The Role of Structural Dynamics and Testing in the Shuttle Flowliner Crack Investigation

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Introduction

During a normal inspection of the main propulsion system at Kennedy Space Center, small cracks were noticed near a slotted region of a gimbal joint flowliner located just upstream from one of the Space Shuttle Main Engines (SSME). These small cracks sparked an investigation of the entire Space Shuttle fleet main propulsion feedlines. The investigation was initiated to determine the cause of the small cracks and a repair method that would be needed to return the Shuttle fleet back to operation safely. The cracks were found to be initiated by structural resonance caused by flow fluctuations from the SSME low pressure fuel turbopump interacting with the flowliner. The pump induced backward traveling wakes that excited the liner and duct acoustics which also caused the liner to vibrate in complex mode shapes.

The investigation involved an extensive effort by a team of engineers from the NASA civil servant and contractor workforce with the goal to characterize the root cause of the cracking behavior of the fuel side gimbal joint flowliners. In addition to working to identify the root cause, a parallel path was taken to characterize the material properties and fatigue capabilities of the liner material such that the life of the liners could be ascertained. As the characterization of the material and the most probable cause matured, the combination of the two with pump speed restrictions provided a means to return the Shuttle to flight in a safe manner.

This paper traces the flowliner investigation results with respect to the structural dynamics analysis, component level testing and hot-fire flow testing on a static testbed. The paper will address the unique aspects of a very complex problem involving backflow from a high performance pump that has never been characterized nor understood to such detail. In addition, the paper will briefly address the flow phenomena that excited the liners[1], the unique structural dynamic modal characteristics and the variability of SSME operation which has ultimately ensured the safe and reliable operation of the shuttle main engines for each flight.

Hardware

The gimbal joint affected by the cracking is located just upstream of the SSME Low Pressure Fuel Pump (LPFTP) as shown in Figures 1 and 2. The main propulsion feedlines of the Space Shuttle Orbiters are designed to carry the propellant from the External Tank to each of the shuttle engines through a 17" duct through a manifold and into three separate 12" ducts, each containing a number of gimbal and bellow flex joints for mobility and the reduction of misalignment loads.

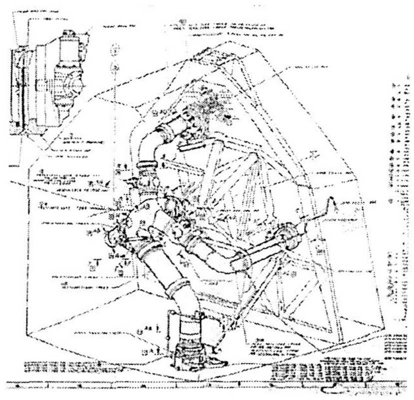

Figure 1. Shuttle Main Propulsion Supply Line.

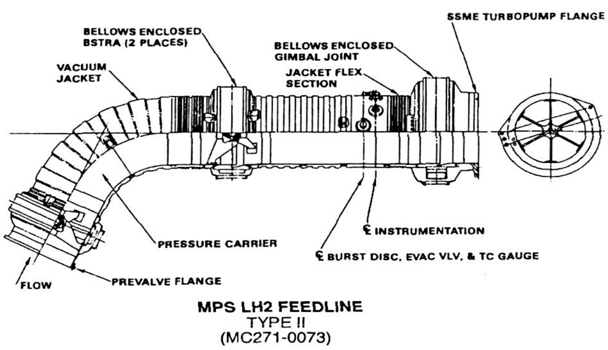

Figure 2. Section of LH2 Feedline.

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The gimbal joints construction consists of a yoke structural bearing member sandwiched between two multi-layered convoluted bellows sections to allow the gimbal joint to articulate similar to a universal joint in an automobile. The flowliners were installed inside the inner bellows to pass the flow smoothly through to the SSME LPFTP during engine operation as shown in Figure 2. Two flowliners were installed into the gimbal joint cantilevered from opposite ends to allow movement between the two when the gimbal joint was articulated, as shown in Figure 3.

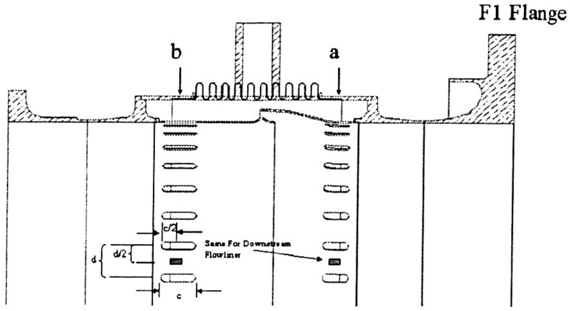

Figure 3. Feedliner Gimbal Joint.

Figure 3 also shows the small slots that were stamped into the liner to allow for drainage and inspection of the welded joint once the liners were installed. It is from these slot locations where the cracking developed and propagated in both the circumferential and axial directions for both the upstream and downstream flowliners.

The SSME Low Pressure Fuel Turbopump has a 4-bladed inducer that increases the pressure of the propellent prior to entering the high pressure pumps. As with all bladed mechanisms, the pumps have an optimum hydrodynamic operational point where the flow is pumped through the blades with little or no flow separation, better known as cavitation. Since the SSME operates at a number of different inlet pressure conditions and pump speeds, a variety of flow phenomena can present themselves throughout a nominal flight. In the case of the flowliner, it was found that the flowliner was sensitive to both the efficient and non-efficient pump operational conditions.

Test Articles

To characterize how the flowliner would respond to the an SSME low pressure fuel pump, a test series was constructed to insert flight-like flowliners on the A1 test stand at the Stennis Space Center (SSC). Two test articles were conceived and constructed to support the flowliner investigation. The first test article, built in a battleship configuration to support intrusive instrumentation was developed with the purpose to characterize the flow phenomena and the flowliner response. The second test article was built to both validate the data obtained during the battleship tests and to look further into the problem to determine if there were any other issues associated with the bellows due to the same forcing functions that affected the flowliners.

The Battleship Test Article (BTA), shown in Figure 4, had a simulated bellows cavity behind the two flowliners aligned facing each other as they are in the fleet articles. The test article had a number of instrumentation ports for static and dynamic pressure transducers, thermal couples and a high density of dynamic strain gages which were attached to the back-side of the liner. The test article was constructed in such a manner that the instrumentation could be applied to the liners prior to assembly, as shown in Figure 5.

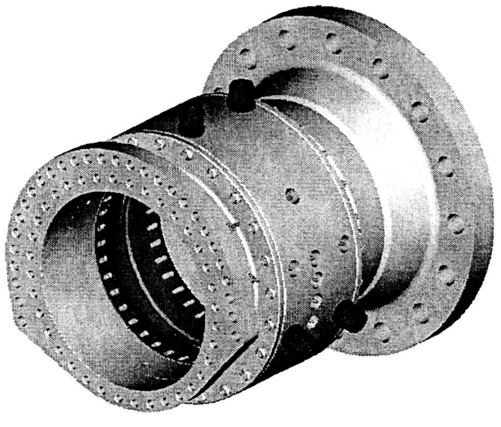

Figure 4. Battleship Test Article (BTA)

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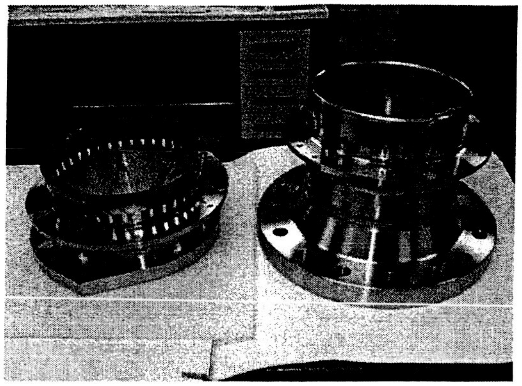

Figure 5. Battleship Test Article Strain Gage Instrumentation

The instrumentation was designed such that it could obtain enough information around the circumference of the flowliners to identify the shape of the mode excited and the amplitude between the slots. The strain amplitude would then be used in conjunction with the shape to extract the strain field across the entire liner using a correlated finite element model anchored to modal test data. The strain field would then be used to assess the fatigue and fracture capabilities of the flowliner for flight.

The second test article was constructed using an actual gimbal joint from the main propulsion test article used to certify the Shuttle Program propulsion system during the early days of the Program. The second test fixture, the Gimbal Test Article (GTA), shown in Figure 6, has an actual gimbal bellows with the flowliners welded inside similar to the BTA. The GTA was unique in that the gimbal joint had to be constructed prior to the insertion of the flowliners.

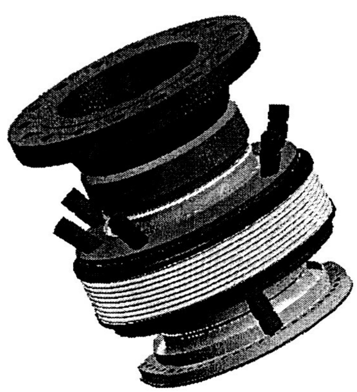

Figure 6. Gimbal Test Article (GTA)

Since the gimbal joint has a complex design, the assembly of the instrumented flowliners were much more difficult for this test article. As shown in Figure 7, the flowliners were required to have the strain gage instrumentation attached to the liner prior to assembly. The lead wires were required to be attached to the outboard side of the liner possibly leading to an adverse affect to the liner damping. The reason the wires were attached in this manner was because the assembly welding process would melt the wiring if they were close to the weld area, as they were for the BTA. To minimize adverse damping effects, the wires were glued and then straped to hold the wiring firmly in place. The challenge to minimize the damping effects with the restrictions placed on the instrumentation proved to be overwhelming. The test data demonstrated higher damping, but was able to confirm the acoustic nature of the flow driving mechanisms further building confidence in the battleship test article.

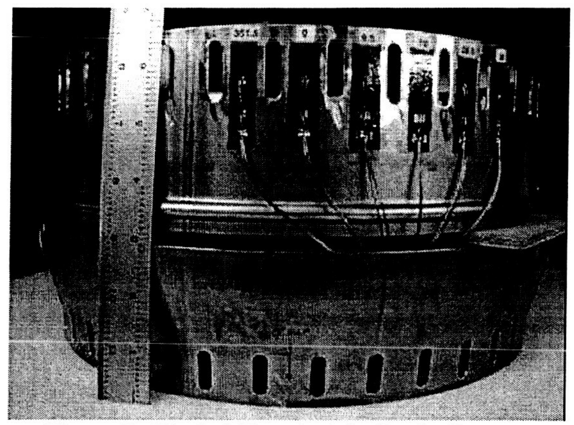

Figure 7. Gimbal Test Article Strain Gage Instrumentation

Verification

To validate the structural characteristics of the test articles, modal tests were performed on the flowliners on both the test articles and the shuttle fleet. The modal tests demonstrated a number of unique structural dynamic characteristics including mistuning and coupled system modes. The mistuning effect was demonstrated in both the test articles and the fleet as shown in Figure 8.

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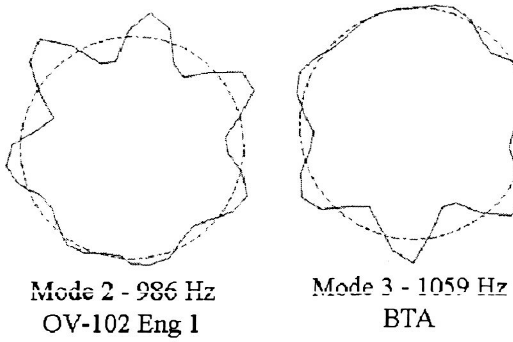

Figure 8. Modal Test Comparison of the Fleet and the Test Articles

The dynamic verification of the test articles was extremely important if the data from the tests was to be utilized for flight rationale. The modal tests demonstrated that there was sufficient correlation between the downstream liners, but found that in the lower diametral modes for the upstream liner was less than perfect as shown in Figures 9 and 10. This difference was due to the stiffness differences between the fleet and test articles. The test articles had a hard mounted flange just upstream of the gimbal joint where the fleet had a thinner duct, with no flange, leading upstream of the liner. This difference also demonstrated that the upstream liner had a higher density of modes at higher frequencies that would lead to some uncertainty in the upstream liner response.

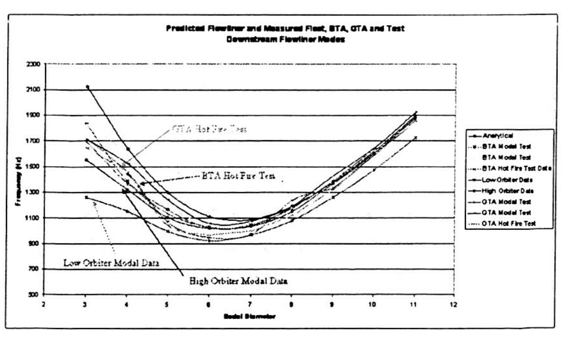

Figure 9. Downstream Flowliner Frequency Correlation.

Even with the differences, it was determined that the test articles were valid test articles to accomplish the intended purpose of the tests. Since the test articles were instrumented with pressure transducers, the ability to determine if the differences would be affected by the measured forcing functions. It was found during the tests that the forcing functions were present in areas where great similarity between the fleet liners and the test article liners was the greatest.

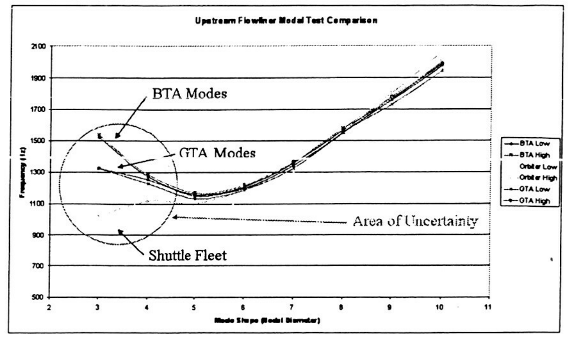

Figure 10. Upstream Flowliner Frequency Correlation.

Further validation was required to anchor the model's strain predictions. Since the strain gages were limited to locations between the slots, as shown in Figures 3 and 7, the model needed to be anchored to determine if the installation process affected the strain gradients. A bench test was developed to map the strain field around the slots. The battleship test article was disassembled and more strain gage instrumentation was placed around the slots. Since the modal characteristics were being anchored, a method for exciting the liner in air had to be developed.

Since diametral modes were the target modes for excitation, a shaker test would not efficiently excite the liner. The MSFC test lab found that by placing a series of speakers next to the liners, they could excite most all the modes, but to very low levels.[2] The strain gage noise floor was a concern, but continued testing and model correlation showed that the analytical predictions were very reasonable. This gave the Program tremendous confidence that the analytical predictions using the hot-fire derived strain measurements could predict the strains at most all locations on the liner. These strain measurements would eventually be used to determine both fatigue and fracture life.

Hot Fire Testing

The two test articles were hot-fire tested in front of an SSME during the early part of 2003. The

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results revealed that the environments generated by the LPFTP proved to be very rich while the flowliners demonstrated structural characteristics of high modal density and very low damping. The hot-fire tests of the two test articles illustrated the vast complexity of the flow field generated by pumps and complexity of flowliner response, as shown in Figure 11. The backward traveling wakes had rich fields of different shape forcing functions and many different frequencies. Some of the forcing functions were proportional to pump speed while other forcing functions were related to asymmetry and cavitation due to flow separation. Another forcing function appeared due to the slots acting as helmholtz resonators exciting the core side duct acoustics. These acoustics would demonstrate a unique characteristic by appearing to be organized by the structural modes of the liners creating an optimum resonant condition which would "lock-in" at a particular frequency and continue to resonate even though the engine power level was changing, as shown in Figure 12.[1]

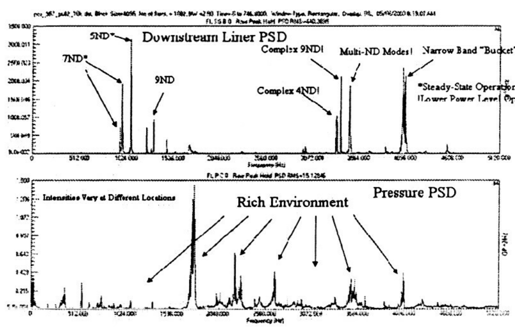

Figure 11. Strain Measurement and Pressure Measurement PSD.

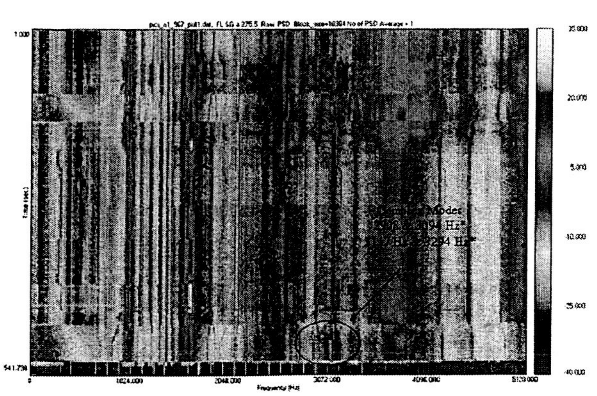

Figure 12. Response Spectragram Demonstrating Modal "Lock-In"

During the tests, it was found that the synchronous hydrodynamic forcing functions excited the flowliners in lower order diametral modes, at approximately 1000 Hz, and other swirling and cavitation flows excited the duct acoustics, which in turn excited higher order diametral modes, at approximately 3000 Hz. Examples of two of the excited modes are shown in Figure 13, where a fundamental 4 nodal diameter mode and a more complex shape 4 nodal diameter mode are shown. The test data demonstrated that the problem involved unusual structural/flow interaction.

The higher order modes at ~3000 Hz are very significant in that they were primarily excited during engine transients where the shuttles spend operational time during each flight. These modes were excited by sinusoidal duct acoustics that generated relatively high pressure fluctuations causing the slot locations on the flowliner to experience high levels of strain.[1] Further, unique bench tests and analysis demonstrated that the strain gradients across the ligaments, where the cracks were found, were extremely high and resulted in a biased strain field that would lend itself to slow and stable crack growth.[2]

Figure 13. Lower and Higher Order Diametral Modes Excited by the LPFTP Backflow

The conclusions from the hot-fire tests were that there were certain "hot-spots" where the shuttle engines can operate that generates a very rich environment. Since the flow liners had such a high density of modes in these regions, the combination was very likely to generate a dynamic response of the liners. It was also found that the resonance could "lock-in" during a gradual throttle down similar to structural resonances that involve vortex shedding, which

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could potentially lead to long periods of resonance during the shuttle's 3-g throttle down in flight. However, there were some differences between the A1 test stand at SSC and the flight ducts that were not accounted for in the tests. The primary difference was the duct length which would affect the core acoustics. With this difference, it became increasingly difficult to depend upon the measured strains entirely and to consider all results completely flight-like. More analysis was performed on when the engines operated in these hot-spots and a binning approach was used to supplement the fracture and fatigue analyses. The combination of these analyses are what eventually led to the completion of the investigation and resolution to the flight rationale.

Summary

In summary, the flowliner investigation has shown to have a number of unusual and unique structural dynamic issues associated with the cracking of the hardware. The complexity of the structural dynamics was extremely unusual due to the design of the flowliner and due to the issue of exciting highly complex, lightly damped modes which interacted with a number of complex forcing functions. The two test articles, with their instrumentation and test anchored models proved to be a significant development in identifying the mechanisms and the variability in structural modes that can be excited by the pump and assisted by the duct acoustics. The liners provided realistic responses to the mechanisms and demonstrated tremendous interaction with the hydrodynamics. This problem was very challenging to both industry and NASA and involved people from across the nation. During the past few years, the importance of the pump/feedline system integration has been demonstrated not only through the work associated with the Shuttle flowliner investigation, but also demonstrated in the Japanese H-2 rocket failure where the pump generated cavitation instigated a failure during a recent launch. In the case of the Shuttle flowliner a tremendous amount of variability from one flight to the next helped to reduce the time at resonance, limiting the accumulated damage during a single flight.

References:

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[2]AIAA-2005-1861, 46th AIAA/ASME/ASCE /AHS/ASC Structures, Structural Dynamics, and Materials Conference, "SSME Flowliner Acoustic Bench Tests Link Hot-fire Shapes to Analytical Strain Fields," G. Frady, K. Smalley, B. Laverde, J. Bishop, April 17, 2005

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