JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 41, No. 5, September–October 2004

Overview of the Development of Dynamic Environments for Atlas V Launch Vehicles

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Development of dynamic environments in the initial phase of launch vehicle design is a challenging task. Acoustic, vibration, and shock levels can be predicted by scaling data from existing launch vehicles if the structures are similar. For new systems, however, ground tests must be performed to provide adequate data. Prediction of environments must be considered as part of the design cycle and not an afterthought. An overview of the approach for the Atlas V family of launch vehicles is given.

Introduction

THE Atlas V family of launch vehicles has been developed by Lockheed Martin under the auspices of the Air Force's Evolved Expendable Launch Vehicle (EELV) program. Figure 1 shows the evolution of the Atlas launch vehicles, with the changes between each configuration. The Atlas III introduced the RD Amross RD-180 booster engine, the single-engine Centaur upper stage, and the stretched Centaur. The Atlas V 400 series replaced the pressure-stabilized stainless-steel booster tank with a structurally stable aluminum isogrid common core booster (CCB). Solid rocket boosters (SRBs) can be added to either Atlas V 400 or 500 series. The Atlas V 500 series adds a 5-m-diam payload fairing based on the fairing developed by Contraves for the Ariane 5, while the Atlas V heavy-lift vehicle (HLV) uses two of the CCBs as liquid rocket boosters. The development of dynamic environments—acoustics, vibration, and shock—for this family of launch vehicles involved analysis to perform extrapolation of available flight data, and a wide range of subscale and full-scale ground tests. The ground tests were also used to develop system-level and component-level mitigation approaches for the dynamic environments.

Because the government wished to maintain assured access to space and hoped to realize cost savings, partial funding for the EELV development program was awarded to two contractors, Lockheed Martin and Boeing. Interchangeability between launch providers was ideal in case one launch system was adversely affected by anomalies, failures, or other reasons. To manage this interchangeability, a standard interface specification (SIS)[1] was created and levied upon each contractor. The SIS was created from a consortium of payload and launch-vehicle requirements. Representative military and commercial payloads, both existing as well as conceptual, were included. For the purposes of this report, the SIS defines enveloping payload requirements for interface shock, vibration, and acoustics. Lockheed Martin was required to demonstrate the capability of the Atlas V to stay within the set guidelines of the SIS.

Presented as Paper 2003-1970 at the AIAA/ASME/ASCE/AHS/ASC 44th Structures, Structural Dynamics, and Materials Conference, Norfolk, VA, 7–10 April 2003; received 24 June 2003; revision received 28 August 2003; accepted for publication 8 September 2003.

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General Approach

Early in the Atlas V program, a general approach for the development of dynamic environments requirements was established. The preferred methodology was analysis using flight data adjusted to the Atlas V configurations, with ground-test data used to verify and fill in as needed. The large body of available Atlas and Titan flight data was of great benefit in developing initial requirements. Because of early involvement of the U.S. Air Force in the Atlas V program, overall philosophical approaches to dynamic environments were altered slightly from previous Atlas programs (II/III). In essence, best commercial practices were augmented with slightly more risk-averse approaches, common in military acquisition, such as those described in Military Standards. MIL-STD-1540C (Ref. 2) was selected as a guide in the development of maximum predicted environments and component qualification requirements. The end results were select increases to component qualification margins and minor changes to test and analysis approaches, compared to previous Atlas programs. Wind-tunnel tests, full-scale and subscale acoustic tests, rocket engine firings, and separation tests were identified and completed to supplement flight data. Table 1 provides an overview of the major ground tests accomplished on the Atlas V program. The following sections describe how predictions were developed for each of the dynamic environments: acoustics, vibration, and shock.

Acoustics

A summary of the primary sources of external and internal acoustic predictions is shown in Fig. 2 for the family of Atlas V vehicles. Initial external liftoff acoustic predictions were developed by using the methodology of NASA SP-8072 (Ref. 3) to define levels along the launch vehicle. The prediction methodology was validated using external flight acoustic data taken on both the Atlas and the Titan programs. Flight data were available from external microphones on the Atlas booster pod and also from launch tower microphones. Titan flight data had been obtained from external microphones on the payload fairing. To reduce liftoff acoustic levels (due to the higher RD-180 liftoff thrust used by Atlas V compared to Atlas III) and associated vibration levels on the launch vehicle, the requirement for an acoustic suppression water system (ASWS) was identified. Both cold- and hot-gas 3.3% subscale launch acoustics tests were performed to refine the design and quantify the benefit of the ASWS.

The cold-gas test was performed initially. An advantage of cold-gas testing is that it is relatively inexpensive compared to hot-gas testing. Nitrogen is forced through the nozzles at pressures designed to model the plume characteristics as closely as possible. However, it is not possible to exactly emulate the dynamic characteristics of the engine plume. For this reason, it was decided early on that a hot-gas test would be conducted in the future. The dynamic characteristics of the full-scale engine plume can be modeled much more closely with hot gas.

The main objectives of the cold-gas test were to characterize the effect of the water suppression system, which was limited to an above-deck system at that time, and the effect of drift on the vehicle acoustics at different elevations above the pad. The vehicle was instrumented with flush-mounted microphones at five vehicle stations, two on the fairing and three on the booster.

A total of 96 runs were evaluated, encompassing four different configurations (one RD-180 and three RD-180 engines, Atlas and Titan IV) and three different launch exhaust duct designs. An important design constraint for the above-pad water system was that the water not be allowed to contact the engine nozzles. Therefore, it was concluded that two water systems were needed: an in-duct system for the lower elevations and an above-deck system for the higher elevations. Considering that design change, it was believed that a mitigation of about 2 dB on the overall sound pressure level could be achieved.

The hot-gas launch acoustic tests were performed approximately two years later, building on the knowledge gained during the cold-gas testing. However, designing a hot-gas plume generator proved to be many orders of magnitude more difficult than designing the cold-gas test. The test times were shorter, and the test matrix not nearly as extensive as that of the cold-gas test. The objectives of the hot-gas test were focused on the actual launchpad design for the EELV vehicles, and confirming the effectiveness and operation of the in-duct and above-deck water systems. The instrumentation locations on the vehicle were similar to the cold-gas launch acoustic test.

Based on the experiences from the cold-gas test, the range of elevations above the pad was extended to ensure that the point of highest liftoff acoustic levels had been reached. The test matrix consisted of 26 test runs, both with and without the water system and with and without drift. The results showed that the benefit as a result of the water system could be increased. Figure 3 shows the benefit as originally assumed and confirmed by the cold-gas testing vs the measured result of the hot-gas test, and the final adjustment applied to the vibration predictions to account for the benefit of the water system. For both launch acoustic tests the data were scaled based on geometric differences, and only the deltas were applied to the previously derived full-scale predictions.

Acoustic predictions for the transonic/max Q flight regime were obtained from two series of buffet/acoustics wind-tunnel tests performed on 7.9%-scale models in the Arnold Engineering Development Center wind tunnel. The first series of tests contrasted the single-body configuration with the three-body configuration. When the 500 configurations were added to the family, another series of wind-tunnel tests was performed to examine the effects of the added solid motors on the acoustics levels. The configurations tested included those with 5, 4, 3, and 0 strap-on solid motors.

A very important aspect of the second series of tests was to examine the effect of different nose-cone shapes of the solid motors on the acoustics of the core vehicle, with emphasis on the acoustic impingement on the exterior of the avionics pod. A standard conic, a canted conic, and a canted ogive nose cone shape were tested. These studies showed that no single configuration could be designed that provided lower levels everywhere, and the final designs were driven by the desire to reduce levels in the vicinity of the most sensitive components.

These tests yielded a very extensive database, with 190 to 330 dynamic pressure measurements, depending on the configuration, and upwards of 400 test data points (Mach number, angle of attack) per configuration. Figure 4 shows the measurement locations for the 400 series vehicle. The number of microphones per station was increased from four to eight in regions where large changes were anticipated, such as in the vicinity of forward- and aft-facing steps. Mach numbers ranged from 0.7 to 1.6, and the alpha/beta combinations ranged from −4 to +4 deg. At each vehicle station, the measurements were averaged and frequency-dependent deltas derived to allow scaling between the single-body and the multiple-body vehicles. The data were broken out into transonic and max Q sound pressure levels.

Table 1 Summary of key ground tests performed on the Atlas V program in support of the definition of dynamic environments

Test	Results
Full-scale ground tests	
RD-180 hot-fire tests	Engine interface vibration
Booster-tank acoustic tests	Booster component vibration
Redesigned 4-m-diam payload fairing (PLF) acoustic blanket acoustic tests	Acoustic blanket absorption and transmissibility
5-m-diam PLF upper-stage module acoustic tests	Centaur, interstage adapter (ISA), and PLF component vibration and acoustics
5-m-diam PLF payload module acoustic tests	PLF noise reduction and component vibration
SRB motor firing tests	SRB-generated acoustics and vibration
Launch head separation tests	Launch vehicle interface shock
Solid rocket motor umbilical detonation transfer tests	Component shock
5-m-diam PLF Centaur Forward Load Reactor deck separation tests	Interface and component shock
5-m-diam PLF separation test	Interface and component shock
Subscale ground tests	
Cold- and hot-gas launch acoustics tests	Liftoff acoustic attenuation with ASWS
Buffet/acoustics wind-tunnel tests	Transonic/max Q acoustics

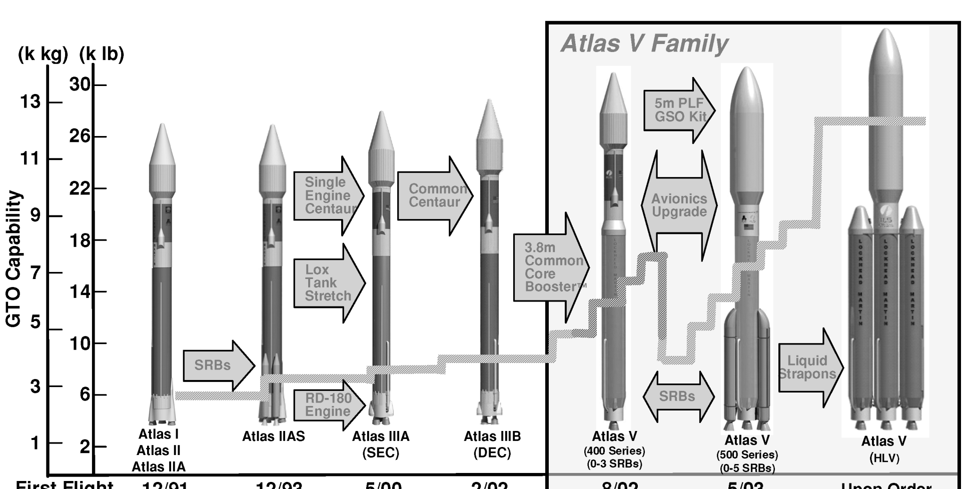

Fig. 1 Evolution of the Atlas launch vehicle.

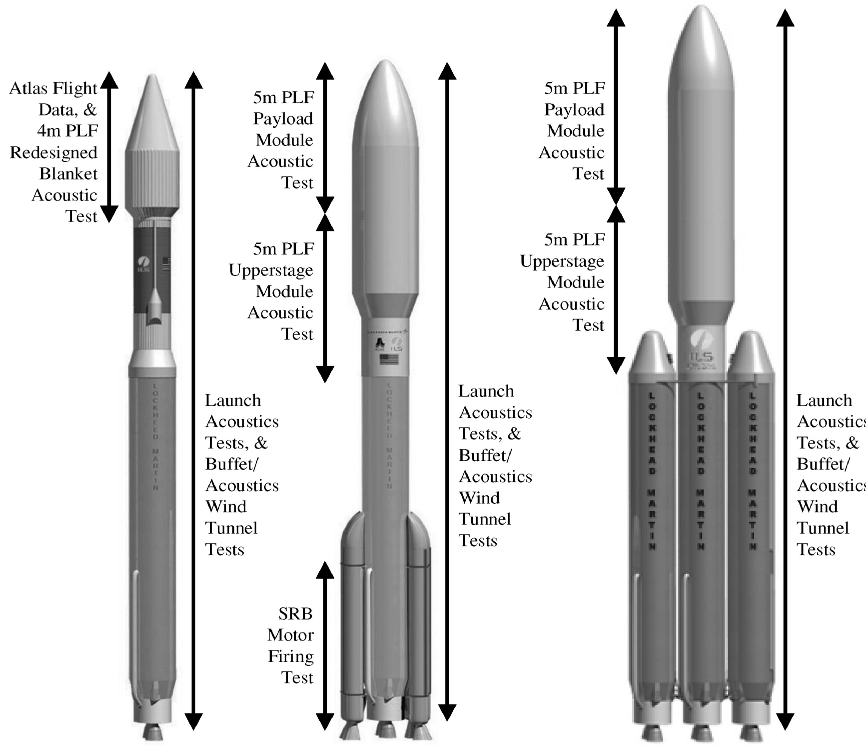

Fig. 2 Primary sources of external and internal acoustic predictions.

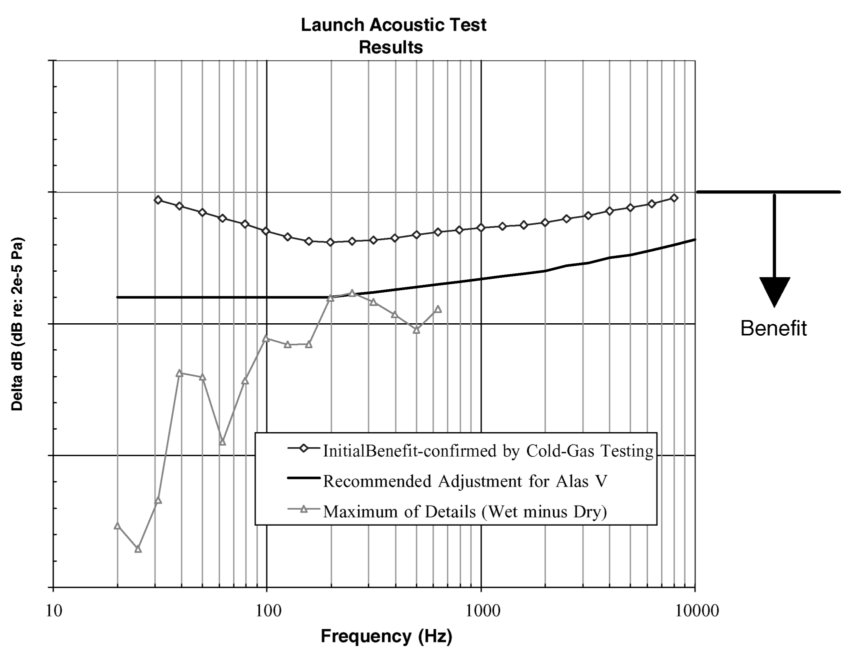

Fig. 3 Launch acoustic test results: benefit of ASWS.

Figure 5 shows that the overall acoustic level varies significantly with the different Atlas V vehicle configurations. Local acoustic levels are influenced by nose-cone shapes and transitions that give rise to shock waves and turbulent flow. Acoustic levels are also a function of dynamic pressure.

Payload acoustics predictions for the Atlas V 400 series configuration were primarily based on analysis validated with Atlas flight data because this configuration uses the same 4-m-diam payload fairing that the heritage Atlas uses. Early in the program, acoustic blankets were baselined for the 4-m fairing, both for mitigation of payload acoustic levels and for mitigation of Centaur equipment module component vibration levels. The 4-m fairing acoustic blankets were modified for Atlas V as a cost-saving initiative, and a series of absorption and transmissibility tests were performed to confirm that the modified design performed at least as well as the previous blankets. Figure 6 shows the acoustic levels of the 4-m fairing are below the SIS requirement.

The Atlas V 500 and HLV configurations use the 5-m-diam payload fairing designed and built by Contraves. Contraves developed initial analytical acoustic predictions, based on their Ariane 5 experience. These predictions were validated with a full-scale acoustic test of the payload module of the Atlas V fairing in the Lockheed

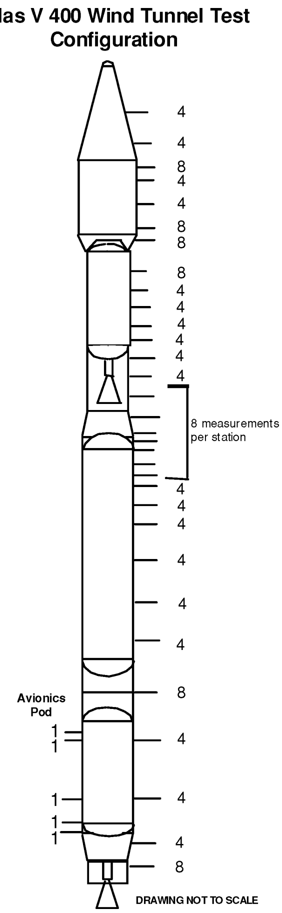

Fig. 4 Wind-tunnel test: Atlas V 400 vehicle measurement locations.

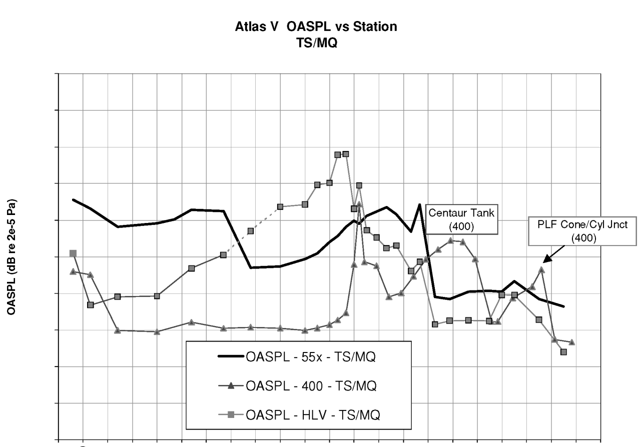

Fig. 5 Overall sound pressure levels for various Atlas V configurations.

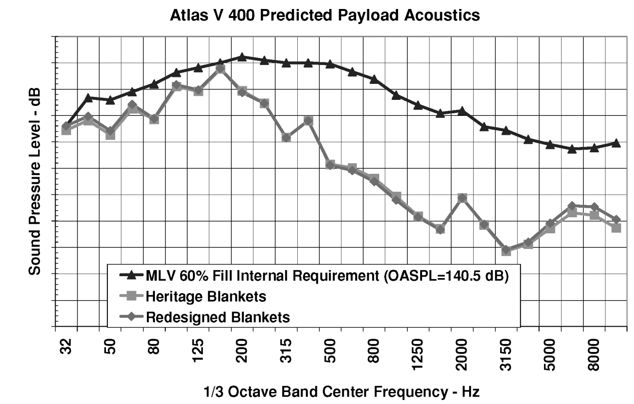

Fig. 6 Overall sound pressure levels for the Atlas V 400 blanket configurations vs requirement.

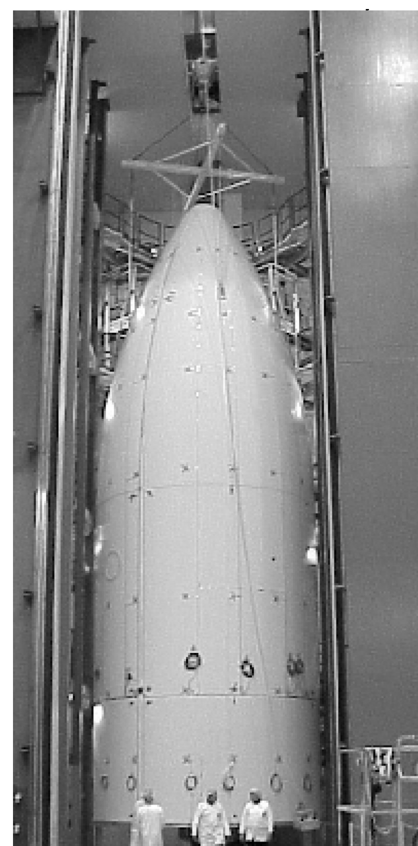

Fig. 7 The 5-m-diam payload fairing payload module in RAL acoustic chamber.

Martin Reverberant Acoustic Laboratory (RAL). Figure 7 shows the fairing installed in the RAL chamber. Test instrumentation consisted of 20 external microphones, 30 internal microphones, and 117 accelerometers.

Figure 8 shows the entire payload fairing, divided into analysis zones. It was important to account for the portion of the payload volume that was not included in the payload fairing acoustic test, the module forward of the Centaur Forward Load Reactor (CFLR). The contribution caused by the CFLR module, which does not have any acoustic treatment installed, was based on a heritage Lockheed Martin analysis model, which allows the modeling of variations in acoustic protection (acoustic blankets or similar treatments), as well as modeling the power flow between zones, based on the available open area between zones. This model is based on the principles of statistical energy analysis and is described in more detail in Ref. 4.

No payload simulator was included in this test. Therefore, "fill effects" caused by the payload have to be accounted for analytically. Payload fill effects are based on the method developed by C. S. Tanner of The Aerospace Corporation from space shuttle data.[5] Differences in fairing noise reduction between the reverberant acoustic field and the launch acoustic field were accounted for analytically. Figure 9 shows a comparison of the test-validated payload acoustic predictions vs the requirements established by the U. S. Air Force in the SIS.

Vibration

A summary of the primary sources of vibration predictions is shown in Fig. 10 for the family of Atlas V vehicles. Vibration

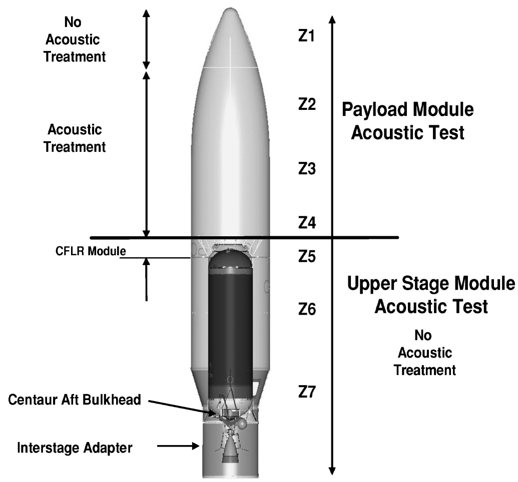

Fig. 8 The 5-m-diam payload fairing acoustic analysis zones.

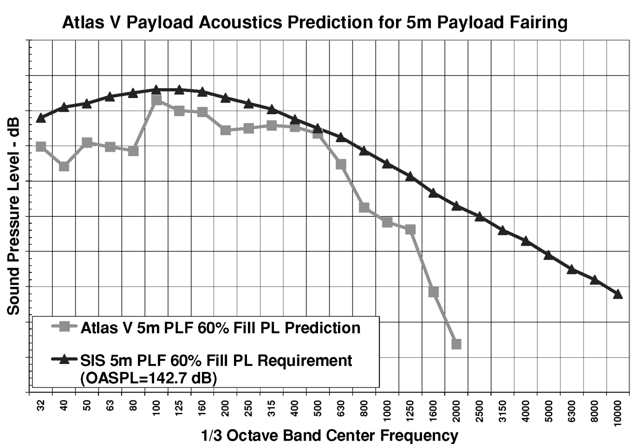

Fig. 9 Test-validated payload acoustic predictions vs requirements.

requirements for the Centaur upper-stage and 400 series ISA and 4-m-diam payload fairing were developed primarily from Atlas flight data, because of the similarity of these structures to the heritage Atlas structures. Because the booster was entirely new, engineering development tests were devised to estimate vibration levels using prototype booster hardware. Booster vibration levels near the engine interface were initially defined based on data obtained in RD-180 hot-fire tests performed at the NASA Marshall Space Flight Center and were subsequently updated based on Atlas III flight data. Vibration data were also gathered during the ground-fire tests of the SRBs and are presently being evaluated.

Two series of full-scale acoustic tests were performed on the fuel tank in the Lockheed Martin RAL chamber (Fig. 11). The first

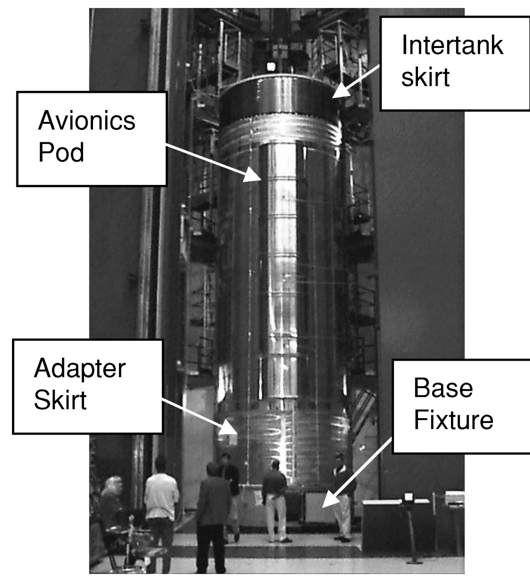

Fig. 11 Booster fuel tank in RAL acoustic chamber.

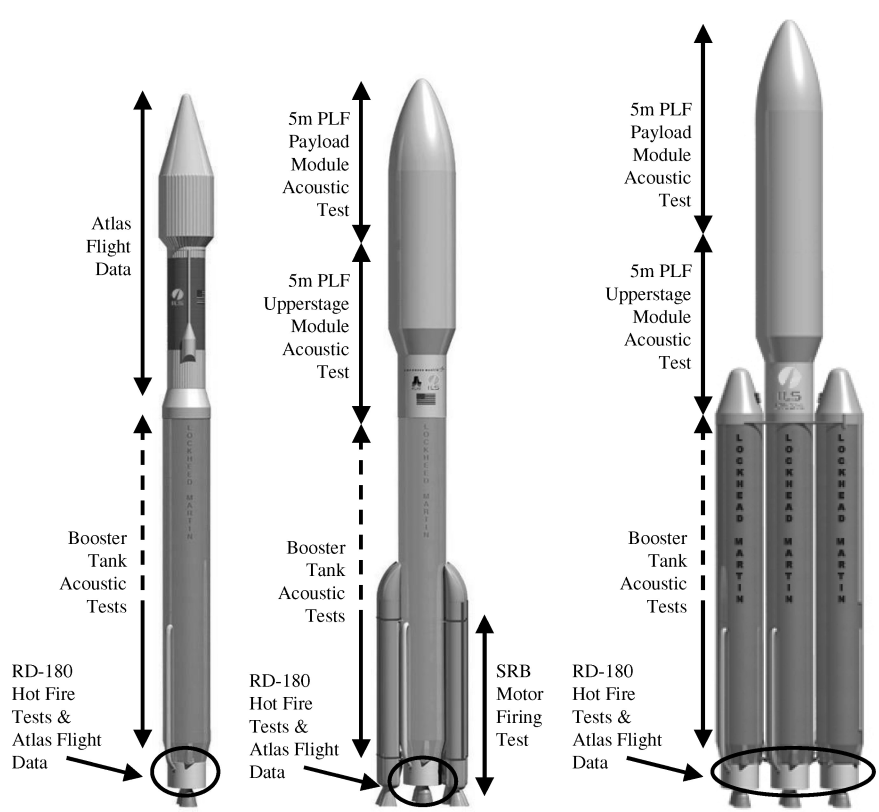

Fig. 10 Primary sources of vibration predictions.

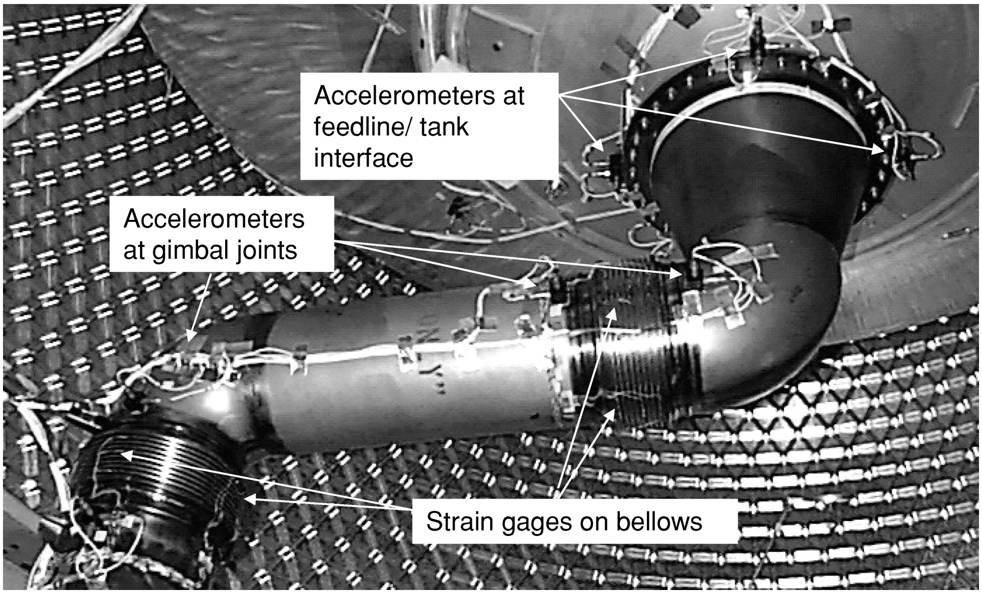

Fig. 12 Fuel feedline and instrumentation.

series of tests was used primarily to define requirements for avionics components mounted in the pod on the side of the fuel tank, while the second series was aimed at defining requirements for booster propulsion components such as fuel and oxidizer feedlines, ducts, and pneumatic assemblies. A significant amount of data was collected during the two tests: 18 acoustic measurements both internal and external to the booster, over 400 vibration measurements on primary structure and on components, approximately 90 strains on feedline bellows, and 12 force measurements at avionics component interfaces. These tests were also used to investigate a number of system-level and component-level vibration mitigation approaches as well as provide information for validation of analyses and assumptions.

An illustration of the comprehensive data is the fuel feedline. The 10-in.-diam line has three gimbal joints to accommodate relative motion between the tank and engine (Fig. 12). There is a valve on the feedline to allow loading and draining of the fuel. The gimbal joints and valve are the feedline components most sensitive to random vibration, and so measurements were taken to characterize acceleration at these locations. Accelerations were measured at the interfaces of the feedline to the booster. Strains were measured on the bellows of the gimbal joints. Power spectral densities (PSDs) were calculated from the test acceleration and strain data. The PSDs were scaled from test to flight levels based on the relative acoustics. Because of the high fidelity of the test article, no adjustment was needed for structural differences. The strain data from the acoustic test were combined with similar measurements from the Marshall hot-fire test of the RD-180 to predict total dynamic strain responses in the bellows. A wealth of information describing the response of the fuel feedline was now available to be used in both analysis of the feedline subsystem and the development of vibration requirements for the components.

A number of mitigation approaches were investigated for components mounted in the avionics pod on the tank. These included adding acoustic blankets to the pod covers, adding visco-elastic material to the pod covers, purging the pod with helium, applying foam bumpers between the component mounting trays and tank, and using standard vibration isolators. From these tests it was determined that vibration levels of the pod components were driven by the entire tank, and so mitigation approaches focused on the pod did not provide significant relief. The most successful mitigation approach was found to be vibration isolation of individual components, or isolation of an entire tray of components.

In some cases, such as the pressurization system flow-control assemblies, it was found that varying the mounting arrangement of the valves significantly reduced their vibration levels. Two assemblies

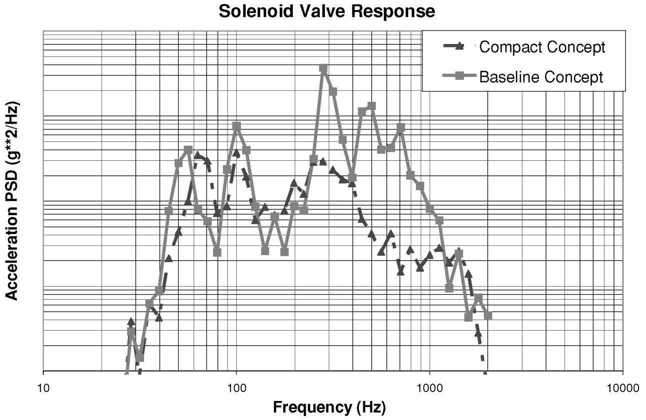

Fig. 13 Comparison of valve response for flow-control assembly design concepts.

regulate the flow of helium for ullage pressure in both the oxidizer and fuel tanks. The solenoid valves are the sensitive component in the assemblies. The first fuel tank acoustic test provided vibration environment used to base-drive finite element models of the assemblies and predict valve responses. The results were not very palatable because they were high with respect to previous requirements for similar solenoid valves. Installation of isolators was undesirable because it required use of flex hoses rather than hard tubing. Rather than drive a totally new design of the valve, it was decided to test different concepts for the assemblies and choose the design that resulted in the best match to the existing valve requirement. Testing would also provide data to ground the finite element analysis. Two designs were chosen: the baseline design and a compact option. A comparison of the responses is shown in Fig. 13. The compact configuration was chosen because it gave reduced levels in high frequencies.

The 500 series and HLV uses a new composite ISA, and initial analytical prediction of vibration levels for components mounted on the Centaur aft bulkhead indicated the potential need to requalify a number of these components. To avoid the expense and risk of these requalifications, the approach of purging the compartment with helium was developed and tested in a full-scale acoustic test. The test article included the ISA, Centaur, and the upper-stage module (USM) of the 5-m-diam payload fairing, as shown in the schematic of Fig. 8. The basic instrumentation for the acoustic test consisted of a total of 334 accelerometers, 32 microphones (9 used for control), and 28 strain gauges. Figure 14 shows that acoustic levels within the ISA were significantly lower with the helium purge. The effect of the helium purge on component vibration levels varied, depending on how strongly the individual component was driven by internal acoustics vs structure-borne vibration. The test was successful in showing that most components did not require additional qualification testing with the addition of the helium. This test also was used to develop updated vibration levels for components mounted to the USM.

Shock

A summary of the primary sources of shock predictions is shown in Fig. 15 for the family of Atlas V vehicles. Many of the shock sources for the Atlas V family of launch vehicles are common with the heritage Atlas or Titan programs: the Atlas 4-m payload fairing separation system, the Centaur separation system, and most of the payload separation systems. Consequently, existing shock requirements could be used for these events. New shock sources were identified, and ground-test programs were conducted to characterize these shock levels. The Atlas V launch hold-down system uses a 2-in.-diam frangible nut to release the rocket at launch, and a series of firings of this system under load was conducted at Lockheed Martin. Another new source of shock was the separation of the CFLR deck, which is used to share load between the Centaur and the 5-m payload fairing in the 500 and HLV configurations. CFLR separation tests were conducted by Contraves and data obtained to show that shock levels were within allowable levels (Fig. 16). Shock levels caused by the separation of the 5-m payload fairing itself were measured in a test conducted by Contraves at the NASA Plumbrook facility. Again, measured shock levels were found to be within allowable levels, as shown in Fig. 17. The method used to ignite the SRBs on the Atlas V program is a detonation transfer from the core to the SRB through an SRB umbilical. This detonation transfer also creates a shock environment, which was measured through a series of tests and used to define shock environments on nearby components. Ground tests have been found to be a reliable source of shock data because shock levels are not significantly affected by flight conditions.

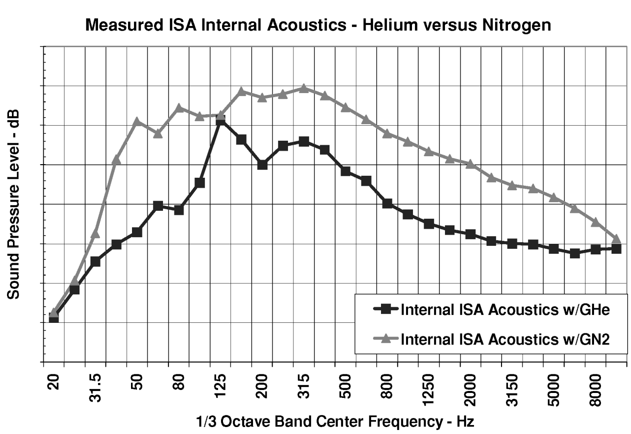

Fig. 14 ISA internal acoustic levels: helium vs nitrogen purge.

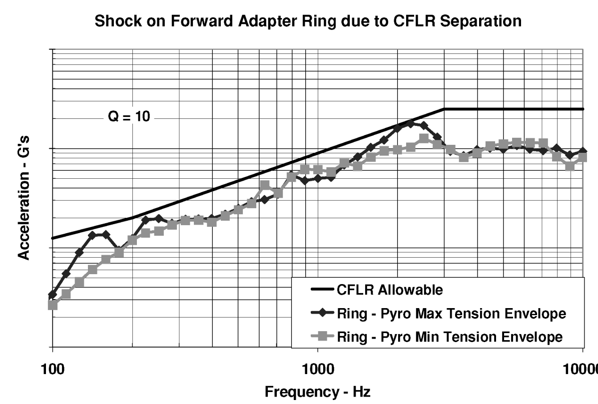

Fig. 16 Shock at Centaur/CFLR deck interface caused by CFLR deck separation.

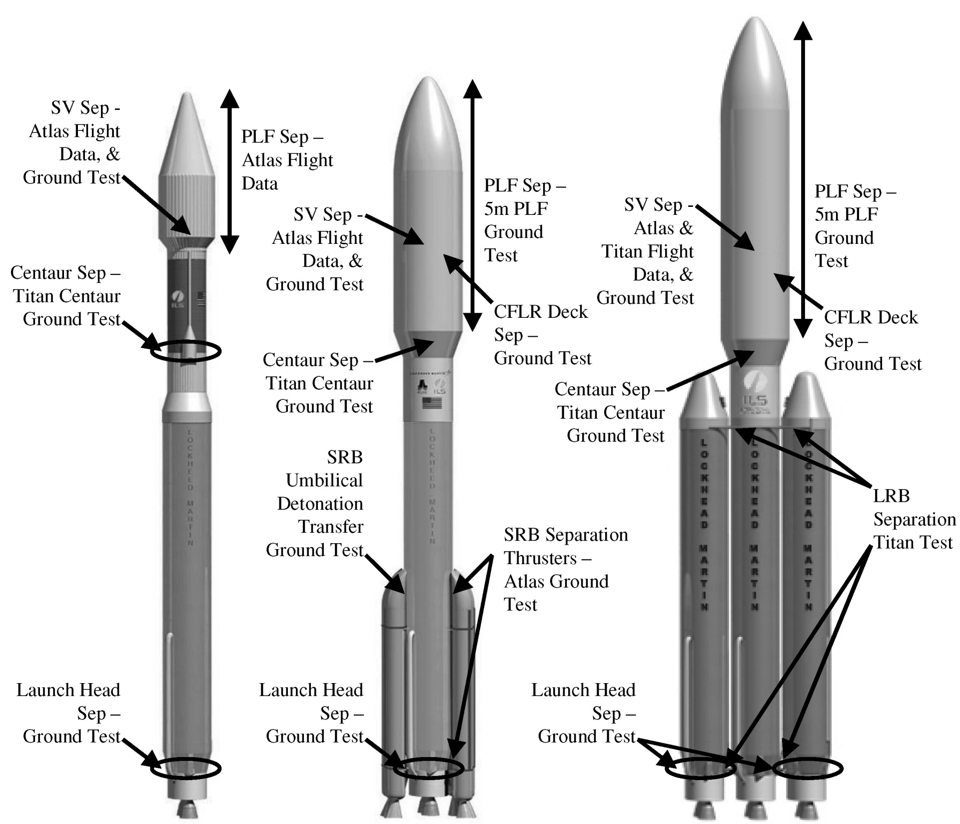

Fig. 15 Primary sources of shock predictions.

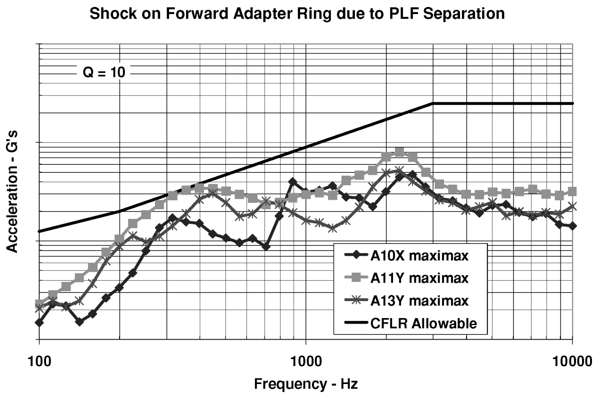

Fig. 17 Shock at Centaur/CFLR deck interface caused by PLF separation.

Summary

Analysis of a large body of flight data and a comprehensive series of subscale and full-scale ground tests were required to develop dynamic environment requirements and mitigation approaches for the Atlas V family of launch vehicles. Ground tests on detailed flight-like hardware minimized scaling for structural differences, thereby increasing accuracy and decreasing conservatism of predictions. Validation of the predictions, along with quantification of the conservatism/margin in them, will be through comparison with flight data obtained on the first several flights of the various configurations of the Atlas V. Comparisons for the first Atlas V flight (a 400 configuration) showed that where applicable flight- or ground-test data were available the predicted dynamic environments compared well with flight data. Most of the shortfalls in the predicted environments occurred when there were no directly applicable data available before the flight, or when unforeseen sources of vibration or shock such as flow-induced vibration or engine induced transients occurred. The environments are presently being revised to reflect the flight information. Test data have also been used for validation of analysis methods, assumptions, and models as well as to develop relationships between flight measurements and component responses.

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