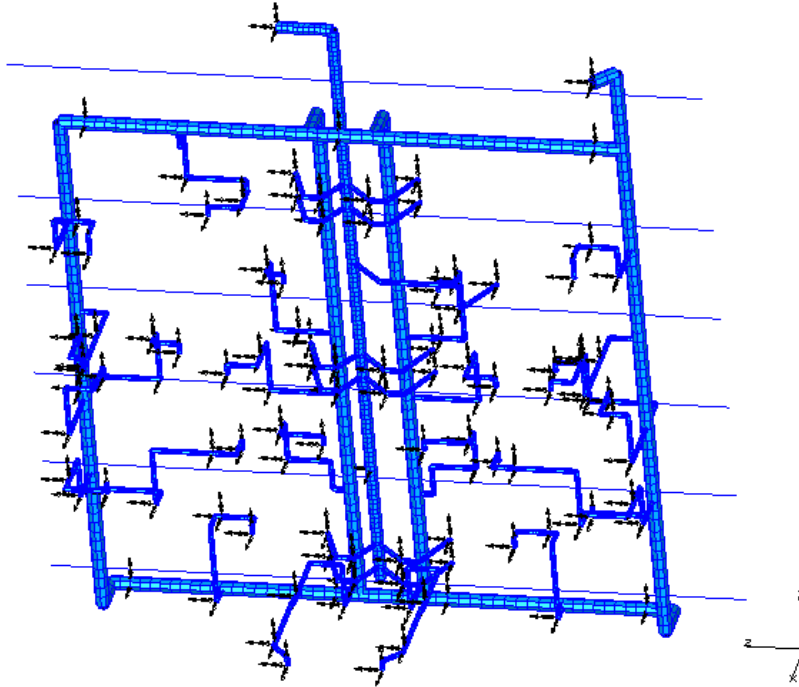


Figure 11.—Pipe system boundary conditions locations (black arrow triads).

Modal Characterization of the Piping System

The high effective mass structural modes of the “baseline,” original design, piping system occur at 3.33 Hz (Fig. 12) and 15.65 Hz (Fig. 13). The 3.33 Hz mode shape is a local mode of the TEAM modulator located on the upper left portion of the 12 in. riser, and has the largest translational displacement in the x-axis. The 15.65 Hz mode shape is a global piping system displacement (z-axis translation). High effective mass modes are important because they are a dynamic measure of the global system vibration participation. Recall the resonant frequencies of the RATF building (<20 Hz) and catwalk (<17 Hz) structures.

Due to the potential dynamic coupling between the structural modes in the “baseline” design contributing to the “T-junction” failures, the analytical objective was to increase the modal frequencies of the piping system’s global high effective mass modes to be double the frequency of the RATF building and catwalk modes providing dynamic isolation. The effect of dynamic isolation is shown in the transmissibility curve in Figure 14. Transmissibility is plotted versus normalized frequency for various damping ratio values. The static response is associated with a transmissibility value equal to 1.0. The dynamic response amplitude at the resonance frequency ($f/f_n = 1.0$) is at its maximum value (transmissibility >1.0). At a frequency two times greater than the resonance frequency ($f/f_n = 2.0$), the dynamic response is reduced below the static response (transmissibility <1) providing dynamic isolation.

The design goal was to decouple the modes and provide dynamic isolation between the piping system structure global modes and the RATF building and catwalk structure modes. This is accomplished by providing at least a factor of two frequency separation between these modes.

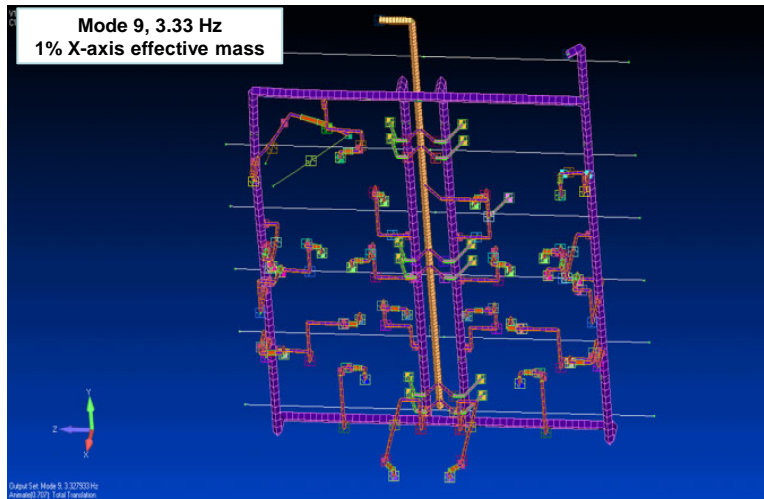


Figure 12.—3.33 Hz high effective mass piping structural mode.

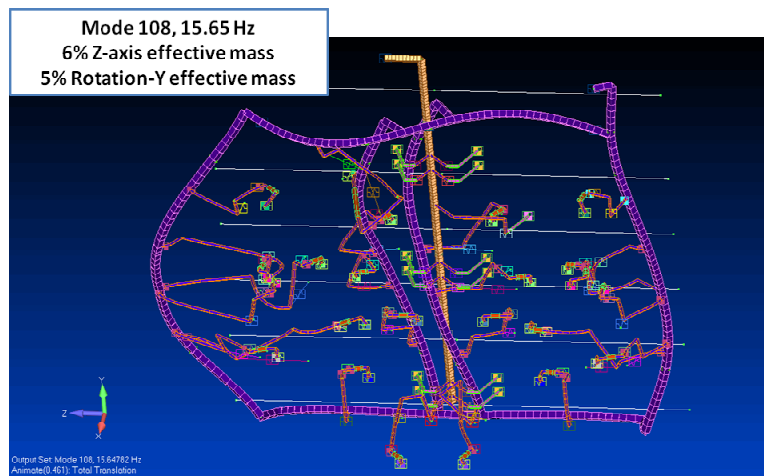


Figure 13.—15.65 Hz high effective mass piping structural mode.

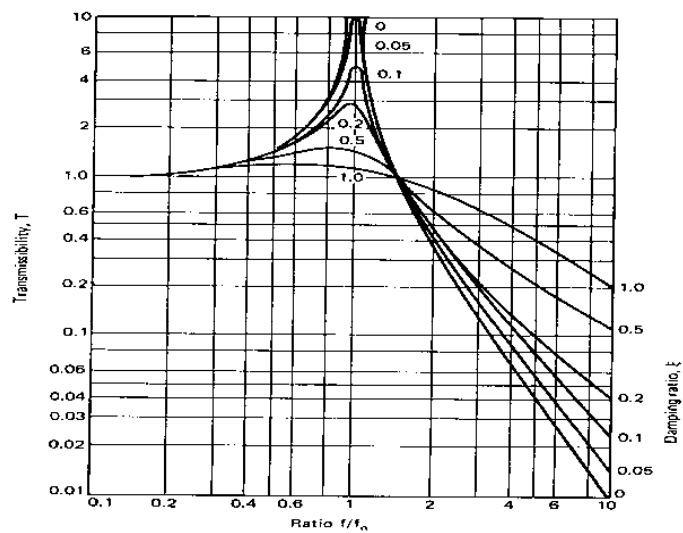


Figure 14.—Transmissibility versus normalized frequency
(Reference: <http://personal.cityu.edu.hk/~bsapplec/design2.htm>).

Design Configurations Analyzed

The following configurations were analyzed to compare against the “baseline” horn room piping system design:

1. Baseline configuration—original SAIC-Benham as-built design per record drawings.
2. Adding lateral constraints to TEAM modulators.
3. Removing all constraints from the TEAM modulators (idealized isolated suspension system).
4. Add 500 lb mass at the base of the TEAM modulators (added mass vibration attenuation).
5. Replace the TEAM modulators’ Mason braided flex hose with the softer Gamma-Flex Red Tank hose stiffness (better isolate the modulators).
6. Reorient the TEAM modulators’ Mason braided flex hose 90° (better isolate the modulators).
7. Add new SAIC-Benham recommended pipe supports (Fig. 15).
8. Add new SAIC-Benham and NASA recommended pipe supports (Fig. 16).
9. *Combine #6 and #8:* New SAIC-Benham and NASA recommended pipe supports with Mason braided flex hose reoriented 90°.
10. *Combine #5 and #8:* New SAIC-Benham and NASA recommended pipe supports with soft connection to TEAM modulators using Gamma flex hose.

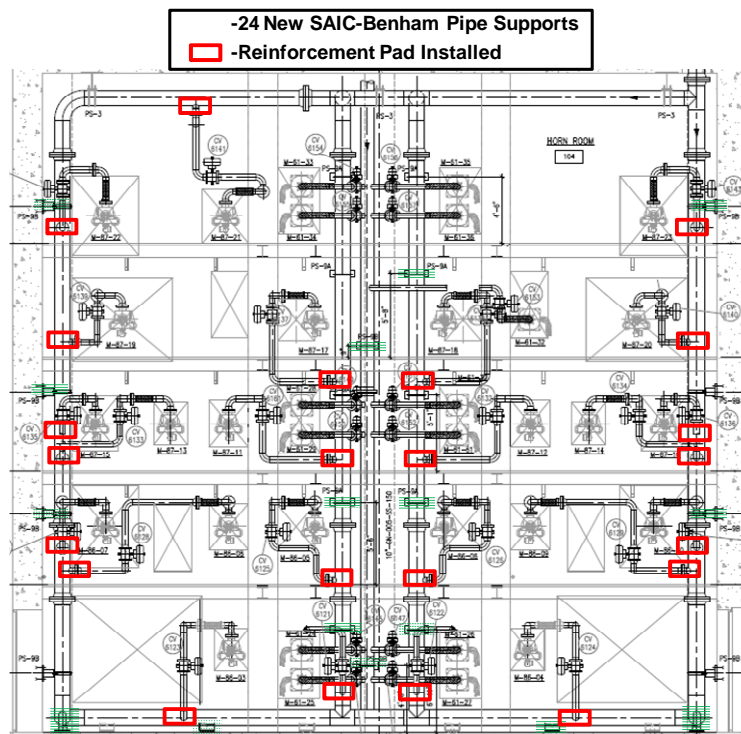
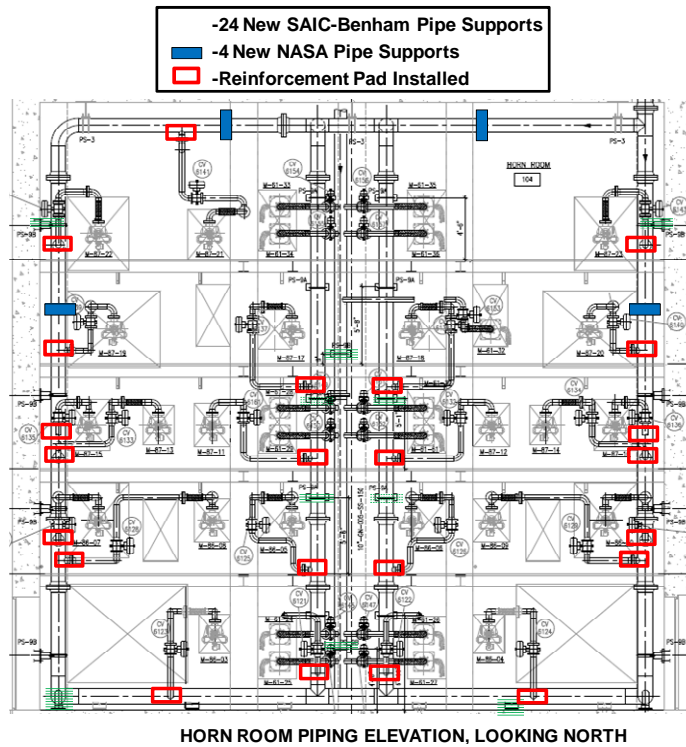


Figure 15.—Configuration 7 with new SAIC-Benham recommended pipe supports (horn room piping elevation, looking North).



HORN ROOM PIPING ELEVATION, LOOKING NORTH
 Figure 16.—Configuration 8 with new SAIC-Benham and NASA recommended pipe supports (horn room piping elevation, looking North).

Summary of Modal Characterization Results

The objective of the modal characterization analysis was to determine a suitable alternate design configuration that provides dynamic isolation for the piping system from the RATF building (<20 Hz) and catwalk (<17 Hz) structural modes.

Each design configuration analyzed represents a unique, individual change from the as-built baseline configuration. Due to the large number of modes encountered for each configuration, modal characterization results were summarized (Figs. 17 to 28) in the following format:

- Number of modes in the frequency range analyzed
- Cumulative modal effective mass fraction in each orthogonal axes in the frequency range analyzed
- Frequency range characterization for the TEAM modulator and WAS 5000 modulator
- Piping system high effective mass modes (largest high effective mass global modes highlighted in red)
- Mode shape illustration for the largest high effective mass global modes

The analysis results indicate that adding pipe supports increases the frequency of the piping system high effective mass global modes. The frequency of the largest high effective mass global modes increased from 10 and 15 Hz for the “baseline” Configuration 1 (Fig. 17), to greater than 90 Hz with the recommended addition of the SAIC-Benham pipe supports (Configuration 7, Fig. 23) and the combination of SAIC-Benham and NASA pipe supports (Configuration 8, Fig. 26). In Configuration 8, the addition of the NASA recommended mid-span pipe supports at locations where the mode shape displacement is greatest (Figs. 24 and 25) minimizes large displacements, limiting long term piping fatigue.

Configuration Analyzed

1. Baseline Configuration

- Modal effective mass summary: 282 modes, 0-50 Hz, 83% X, 21% Y, 80% Z

Description	Frequency (Hz)
TEAM Modulator Piping Modes	3.00-50.26 Hz
WAS 5000 Modulator Piping Modes	3.91-49.37 Hz
Piping System High Effective Mass Modes	10.66 Hz , 13.68 Hz, 15.65 Hz, 15.72 Hz , 47.20 Hz

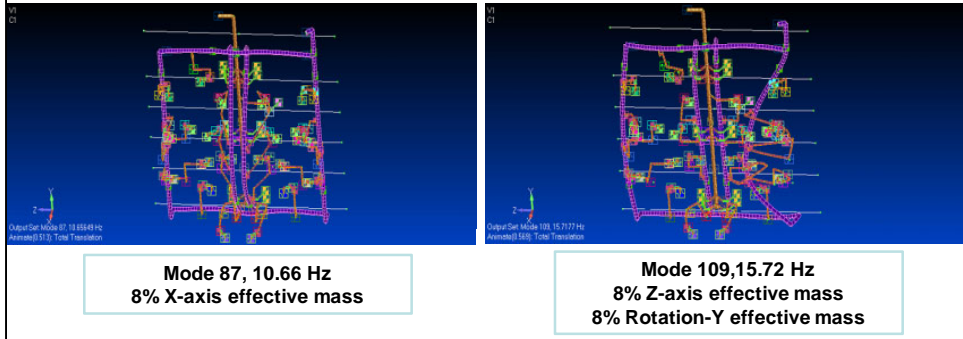


Figure 17.—Configuration 1 modal characterization.

Configurations 2, 3, and 4 provide a design with additional constraints and adding mass (providing mass attenuation) to the TEAM modulators. There is no significant benefit from these design changes in terms of increasing the frequency of the piping system high effective mass global modes (Figs. 18 to 20).

Configurations 5 and 6 provide a design with a soft piping connection to the TEAM modulator. There is little benefit from this design change in terms of increasing the frequency of the piping system global modes (Figs. 21 and 22).

Configurations 9 and 10 provide a design that uses a soft piping connection to the TEAM modulators combined with the SAIC-Benham and NASA pipe supports. As shown in Figures 9 and 10, both configurations satisfy the design goal of significantly increasing the frequency of the piping system.

Only Configurations 7, 8, 9, and 10 provide an increase in the frequency of the piping system, satisfying the objective of providing dynamic isolation of the piping system from the RATF building and catwalk structural modes. Figure 29 provides an overall summary of the frequency characterization results.

Configuration Analyzed

2. Adding lateral constraints to TEAM modulators

- Modal effective mass summary: 282 modes, 0-50 Hz, 83% X, 21% Y, 80% Z

Description	Frequency (Hz)
TEAM Modulator Piping Modes	6.92-50.26 Hz
WAS 5000 Modulator Piping Modes	3.91-49.37 Hz
Piping System High Effective Mass Modes	10.44 Hz , 13.29 Hz, 15.75 Hz , 47.20 Hz

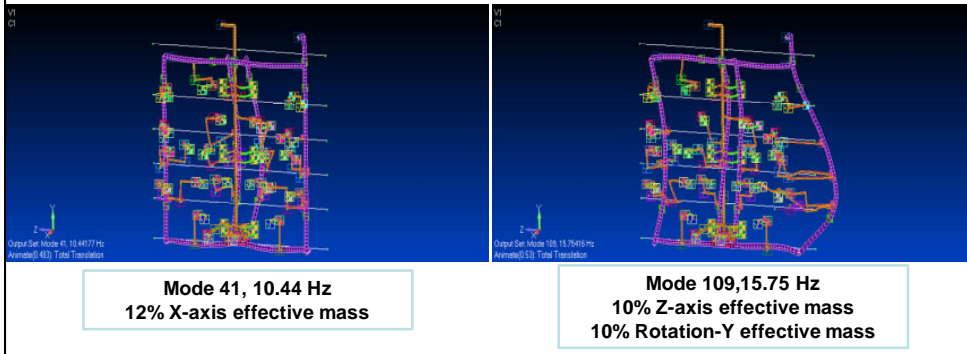


Figure 18.—Configuration 2 modal characterization.

Configuration Analyzed

3. Removing all constraints from the TEAM modulators

- Modal effective mass summary: 305 modes, 0-50 Hz, 83% X, 70% Y, 80% Z

Description	Frequency (Hz)
TEAM Modulator Piping Modes	2.52-50.27 Hz
WAS 5000 Modulator Piping Modes	3.91-49.37 Hz
Piping System High Effective Mass Modes	10.67 Hz , 13.71 Hz, 15.72 Hz , 34.92 Hz, 47.20 Hz

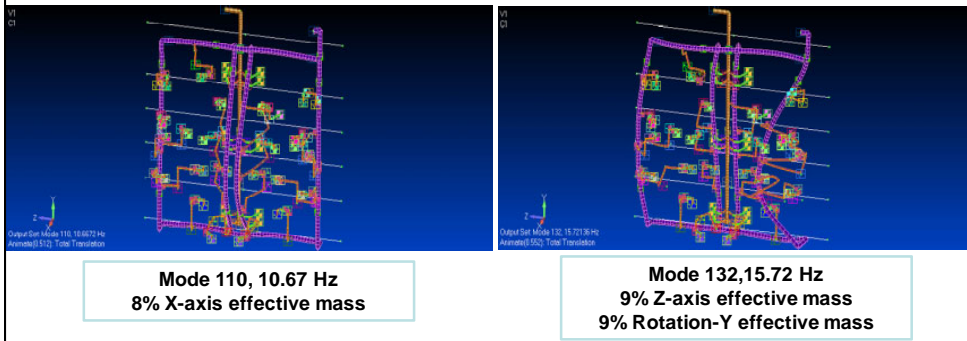


Figure 19.—Configuration 3 modal characterization.

Configuration Analyzed

4. Add 500lb mass to the base of the TEAM modulators

- Modal effective mass summary: 282 modes, 0-50 Hz, 87% X, 16%Y, 85% Z

Description	Frequency (Hz)
TEAM Modulator Piping Modes	2.35-50.19 Hz
WAS 5000 Modulator Piping Modes	3.91-49.37 Hz
Piping System High Effective Mass Modes	10.63 Hz, 13.58 Hz, 15.60 Hz, 15.70 Hz, 47.17 Hz

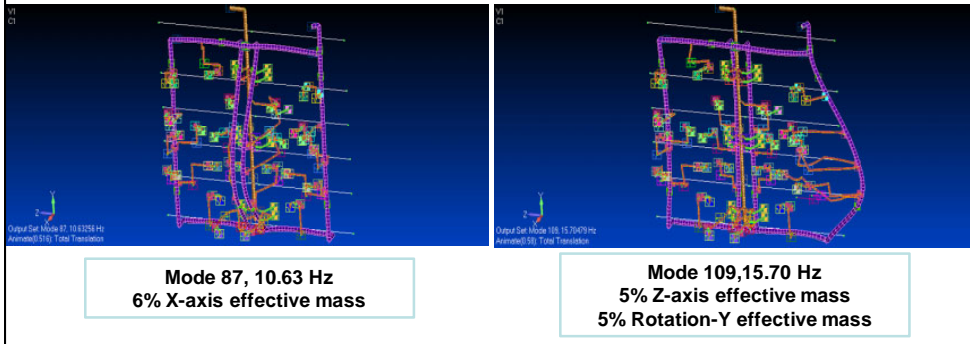


Figure 20.—Configuration 4 modal characterization.

Configuration Analyzed

5. Isolate the TEAM Modulators – Gamma flex hose

- Modal effective mass summary: 430 modes, 0-50 Hz, 83% X, 21%Y, 80% Z

Description	Frequency (Hz)
TEAM Modulator Piping Modes	1.11-50.95 Hz
WAS 5000 Modulator Piping Modes	3.91-49.37 Hz
Piping System High Effective Mass Modes	10.17 Hz, 12.03 Hz, 14.87 Hz, 15.40 Hz, 47.33 Hz

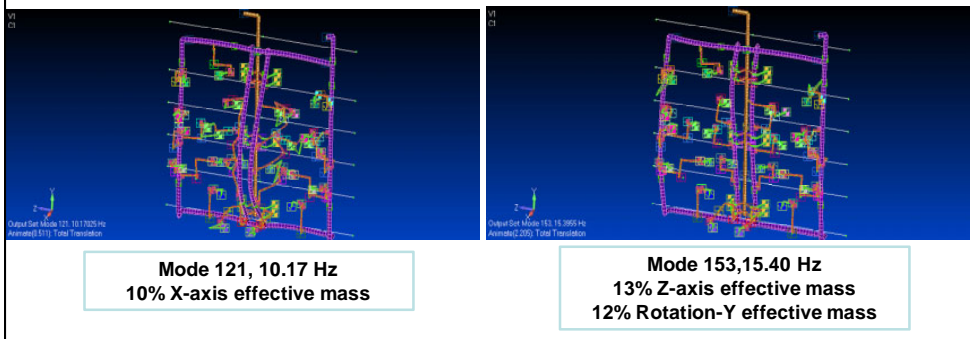


Figure 21.—Configuration 5 modal characterization.

Configuration Analyzed

6. Isolate the TEAM modulators –Mason braided flex hose reoriented 90°

- Modal effective mass summary: 283 modes, 0-50 Hz, 83% X, 21%Y, 80% Z

Description	Frequency (Hz)
TEAM Modulator Piping Modes	2.90-50.80 Hz
WAS 5000 Modulator Piping Modes	3.91-49.37 Hz
Piping System High Effective Mass Modes	10.66 Hz , 13.67 Hz, 15.63 Hz, 15.69 Hz , 47.20 Hz

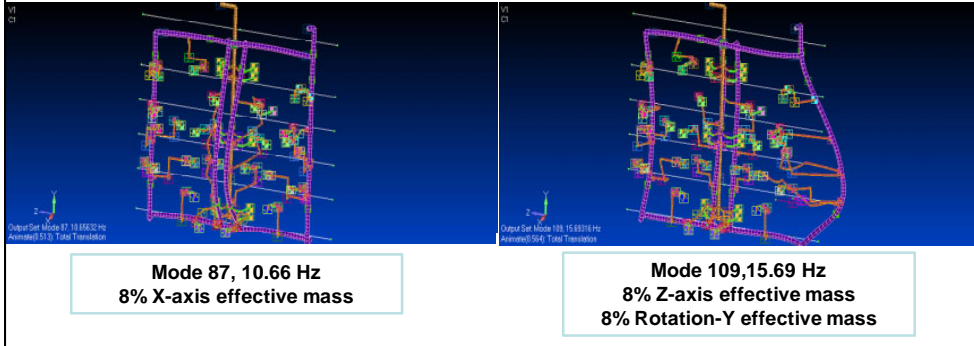


Figure 22.—Configuration 6 modal characterization.

Configuration Analyzed

7. Add new Benham recommended pipe supports (5/24/11)

- Modal effective mass summary: 399 modes, 0-100 Hz, 77% X, 29%Y, 74% Z

Description	Frequency (Hz)
TEAM Modulator Piping Modes	3.05-100.14 Hz
WAS 5000 Modulator Piping Modes	3.91-100.21 Hz
Piping System High Effective Mass Modes	23.58 Hz, 33.51 Hz, 91.22 Hz , 94.19 Hz

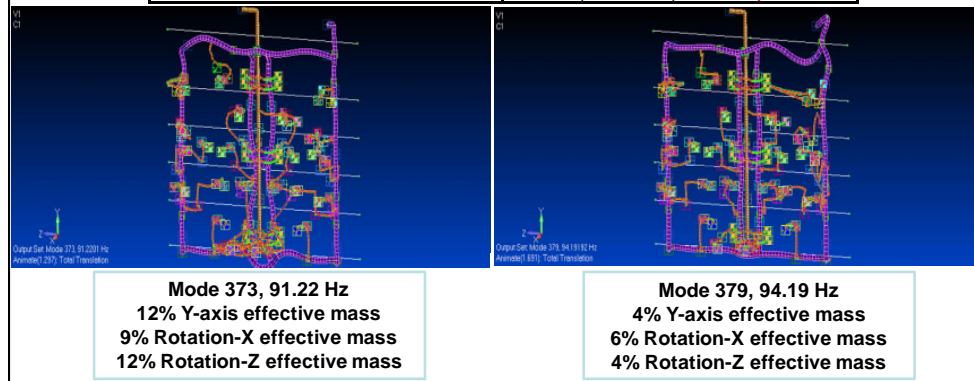


Figure 23.—Configuration 7 modal characterization.

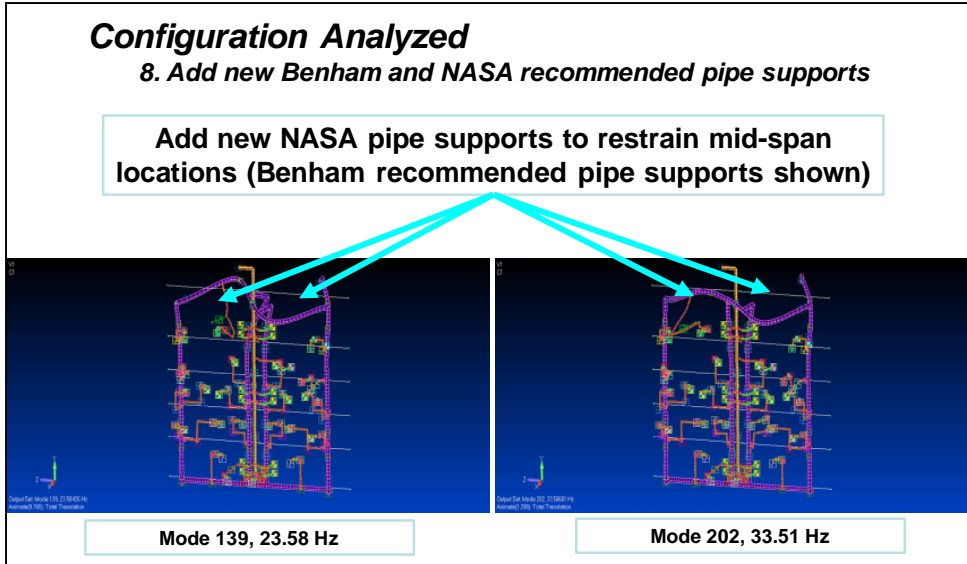


Figure 24.—Configuration 8 modal characterization for mid-span locations.

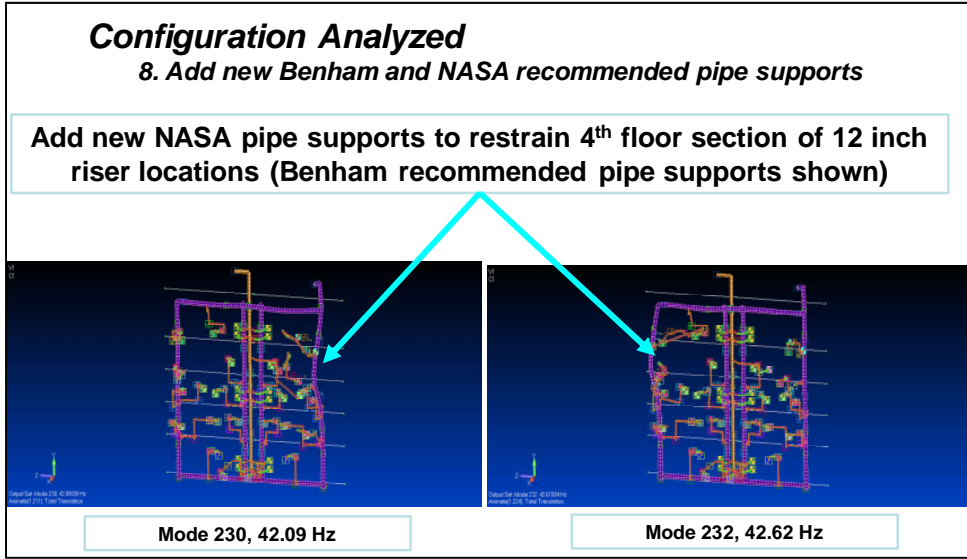


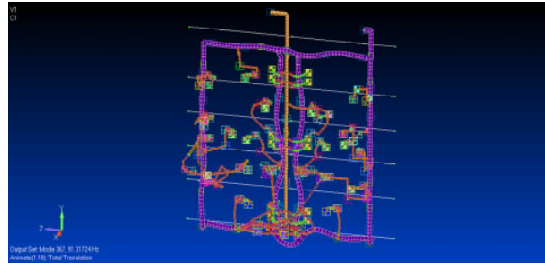
Figure 25.—Configuration 8 modal characterization for 4th floor section of 12 in. riser locations.

Configuration Analyzed

8. Add new Benham and NASA recommended pipe supports

- Modal effective mass summary: 393 modes, 0-100 Hz, 75% X, 25%Y, 73% Z

Description	Frequency (Hz)
TEAM Modulator Piping Modes	3.05-100.19 Hz
WAS 5000 Modulator Piping Modes	3.91-100.21 Hz
Piping System High Effective Mass Modes	30.96 Hz, 31.11 Hz, 91.32 Hz



Mode 367, 91.32 Hz
8% Y-axis effective mass
7% Rotation-X effective mass
8% Rotation-Z effective mass

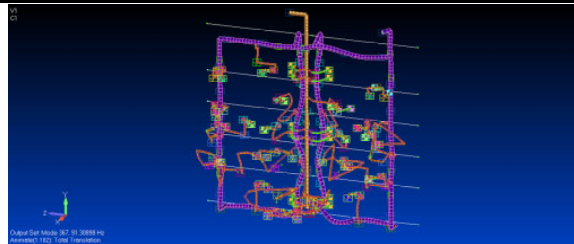
Figure 26.—Configuration 8 modal characterization.

Configuration Analyzed

9. Combine #6 and #8: New Benham and NASA recommended pipe supports with Mason braided flex hose reoriented 90°

- Modal effective mass summary: 393 modes, 0-100 Hz, 75% X, 24%Y, 73% Z

Description	Frequency (Hz)
TEAM Modulator Piping Modes	2.93-100.18 Hz
WAS 5000 Modulator Piping Modes	3.91-100.21 Hz
Piping System High Effective Mass Modes	30.89 Hz, 31.23 Hz, 91.31 Hz



Mode 367, 91.31 Hz
9% Y-axis effective mass
8% Rotation-X effective mass
9% Rotation-Z effective mass

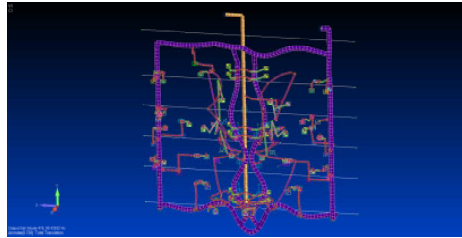
Figure 27.—Configuration 9 modal characterization.

Configuration Analyzed

10. **Combine #5 and #8:** New Benham and NASA recommended pipe supports with soft connection to TEAM modulators using Gamma flex hose

- Modal effective mass summary: 502 modes, 0-100 Hz, 75% X, 25%Y, 74% Z

Description	Frequency (Hz)
TEAM Modulator Piping Modes	1.10-100.09 Hz
WAS 5000 Modulator Piping Modes	3.91-100.21 Hz
Piping System High Effective Mass Modes	1.13 Hz, 1.32 Hz, 8.85 Hz, 48.86 Hz, 90.43 Hz



Mode 476, 90.43 Hz
 9% Y-axis effective mass
 8% Rotation-X effective mass
 9% Rotation-Z effective mass

Figure 28.—Configuration 10 modal characterization.

Configurations Analyzed Summary of Results

LEGEND:

= High effective mass piping modes

Configuration Analyzed	TEAM Modulator Piping Modes	WAS 5000 Modulator Piping Modes	Piping System High Effective Mass Modes
1. Baseline Configuration	3.00-50.26 Hz	3.91-49.37 Hz	10.66 Hz , 13.68 Hz, 15.65 Hz, 15.72 Hz , 47.20 Hz
2. Adding lateral constraints to TEAM modulators	6.92-50.26 Hz	3.91-49.37 Hz	10.44 Hz , 15.75 Hz , 13.29 Hz, 47.20 Hz
3. Removing all constraints from the TEAM modulators	2.52-50.27 Hz	3.91-49.37 Hz	10.67 Hz , 13.71 Hz, 15.72 Hz , 34.92 Hz, 47.20 Hz
4. Add 500lb mass to the base of the TEAM modulators	2.35-50.19 Hz	3.91-49.37 Hz	10.63 Hz , 13.58Hz, 15.60 Hz, 15.70 Hz , 47.17 Hz
5. Isolate the TEAM Modulators – Gamma flex hose	1.11-50.95 Hz	3.91-49.37 Hz	10.17 Hz , 12.03 Hz, 14.87 Hz, 15.40 Hz , 47.33 Hz
6. Isolate the TEAM modulators – Mason braided flex hose reoriented 90°	2.90-50.80 Hz	3.91-49.37 Hz	10.66 Hz , 13.67 Hz, 15.63 Hz, 15.69 Hz , 47.20 Hz
7. Add new Benham recommended pipe supports	3.05-100.14 Hz	3.91-100.21 Hz	23.58 Hz, 33.51 Hz, 91.22 Hz , 94.19 Hz
8. Add new Benham and NASA recommended pipe supports	3.05-100.19 Hz	3.91-100.21 Hz	30.96 Hz, 31.11 Hz, 91.32 Hz
9. Combine #6 and #8: New Benham and NASA recommended pipe supports Mason braided flex hose reoriented 90°	2.93-100.18 Hz	3.91-100.21 Hz	30.89 Hz, 31.23 Hz, 91.31 Hz
10. Combine #5 and #8: New Benham and NASA recommended pipe supports with soft connection to TEAM modulators using Gamma flex hose	1.10-100.09 Hz	3.91-100.21 Hz	1.13 Hz, 1.32 Hz, 8.85 Hz, 48.86 Hz, 90.43 Hz

Figure 29.—Frequency summary for all 10 configurations analyzed.

Forced Response Analysis of Alternate Piping Configurations

A forced response analysis was conducted at the “T-junction” worst failure location on the 4th floor of the horn room near the TEAM modulator and 35 Hz horn. The forced response analysis was performed for each of the 10 piping system configurations by applying a unit acceleration forcing function to the TEAM modulator in the thrust direction (Fig. 30), recovering dynamic bending moments at the “T-junction.” The unit acceleration forcing function is a flat random vibration spectrum from 1 to 100 Hz with a magnitude of 1.0 g^2/Hz . Although the forcing functions for the horn room are unknown (structure-borne vibration from the RATF building, catwalk, and modulators; direct acoustic excitation; and possible flow induced vibration), the generalized forced response analysis results can be extended to any input excitation.

The dynamic bending moment results are shown in Figure 31 for the 12 in. riser and Figure 32 for the 4 in. connector. The results of the forced response analysis for all configurations can be used to inform which configuration provides the most reduction in “T-junction” dynamic bending moment (corresponding to the highest TEAM modulator isolation).

Examining the bending moment results for the 4 in. connector and 12 in. riser indicates that Configurations 5 and 10 provide the largest reduction in bending moment compared to Configuration 1 (baseline). The forced response analysis indicates tremendous bending moment reduction with a soft connection to the TEAM modulator (Gamma flex hose) coupled with the added pipe supports. It is important to note that this analysis showed that no additional pipe supports were needed for the 10 in. riser. The as-built configuration (Configuration 1) with the soft Gamma flex hose connection to the WAS 5000 modulator structurally isolates the WAS 5000 modulators from the 10 in. pipe.

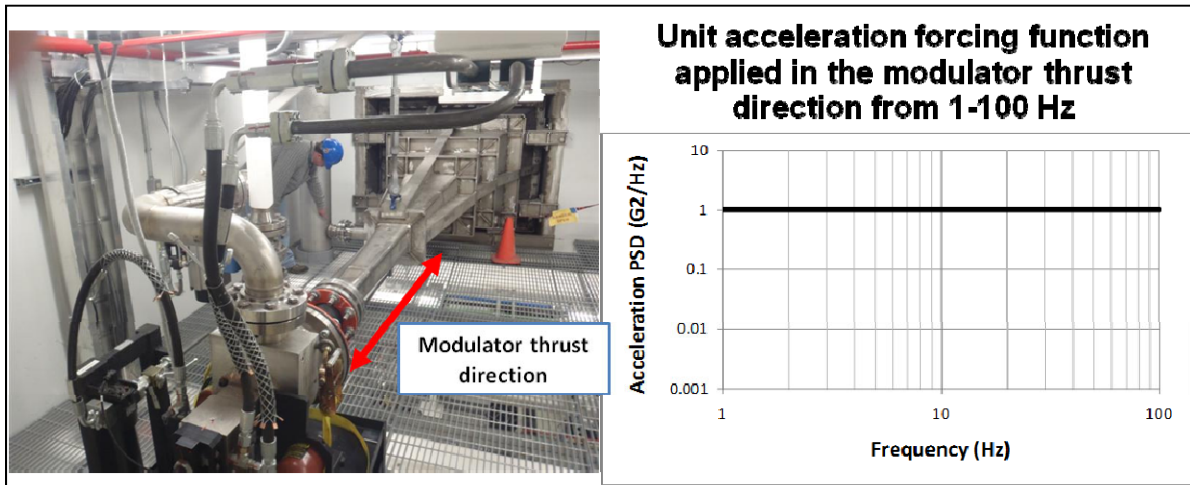


Figure 30.—“T-junction” forced response analysis.

Forced Response Analysis

12 inch riser dynamic Y-plane bending moment

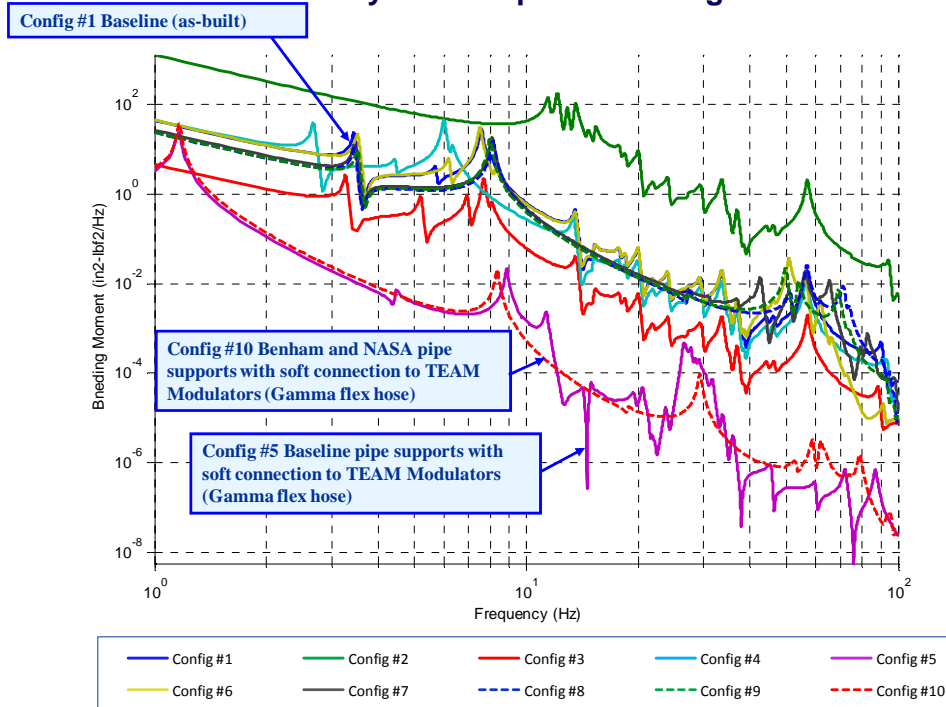


Figure 31.—12 in. riser Y-plane dynamic bending moment.

Forced Response Analysis

4 inch connector dynamic Z-plane bending moment

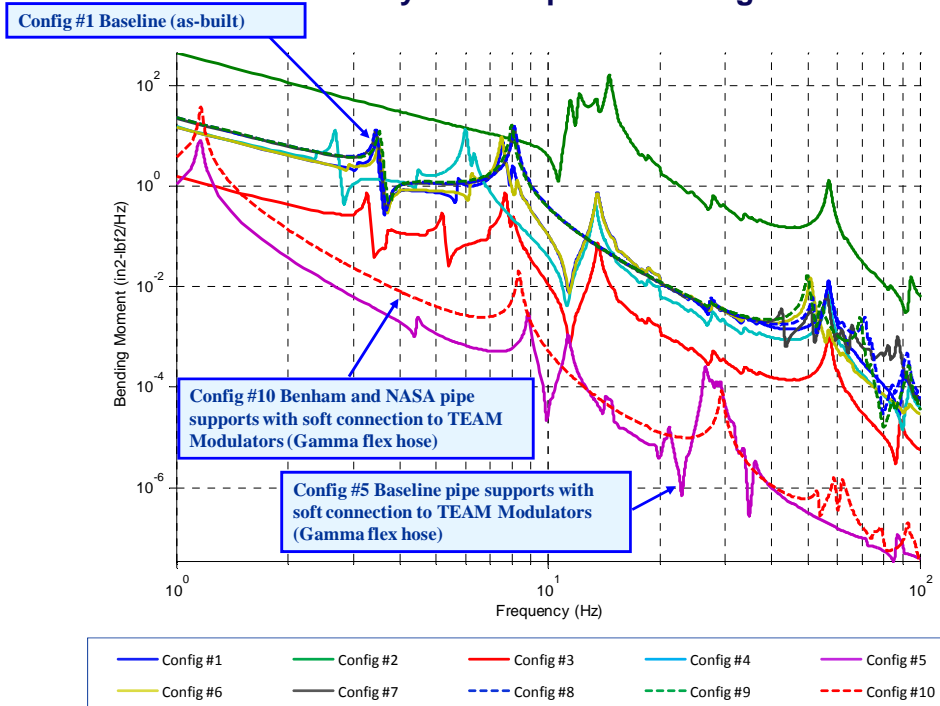


Figure 32.—4 in. connector Z-plane dynamic bending moment.

Piping System Repairs

SAIC-Benham cited high cyclic stress causing fatigue cracks in the “T-junction” at the toe of the welds. The high cycle fatigue was driven by the high acoustic levels in the RATF chamber (and horn room) and corresponding vibration transmission to the piping system. The SAIC-Benham “T-junction” repairs included the installation of a welded reinforcement pad (Fig. 33) around the weld-o-let fitting at the 23 TEAM modulator locations (Fig. 15). With the new design, the predicted structural safety margin at the “T-junction” is greater than 3,000 percent based on allowable stress.

SAIC-Benham implemented Configuration 8 with NASA GRC concurrence, for the redesign and repair of the RATF piping system using their CAESAR piping analysis (which incorporated the TEAM modulator operational thrust force and new pipe support constraints). The repairs included:

- “T-junction” reinforced pad installed at all 23 locations (Fig. 15)
- 24 additional pipe supports recommended by SAIC-Benham (Fig. 15)
- 4 additional pipe supports recommended by NASA (Fig. 16)
- Additional 4 in. branch pipe supports near elbows or long unsupported runs
- Schedule 40 piping was added at the highly stressed elbows of the 4 in. branch

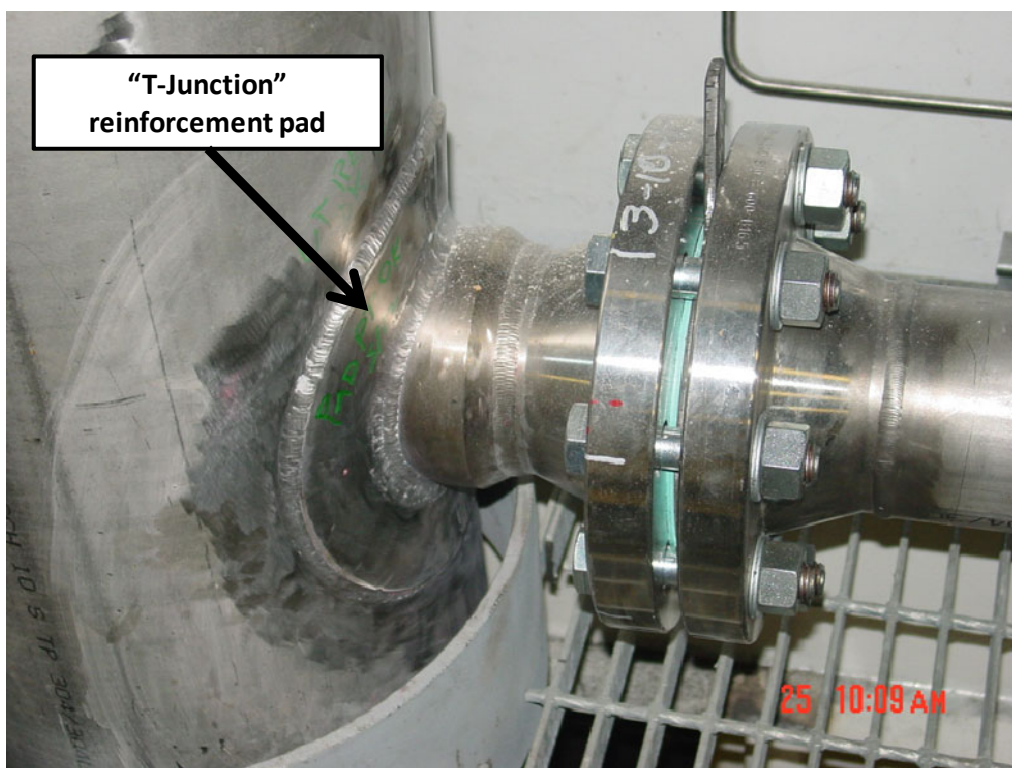


Figure 33.—“T-junction” reinforcement pad repair.

Horn Room and GN2 Exhaust Duct Health Monitoring

NASA installed health monitoring instrumentation in the horn room and Vibro-Acoustic Highbay mezzanine to monitor the newly repaired piping system and chamber exhaust ducts during acoustic verification testing. Reference 6 provides the detailed instrumentation plan for the health monitoring system.

The main objectives and use of the health monitoring system include:

- Measure the peak dynamic stresses at specific locations on the horn room piping relative to SAIC-Benham's acoustic verification test levels.
- Measure the peak dynamic stresses at specific locations on the exhaust ducting relative to SAIC-Benham's acoustic verification test levels.
- Real-time monitor strain gage time histories near "T-junctions" during SAIC-Benham's acoustic verification testing.
- Real-time monitor accelerometer and microphone time histories located in the horn room and Vibro-Acoustic Highbay mezzanine during SAIC-Benham's acoustic verification testing.

The health monitoring system included a 44-channel data acquisition system, 6 accelerometers (4 accelerometers in the horn room, and 2 accelerometers on the GN2 exhaust ducts), 36 single channel strain gages (selected from 24 rosettes in the horn room, and 8 rosettes on the GN2 exhaust ducts), 2 acoustic microphones (1 microphone in the horn room, and 1 microphone in the mezzanine near the GN2 exhaust ducts). In summary, the health monitoring system provides 44 real-time viewable time-history traces including 36 dynamic stress-related traces, 6 dynamic acceleration-related traces, and 2 dynamic sound-pressure related traces. An 8-channel video camera system (with remote control pan, tilt, and zoom capability) was also installed to monitor each level of the horn room.

Pre-test stress analysis of the horn room and duct system was used to prioritize the location and placement of the strain gages. Strain gages were installed near the "T-junction" reinforcement pads to ensure that strain levels measured during the acoustic verification testing did not exceed a predetermined strain threshold to preclude fatigue. A "T-junction" stress model (Fig. 34) was created to help determine the placement and orientation of the strain gages.

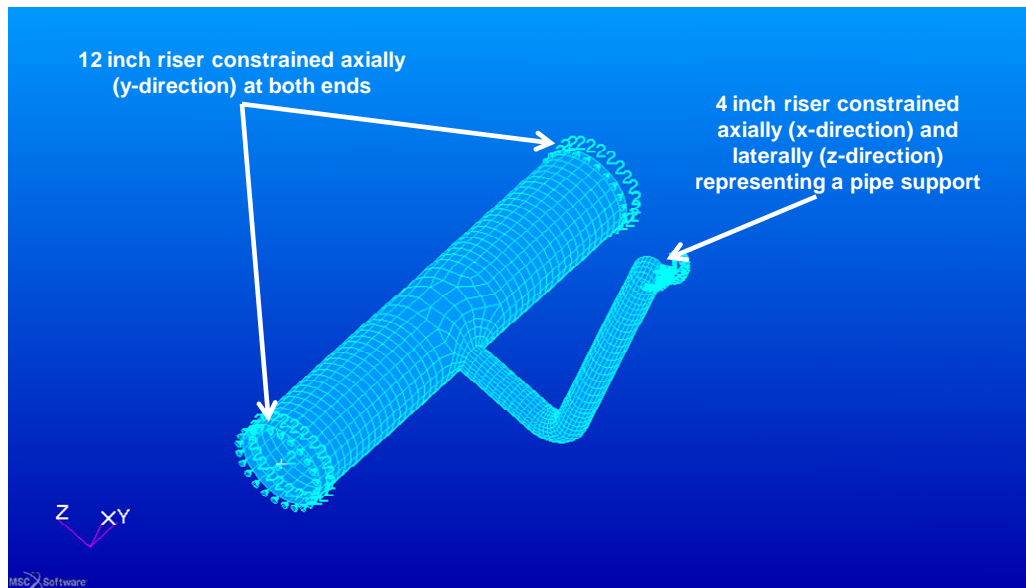


Figure 34.—Stress model of the "T-junction."

Strain gages were installed near the “T-junctions” based upon the high stress regions produced by an enforced displacement analysis of the stress model of the “T-junction.” The enforced displacements were derived from the high effective mass global modes of the piping system.

This enforced displacement analysis methodology was validated by modeling the “T-junction” failure location for the baseline configuration (Configuration 1, original as-built) and assessing whether the actual failed regions corresponded to the predicted high stress regions. As shown in Figure 35, the analytically predicted high stress region, using the 10.66 Hz high effective mass global mode, corresponded to the region where the “T-junction” failed.

The enforced displacement analysis (using the 94.19 Hz high effective mass global mode) for the repaired “T-junction,” incorporating the reinforcement pad and added SAIC-Benham pipe supports (Configuration 7), is shown in Figure 36. The maximum principal stress provided guidance for the placement and orientation the strain rosette gage in the high stress region near the “T-junction” in order to measure axial, tangential, and hoop stresses. It should be noted that the stresses reported in Figure 36 are fictitious because the enforced displacement are based upon a mode shape and not an actual displacement vector.

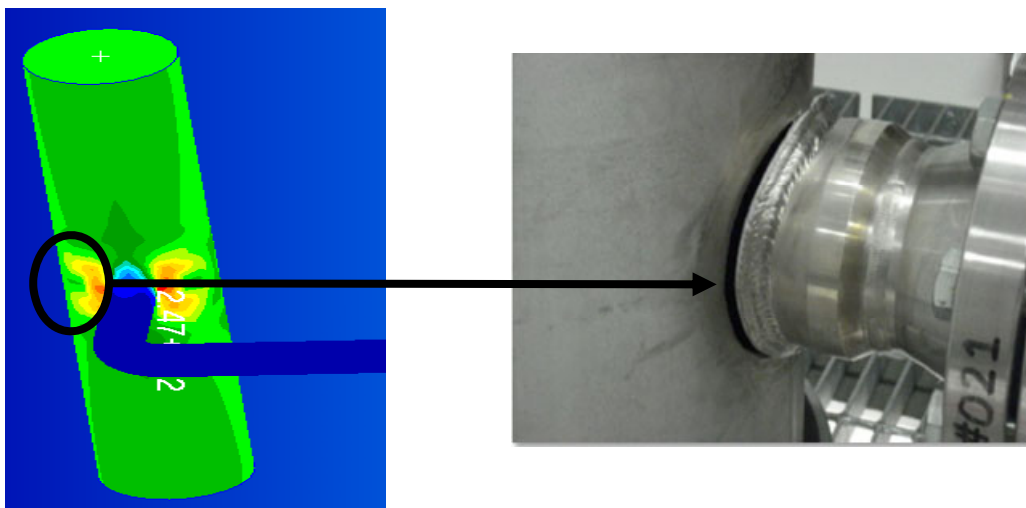


Figure 35.—Correlation of the Von Mises stress field analysis for configuration 1 (original as-built).

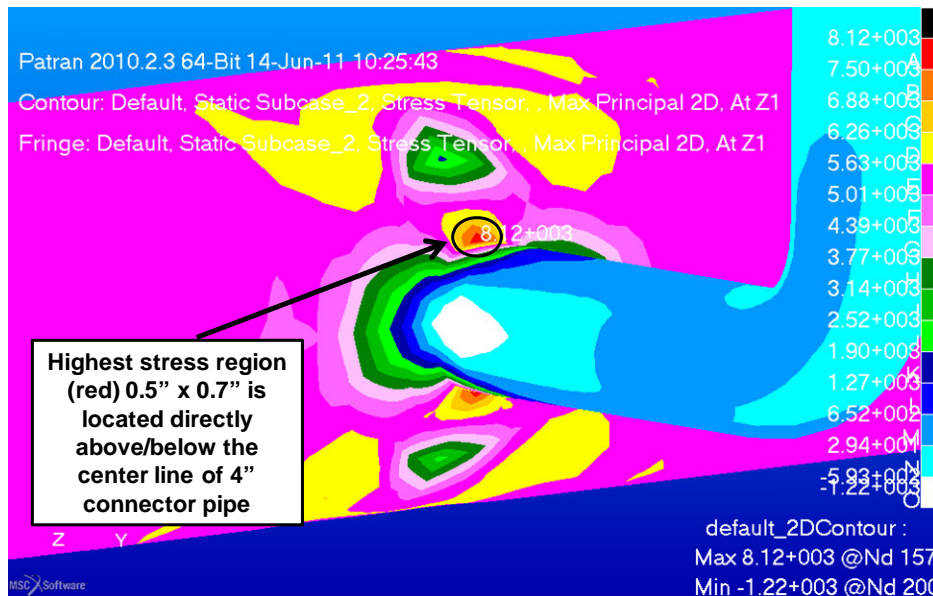


Figure 36.—Maximum principal stress plot for the 94.19 Hz eigenvector case.

RATF Acoustic Verification Testing

Acoustic verification testing was successfully conducted in the RATF on September 8 to 9, 2011. The C7 test spectrum was initially tested at 153 dB OASPL, and then this test spectrum shape was uniformly increased to 156 dB OASPL (Fig. 37). The C7 test spectrum represents the envelope of relevant acoustic environments for a wide number of commercial launch vehicles' internal payloads. In addition, the C5 test spectrum shape was tested at 159 dB OASPL (C5 – 4 dB) and extended to 161 dB OASPL (C5 – 2 dB, Fig. 38). The C5 test spectrum represents one of interest to the Orion program.

During the acoustic verification testing to 161 dB OASPL, only a portion of the RATF total acoustic power was utilized; with the excess acoustic power available, the RATF is believed to be capable of achieving its design requirement of 163 dB OASPL.

During acoustic verification testing, the strain levels measured near the “T-junction” were well below the predetermined strain threshold; subsequent visual inspection of the horn room indicated no evidence of piping system fatigue. Post processing of the strain time history measurement into a Power Spectral Density (PSD) function (Fig. 39) illustrates a dominant structural response at 99 and 105 Hz, validating the structural dynamic model used to predict the piping system dynamic global modes and the rework goal of moving the major piping system modes to greater than 90 Hz.

Post-test analysis of the strain measurements at the “T-junction” for the C7 and C5 test spectra indicates that the maximum combined static and dynamic stress did not exceed the 304L stainless steel pipe material infinite allowable stress. The static stress is due to the internal pressurization of the pipe based on the 231 psig relief valve set point for the TEAM modulators. The maximum dynamic stress is based on the measured dynamic strain during acoustic verification testing. Extrapolation of the C7 and C5 shaped spectra test results indicates the RATF piping system can withstand up to 165 dB OASPL (Fig. 40) for infinite fatigue life (10^7 alternating stress cycles). This result is dependent on the shape of the acoustic test spectrum; test spectra with larger low frequency acoustic levels could alter this conclusion.

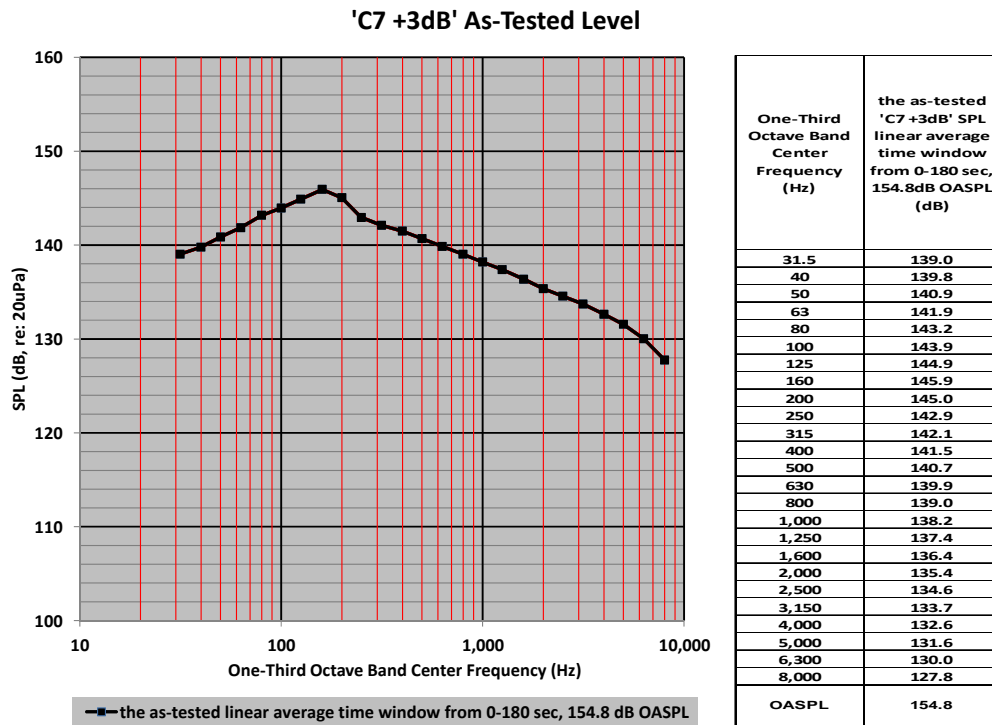


Figure 37.—As-tested C7 + 3 dB test spectra (156 dB OASPL).

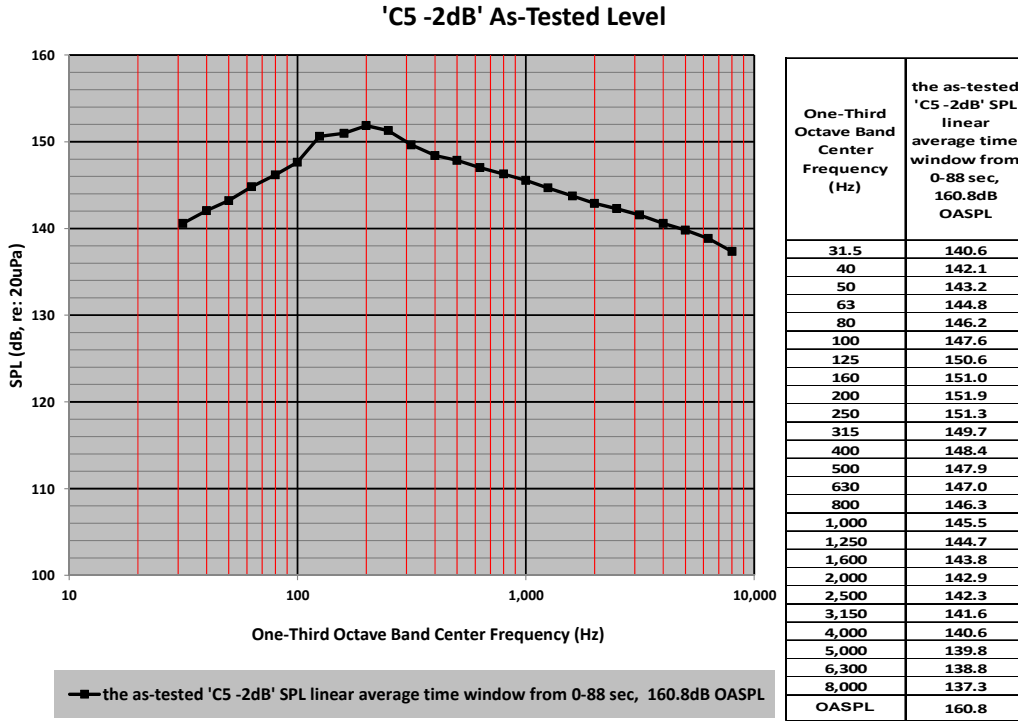


Figure 38.—As-tested C5 – 2 dB test spectra (161 dB OASPL).

T-Junction Strain Measured from “C5-2dB” 161dB OASPL Verification Test (Near the Team Mark-VII Modulator, 4th Floor West, Coupled to 35Hz Horn)

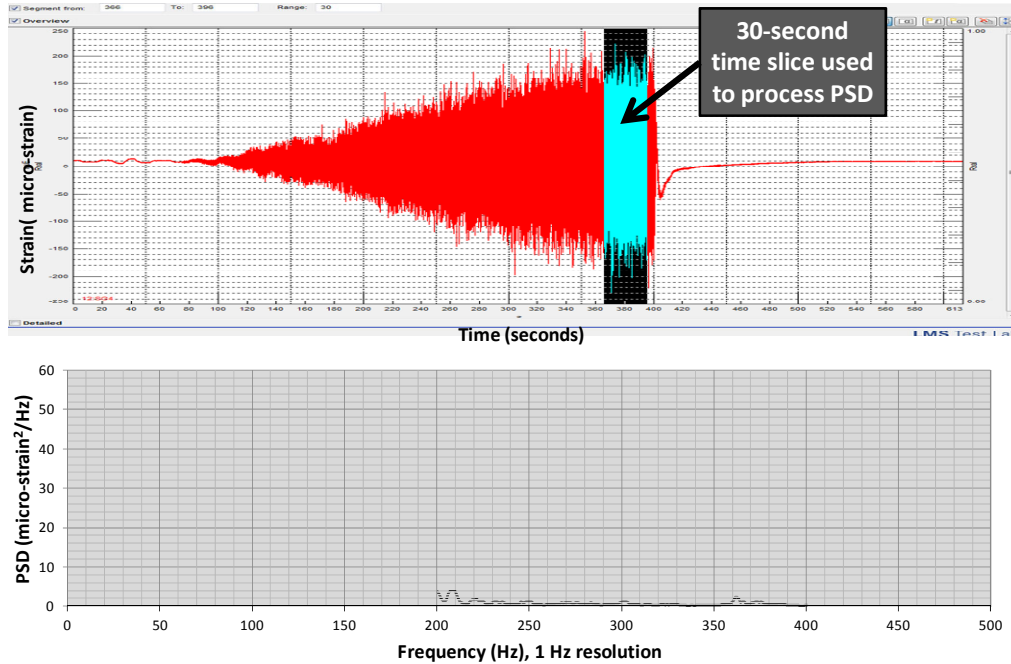


Figure 39.—Strain measurement at “T-junction” during acoustic verification testing.

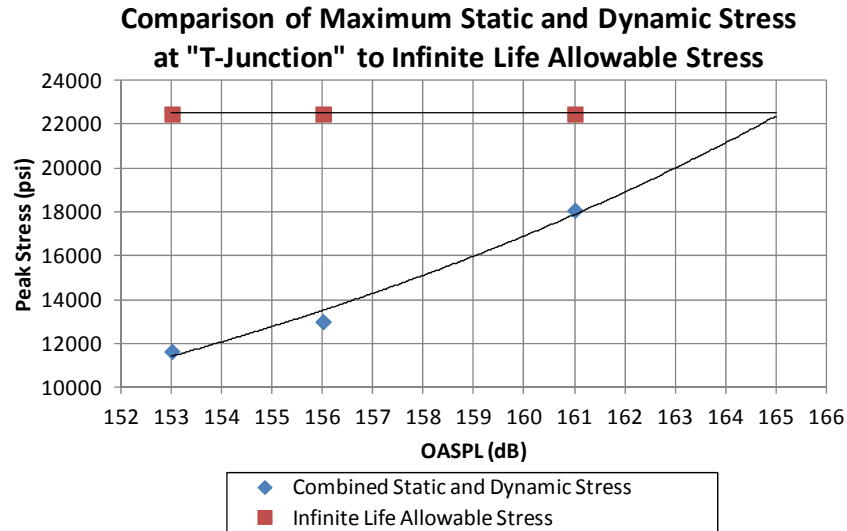


Figure 40.—Comparison of combined maximum static and dynamic stress at “T-junction” to infinite life allowable stress for 304L stainless steel.

Conclusions

NASA GRC’s new reverberant acoustic test facility had GN2 piping system failures during initial acoustic checkout testing. The failures are believed to have been caused by dynamic coupling between the piping system and the RATF building and horn room catwalk structural modes. The high stress region near the “T-junctions” also contributed to the initial structural failures.

Structural dynamic modelling of the RATF horn room piping system provided design guidance to ensure dynamic isolation of the new piping system from RATF building (<20 Hz) and catwalk (<17 Hz) structural modes. Additional pipe supports increased the piping system original structural modes of 10 and 15 Hz to greater than 90 Hz.

SAIC-Benham’s repair of the piping system (Configuration #8) included:

- “T-junction” reinforced pad repair at all 23 locations
- SAIC-Benham recommended 24 additional pipe supports
- NASA recommended 4 additional pipe supports
- Additional 4 in. branch pipe supports near elbows or long unsupported runs
- Schedule 40 piping was added at the highly stressed elbows of the 4 in. branch

The implementation of a health monitoring instrumentation for the piping system provided real-time strain data monitoring during RATF acoustic verification testing. Measured strain levels were compared to the predetermined strain threshold to preclude fatigue thereby ensuring safe operations. Placement of the rosette strain gages was guided by and enforced displacement analysis using the mode shapes from the high effective mass global modes.

The horn room piping system repairs implemented by SAIC-Benham proved to be effective. During RATF acoustic verification testing up to and including test levels of 161 dB OASPL, the strain gage measurements were well below the predetermined threshold limits for fatigue. Considering infinite life, the RATF piping system can withstand up to 165 dB OASPL based on the C7 and C5 shaped spectrum.

The lesson learned is that the dynamics of the piping system, including their coupling with the structural modes of the building, must be taken into consideration when designing a piping system when dealing with high acoustic excitation levels.

**Appendix A—Typical Pipe Support Configurations at the
NASA GRC Plum Brook Station Reverberant Acoustic
Test Facility (RATF)**



*12 inch Riser Ceiling Pipe Support
(PS-3)*



*12 inch Riser Ceiling Pipe Support
(PS-8)*



*12 inch Riser Floor Pipe Support
(PS-1)*



*12 inch Riser Pipe Support
(PS-9)*

Figure 41.—Typical 12 in. riser ceiling pipe supports.



*4 inch Riser Elbow Support
(PS-8)*

Figure 42.—Typical 4 in. riser elbow pipe supports.

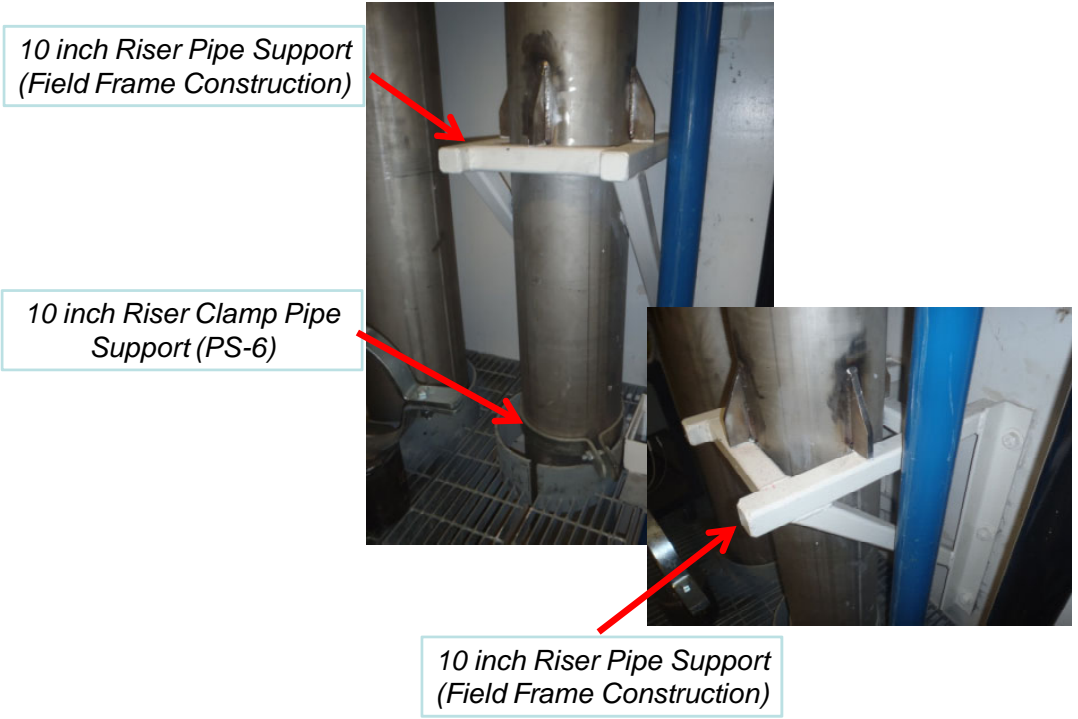


Figure 43.—Typical 10 in. riser pipe supports.

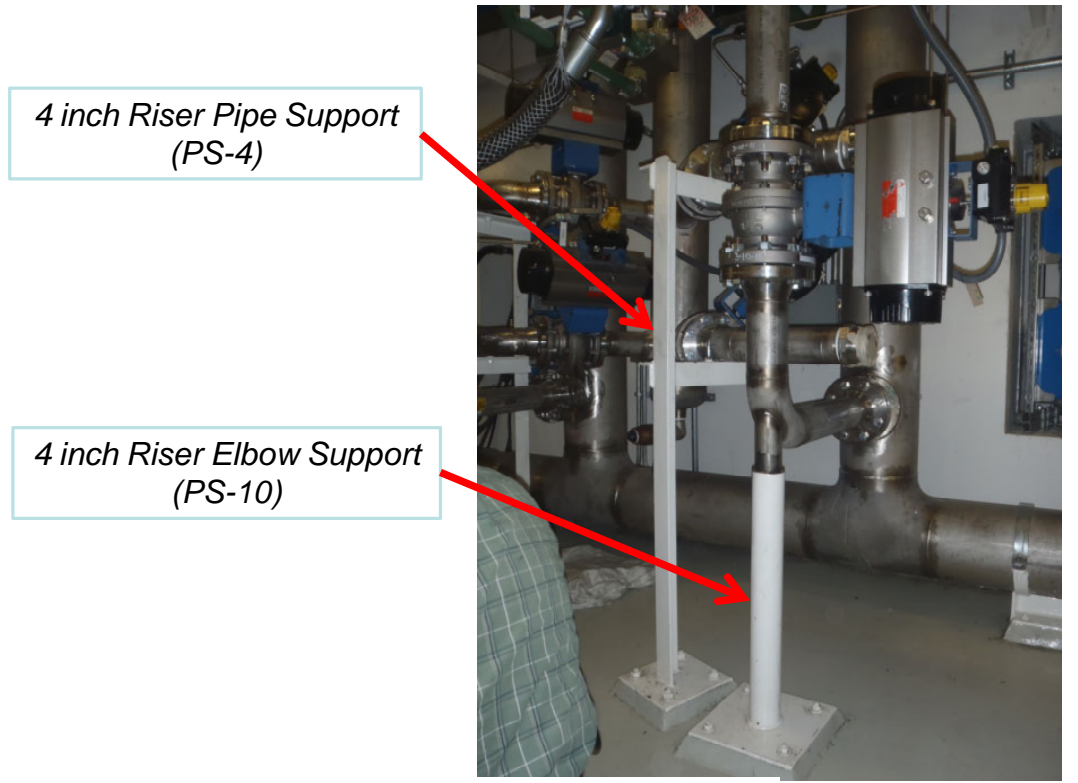


Figure 44.—Typical 4 in. riser pipe supports.

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14. ABSTRACT The National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) has led the design and build of the new world-class vibroacoustic test capabilities at the NASA GRC's Plum Brook Station in Sandusky, Ohio, USA from 2007 to 2011. SAIC-Benham has completed construction of a new reverberant acoustic test facility to support the future testing needs of NASA's space exploration program and commercial customers. The large Reverberant Acoustic Test Facility (RATF) is approximately 101,000 ft ³ in volume and was designed to operate at a maximum empty chamber acoustic overall sound pressure level (OASPL) of 163 dB. This combination of size and acoustic power is unprecedented amongst the world's known active reverberant acoustic test facilities. Initial checkout acoustic testing was performed on March 2011 by SAIC-Benham at test levels up to 161 dB OASPL. During testing, several branches of the gaseous nitrogen (GN2) piping system, which supply the fluid to the noise generating acoustic modulators, failed at their "T-junctions" connecting the 12 in. supply line to their respective 4 in. branch lines. The problem was initially detected when the oxygen sensors in the horn room indicated a lower than expected oxygen level from which was inferred GN2 leaks in the piping system. In subsequent follow up inspections, cracks were identified in the failed "T-junction" connections through non-destructive evaluation testing. Through structural dynamic modeling of the piping system, the root cause of the "T-junction" connection failures was determined. The structural dynamic assessment identified several possible corrective design improvements to the horn room piping system. The effectiveness of the chosen design repairs were subsequently evaluated in September 2011 during acoustic verification testing to 161 dB OASPL.					
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