Flight Testing of the Gulfstream Quiet Spike™ on a NASA F-15B

James W. Smolka (AF), Project Pilot, NASA DFRC
Robert A. Cowart, Project Engineer, Gulfstream Aerospace
Leslie M. Molzahn, Operations Engineer, NASA DFRC
Thomas J. Grindle, Project Chief Engineer, NASA DFRC
Tim Cox, Control Systems Engineer, NASA DFRC
Steve Cumming, Aerodynamics Engineer, NASA DFRC
Marty Brenner, Structural Engineer, NASA DFRC
Natalie Spivey, Structural Engineer, NASA DFRC
Leonard Voelker, Structural Engineer, NASA DFRC
Kirk Caldwell, System Safety Engineer, NASA DFRC
Melissa Couper, Aerial Refueling Engineer, 445 FTS, AFFTC

Introduction and Background

Gulfstream Aerospace has long been interested in the development of an economically viable supersonic business jet (SBJ). A design requirement for such an aircraft is the ability for unrestricted supersonic flight over land. Although independent studies continue to substantiate that a market for a SBJ exists, regulatory and public acceptance challenges still remain for supersonic operation over land. The largest technical barrier to achieving this goal is sonic boom attenuation. Gulfstream's attention has been focused on fundamental research into sonic boom suppression for several years. This research was conducted in partnership with the NASA Aeronautics Research Mission Directorate (ARMD) supersonic airframe cruise efficiency technical challenge. The Quiet Spike, a multi-stage telescopic nose boom and a Gulfstream-patented design (references 1 and 2), was developed to address the sonic boom attenuation challenge and validate the technical feasibility of a morphing fuselage. The Quiet Spike Flight Test Program represents a major step into supersonic technology development for sonic boom suppression.

The Gulfstream Aerospace Quiet Spike was designed to reduce the sonic boom signature of the forward fuselage for an aircraft flying at supersonic speeds. In 2004, the Quiet Spike Flight Test Program was conceived by Gulfstream and NASA to demonstrate the feasibility of sonic boom mitigation and centered on the structural and mechanical viability of the translating test article design. Research testing of the Quiet Spike

consisted of numerous ground and flight operations. Each step in the process had unique objectives, and involved numerous test team members from the NASA Dryden Flight Research Center (DFRC) and Gulfstream Aerospace.

Flight testing of the Quiet Spike was conducted at the NASA Dryden Flight Research Center on an F-15B aircraft from August, 2006, to February, 2007. During this period, the Quiet Spike was flown at supersonic speeds up to Mach 1.8 at the maximum design dynamic pressure of 685 pounds per square foot. Extension and retraction tests were conducted at speeds up to Mach 1.4. The design of the Quiet Spike to shape the forward shock wave environment of the aircraft was confirmed during near-field shock wave probing at Mach 1.4. Thirty-two flights were performed without incident and all project objectives were achieved. The success of the Quiet Spike Flight Test Program represents an important step towards developing commercial aircraft capable of supersonic flight over land within the continental United States and in international airspace.

Project Objectives

The objectives for the Quiet Spike flight test phase were identified to meet Gulfstream technical objectives for the Quiet Spike experiment and to meet NASA airworthiness and flight safety objectives for the F-15B test aircraft.

The Gulfstream Aerospace technical objectives were:

1. Measure structural loads and dynamics of the Quiet Spike.
2. Extension and retraction functionality at operational conditions.
3. Near-field shock wave characterization.

The NASA airworthiness and flight safety objectives were:

1. Air data calibrations (airspeed, altitude, angle-of-attack, sideslip angle).
2. Flutter clearance.
3. Flying qualities clearance.
4. Structural loads on the aircraft bulkhead attachment points for the Quiet Spike.

Participating Organizations

The Quiet Spike project involved Gulfstream Aerospace Corporation, Savannah, Georgia, the NASA Dryden Flight Research Center (DFRC) and the Air Force Flight Test Center (AFFTC) at Edwards AFB, California, the 46th Test Group at Holloman AFB, New Mexico, and the Boeing Aerospace Company in St. Louis, Missouri. Gulfstream was responsible for the engineering design, fabrication, and instrumentation of the Quiet Spike experiment. NASA provided the F-15B test aircraft, aircraft modification and maintenance, aircraft instrumentation, integration of the Quiet Spike and instrumentation with the aircraft system, engineering support for ground and flight tests, flight planning and operations, hazard analysis and risk mitigation, and control room monitoring of test flights. NASA also maintained airworthiness and flight safety responsibility throughout the program. The Air Force Flight Test Center was responsible for helping NASA DFRC obtain flight clearance for air refueling the Quiet Spike equipped F-15. The 46th Test Group allowed Mr. Tom Hill to support NASA during near field shock wave probing flights as the pilot for the probing NF-15B aircraft. Boeing provided simulator support to NASA to explore aircraft stability and control boundary issues in preparation for the Quiet Spike test project. It is noteworthy that the Gulfstream-NASA team was fully integrated in the accomplishment of this test project. NASA was involved at a relatively early stage of the Quiet Spike hardware development effort at Gulfstream, which aided greatly in integrating the test article with the aircraft. Gulfstream maintained on-site representation at NASA throughout the aircraft modification and flight program.

Background and Theory of the Quiet Spike Concept

The Quiet Spike is a forward-extending, telescopic nose boom designed to increase the overall fuselage length by 30 percent and produce a "shaped" near-field pressure signature for the forward fuselage of a supersonic aircraft. Gulfstream showed that by introducing a weak shock or series of weak shocks ahead of the aircraft (reference 3) one can greatly reduce the initial overpressure and increase the rise-time of the overall shock wave, resulting in a shaped signature as shown in figure 1. These weaker shockwaves can be generated by placing aerodynamic shapes at precise locations in front of the nose of the aircraft, thus breaking down the strength of the initial bow shock.
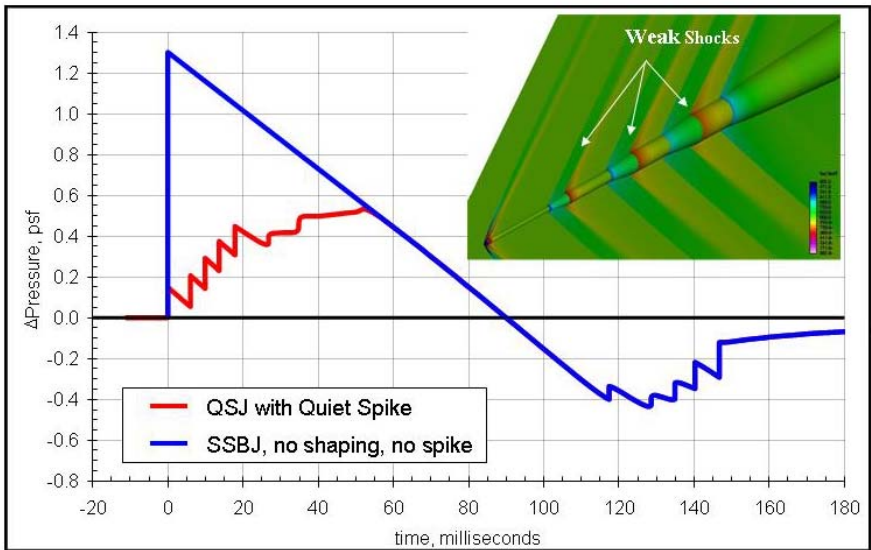
Figure 1. Quiet Spike shock wave "shaping" in near-field and ground signatures. (Note: QSJ – Quiet Supersonic Jet, SSBJ – Supersonic Business Jet)

Beginning in 2001, initial design efforts resulted in a series of segmented, cylindrical aerodynamic configurations for shaping sonic boom pressure signatures. As the design matured, higher-order Computational Fluid Dynamics (CFD) solutions were developed and wind tunnel test planning began. Gulfstream conducted its first supersonic wind tunnel test at the NASA Langley Unitary Plan Wind Tunnel (UPWT) in August 2002, confirming the favorable low boom characteristic of the Quiet Spike. Figure 2 shows sample test results compared to the CFD solution.

In parallel with the aerodynamic work, Gulfstream structural engineers began work on spike structural concepts and mechanism designs. Since aircraft ground operation with a long spike would be impractical, telescopic configurations were developed to stow the nose spike into a smaller volume. Realizing that the segment-to-segment joint stiffness would be critical to the overall dynamic response, a subscale dynamic test was proposed. In very short order, design and fabrication of the quarter-scale dynamic test model began in the Experimental and Structural Test Hangar in Savannah. Testing was later conducted on this model at the University of South Carolina in Columbia, SC, establishing a baseline stiffness requirement for detailed design of the segment joints.
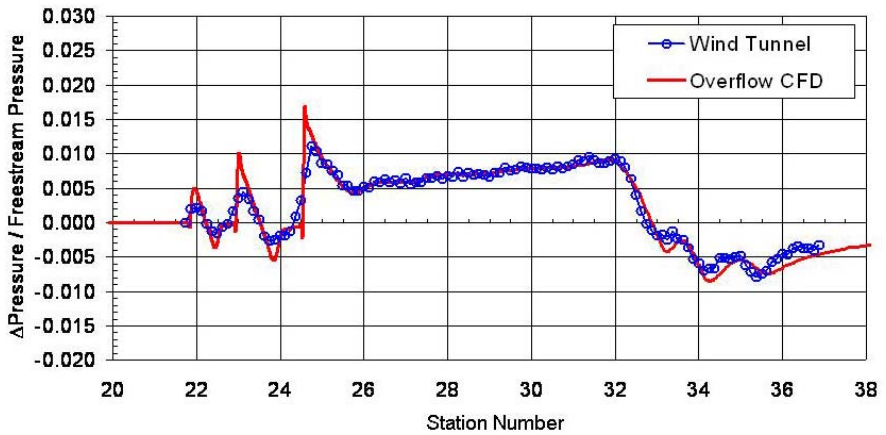
Figure 2. Results of Quiet Spike testing at NASA Langley UPT wind tunnel.

Throughout 2003, Gulfstream continued its focus on static and dynamic structural characterization of the multi-segmented design. In January 2004, a half-scale prototype design and fabrication effort began for further development of the extension and retraction mechanism. The first segment movement on this model was accomplished four months later in April using a pneumatic system. The pneumatic system proved inadequate to precisely control spike position and speed of translation and was converted to a more conventional electrically-driven cable and pulley system.

As confidence was gained, discussions with NASA began about a possible Quiet Spike flight test program. It was quickly determined that ground signature measurement would not be possible as in the Supersonic Boom Demonstrator (SSBD) program (reference 4). Combining the Quiet Spike with any existing supersonic aircraft would result in a traditional N-wave ground signature as the stronger shocks of today's aircraft would overtake the spike's weak shocks within a short distance below the flight path. Only in-flight near-field shock probing could be obtained for further aero-acoustic validation. Since wind tunnel testing had already validated the aerodynamic theory, in-flight measurement of a large-scale spike was not considered necessary, but would add to the credibility of the concept. It was agreed that overcoming the physical challenge of building a large-scale, functioning, structural flight test article was justification enough to

proceed with test planning. Clearly taking a thirty-foot long telescoping nose boom to supersonic speeds would demonstrate the structural feasibility of such a device. Hence, flight test program objectives were defined as previously stated. After reviewing the cruise altitude for a conceptual supersonic business jet, the Quiet Spike design test point was defined as Mach 1.8 at an altitude of 45,000 feet and the NASA F-15B aircraft was selected as the test vehicle.

In December 2005, the Quiet Spike Critical Design Review (CDR) was held at NASA DFRC and the test article was cleared for fabrication.

Test Article Development

Design Loads Development and Criteria

As discussed in reference 13, the design criteria for the Quiet Spike were a combination of Federal Aviation Regulations (FARs), Military Specifications (MIL-SPEC), and Gulfstream and NASA DFRC standards. Preliminary load conditions considered landing, wind gust, symmetric and asymmetric maneuvers, ground maneuvers, crash load factors, and thermal induced loading. The following table summarizes the primary criteria used for the spike development.

Table 1. Quiet Spike Development Design Criteria	
Maximum speed	Mach 1.8
Maximum dynamic pressure	685 pounds per square foot (psf)
Landing sink rate	5 feet per second (fps) with spike extended
Minimum factors of safety	Tested Structure, 1.5 Untested Structure, 2.25 Untested Composite Structure, 3.0
Flutter margin	Maintain a minimum 15 percent margin on flutter speeds
Mechanical system	- Must not have any uncommanded movement - Must be direct drive system by operator with no software in the loop
Operating temperature	Mechanical system must operate flawlessly at temperature extremes of -67°F to 200°F
Maximum temperature	Composite structure must not exceed 200°F due to aerodynamic heating

Structural Design and Fabrication

The structural components of the Quiet Spike are a combination of graphite epoxy outer mold line (OML) skins and aluminum internal substructure. The earlier work on segment-to-segment joint stiffness paid off when it came to designing the flight test article. The interface between segments is accomplished with a series of internal bulkheads with rollers to allow the composite tubes to translate. At any point in the spike extension, there are at least two bulkheads supporting the overhanging bending moment such that the spike behaves like a continuous cantilever beam.

Two identical fully functioning Quiet Spike test articles were fabricated. The first unit, completed in September 2005, was used for load calibration and ground vibration testing at Gulfstream, shipped to NASA Dryden in October, and became the flight test article. A second complete unit was finished in November 2005 and was used for static structural testing in Savannah. The testing went to 200 percent Design Limit Load (DLL) in the vertical direction and 300 percent DLL in the lateral direction. Post-test inspection showed the ground unit was fully functional and had no permanent set or damage in any of the structure.

Mechanism Design

As described above, engineering studies were conducted on various actuation systems for the spike. The effort was narrowed to two systems: a pneumatically actuated piston-type mechanism and more conventional electro-mechanical pulley and cable system. Since the pneumatic system proved insufficient to precisely control speed and position, the electro-mechanical system was selected for design. The extension and retraction system worked essentially as an electric winch. As shown in figure 3, when the spike was to be deployed, a cylindrical drum at the aft end of the spike would rotate such that the extension cables would wind onto the drum. As the cables wound onto the drum, the cable-pulley system would deploy the spike out to its extended position. To retract the spike, the drum would reverse direction winding the retraction cable onto the drum, pulling the spike segments with it. One deficiency with this system was that it relied on friction to ensure that the forward boom section always extended first, a problem discussed in more detail later. Additionally, the direct-drive system was shut off using proximity sensors installed in the mid-boom segment (figure 3).
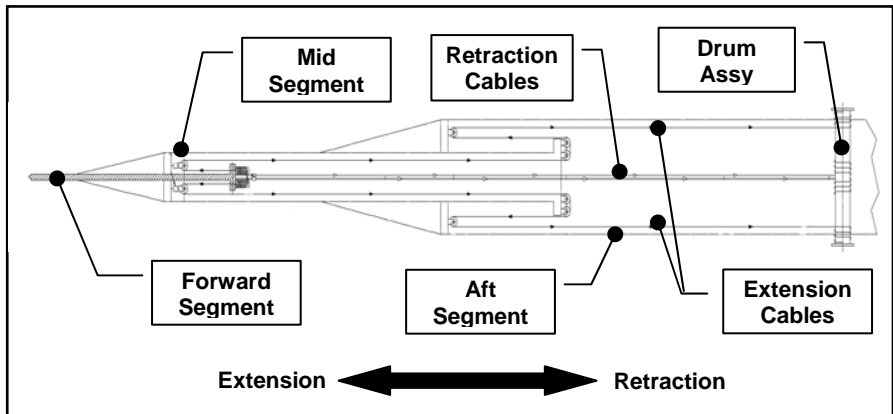
Figure 3. Quiet Spike extension and retraction system schematic.

Instrumentation

Instrumentation on the spike consisted of a multitude of transducers, including strain gages, accelerometers, thermocouples, load cells, pressure transducers, and string potentiometers. The strain gages were used to measure vertical and lateral bending moments in the tubes and were calibrated prior to flight test by hanging dead weight at prescribed locations. In addition, load cells were utilized for extension and retraction cable loads, string potentiometers for segment stroke, and current sensors for servo loading. All of these parameters were available for real-time monitoring via telemetry.

Analysis and Simulation of the Modified Aircraft

In preparation for the flight test of the F-15B with the Quiet Spike nose boom, limited aerodynamic modeling was accomplished to estimate the effects of the spike on aircraft stability. Several modeling techniques, including creating models from empirical data and Computational Fluid Dynamics (CFD) analysis, were used and predictions of the effects of the spike were generated. These predictions indicated that the spike would reduce lateral-directional stability between 3 to 5 percent in the subsonic flight regime and between 3 and 24 percent in supersonic flight. A marginal reduction in pitch stability of between 0 and 5 percent was predicted for the entire flight envelope. The reduced lateral-directional stability at supersonic flight conditions was of major concern entering into the flight test portion of the program.

Stability and Control Analysis

The NASA DFRC simulation facility, relied upon for stability and control analysis, is a fixed-base, real-time, six degree-of-freedom pilot-in-the-loop simulation with standard stick and rudder pedal controls for the pilot, HUD and cockpit pilot flight instruments, and external real-time visual imagery.

Three independently developed aerodynamic models of the spike were implemented into the simulation to support stability and control analysis. Two of the models used Euler CFD methods. The third used an Aerodynamic Vortex Lattice modeling method for a subsonic model and flat plate theory and empirical cone-cylinder drag data for a supersonic model. All models predicted some level of reduced static stability for the aircraft because of the spike, becoming more pronounced in the higher supersonic Mach regime.

The primary objective was to assess aircraft stability and handling qualities throughout the subsonic, transonic, and supersonic flight regimes. There were three main issues: 1) The impact of Quiet Spike on the stability and handling qualities of the F-15B aircraft; 2) The effect of the Quiet Spike on air data and angle-of-attack sensors used by the aircraft flight and engine control systems; and 3) Unfavorable effects caused by the spike during aircraft emergencies, specifically with respect to Control Augmentation System (CAS) or engine failures. Reference 5 addresses in detail the analysis approach.

To address the aerodynamic uncertainty issues, a series of aerodynamic stress cases were defined and analyzed in simulation for several different configurations and flight conditions. The stress cases varied aerodynamic uncertainties in worst case directions in an attempt to excite a dynamic response that would reveal the maximum tolerable model uncertainties. Stability, handling qualities, and maneuver limit metrics were applied to the simulation data to evaluate the stress cases. Critical or potentially undesirable dynamics were identified for piloted simulation evaluations using both the DFRC simulator and the Boeing Company F-15C simulation facility in St. Louis, Missouri.

As a result of the stress analysis and pilot-in-the-loop simulation, regions of acceptable aerodynamic variations for key aerodynamic parameters were defined. Not only did these regions provide a measure of the robustness of the F-15B Quiet Spike configuration, but also a means for flight test clearance. As long as parameter estimation results from flight

test data and the trends that were projected from that data to new flight test clearance points stayed within the region of acceptable variation, those test points were cleared for testing. Key parameters to monitor during flight test were anticipated to be the longitudinal and directional static stability derivatives, C_{m_α} and C_{n_β}, and the pitch and yaw damping derivatives, C_{m_q} and C_{n_r}. Of chief concern was C_{n_β}, especially at the high Mach regime where stability is typically reduced. Because of the very light directional damping at high speeds observed in some of the stress cases with the CAS off, a procedure was implemented to decelerate wings level with minimal maneuvering in the event of a CAS failure.

Results of analysis and simulation with the spike retracted and extended indicated that the retracted spike had about the same or less influence than the extended spike.

Test Aircraft Description

The test aircraft was a production representative F-15B, USAF S/N 74-0141. The aircraft was equipped with production F-100-PW-100 engines. The aircraft radar, gun, ammunition drum and feed system were removed. The ammunition drum was replaced by a NASA instrumentation pallet. Several drag reduction modifications were implemented to improve aircraft performance, including turkey feathers on the engine nozzles, removal of missile launchers and replacement with blank plates, retention of the tail hook shroud, enamel paint, and covering the gun port. The aircraft was modified with an instrumentation system to record flight parameters, GPS data, primary control surface positions (except the left aileron position), pilot stick and rudder pedal control inputs, production angle-of-attack, and pitot-static parameters (altitude, airspeed, and Mach number).

For the baseline data flights, the aircraft was equipped with a YAPS (yaw, angle of attack, pitot static) flight test nose boom to record airspeed, altitude, angle of attack, and sideslip for the instrumentation system. Additionally, in anticipation of the removal of the YAPS nose boom for the Quiet Spike modification, a sideslip vane was added to the underside of the nose just aft of the radome. A fairing was added to the sideslip vane installation to minimize the effects of Mach shocks on the vane. The cockpit gauges were production representative, with the addition of an

instrumentation control panel and a sideslip indicator driven by the added sideslip vane.

For the Quiet Spike flights the YAPS nose boom was removed and the Quiet Spike was installed on the radar bulkhead. A composite nose cone provided aerodynamic fairing of the Quiet Spike installation to the aircraft fuselage. Additional instrumentation was added to monitor loads associated with the Quiet Spike mounts to the aircraft bulkhead. A control panel was added to the rear cockpit to allow extension and retraction of the Quiet Spike. Figure 4 shows the test aircraft in the Quiet Spike configuration.

Figure 4. NASA F-15B modified with Gulfstream Aerospace Quiet Spike[TM] (shown in the fully extended position).

Quiet Spike Test Article Description

The Quiet Spike, shown in figure 5, is a thirty-foot-long, three segment (two of which translated), telescopic nose boom designed to attach to the radar bulkhead of the F-15B aircraft. The first segment is a translating 4 inch diameter tube with a conical aluminum air data head at the tip. The first segment retracted into the second segment, a 10 inch diameter tube, which also translated. The second segment retracted into the third segment. The third segment was a non-translating tube and is 16 inches in diameter. Both the second and third segments have conical composite fairings at the front to allow a smooth fairing shape when retracted. These conical shapes are the weak shock generating components. When fully extended, the spike represents approximately one-third of the length of the vehicle.

A flight test engineer in the aft cockpit initiated the Quiet Spike extension and retraction operations through a control panel, as shown in figure 6. In addition to system status feedback available in the aft cockpit, the engineers in the Mission Control Center had instrumentation information available to assess the operation of the Quiet Spike mechanisms.

Quiet Spike Integration to the Aircraft

Quiet Spike installation began on April 6, 2006 and spanned the next two months. Attachment to the F-15B was accomplished with a slotted pin joint at the aft end of the spike and was supported by four fixed struts, as shown in figure 7. Finally, a composite nose cone fairing closed out the aerodynamic shape from the maximum diameter of the spike to the F-15B fuselage mold line. The Quiet Spike needed to be aligned with the aircraft axes within provided tolerances, have an attach lug centered within a clevis slot to adequately allow for thermal loads and spike expansion and retraction, and have balanced loads among the defined load paths, all within tolerances.
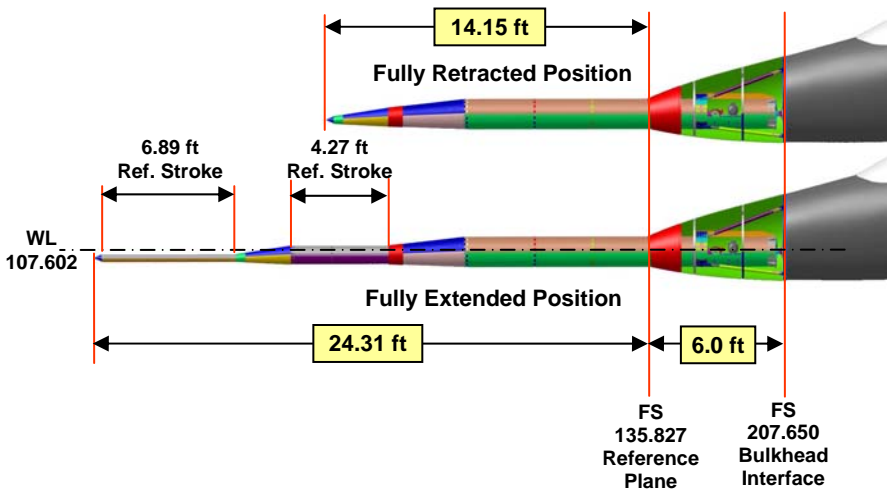

Figure 5. Quiet Spike geometry.

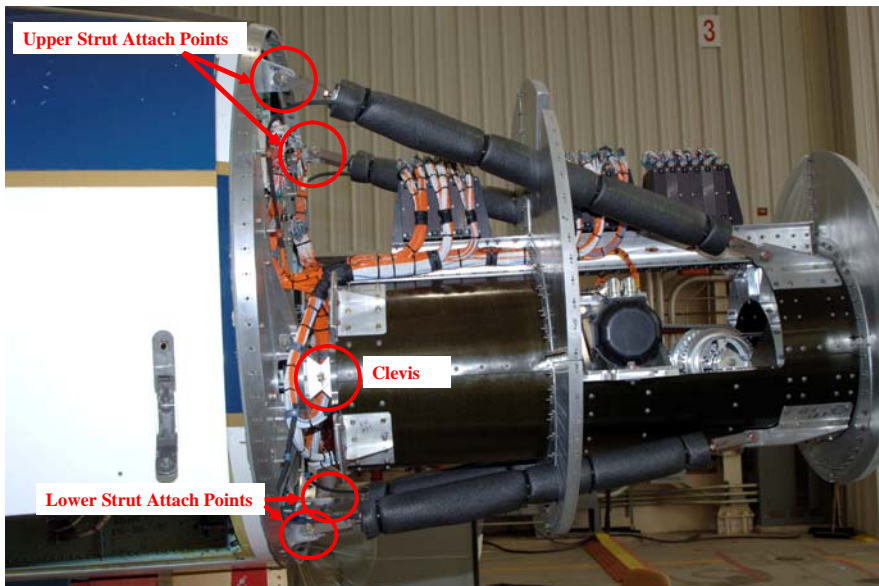Figure 6. Quiet Spike control panel in the rear cockpit.

Figure 7. Five Quiet Spike attachment points to the aircraft radar bulkhead.

Installation was a challenging iterative process. The strut loads and tip alignment adjustments impacted one another. This provided a total of 10 parameters (four retracted strut loads, tip location retracted, four extended strut loads, and tip location extended), each affecting the others. Since the geometry of the Quiet Spike and the installation system did not allow an alignment of all 10 parameters simultaneously, a procedure was developed to install the Quiet Spike within acceptable tolerances.

Ground Testing

Ground testing was performed on the aircraft to calibrate internal structural load instrumentation of the Quiet Spike and the strut mounts to the aircraft radar bulkhead. Testing also evaluated structural mode interaction (SMI) with the aircraft analog flight control system. Additionally, maximum aerodynamic drag loads were measured for inflight extension and retraction of the Quiet Spike at design conditions. Ground vibration tests (GVT) were used to obtain Quiet Spike structural mode frequency data. Electrostatic discharge tests were also conducted. These ground tests not only evaluated the structural instrumentation, mechanical function, and predicted dynamic response of carrying the Quiet Spike on the aircraft, but also provided valuable data in preparation for Quiet Spike research flights.

Panel Flutter

Panel flutter, unlike classical flutter, is a self-limiting amplitude aeroelastic instability and usually occurs only at transonic or supersonic airspeeds. Generally it does not lead to immediate structural failure, but over time can result in failure of various skin panels from fatigue or delamination. For the Quiet Spike program, a specially designed nose cone, as shown in figure 8, of composite materials was provided by Gulfstream to accommodate the spike installation on the F-15B. The nose cone panels retained the same shape as the original F-15B radome but were of a completely different structural design. In addition, these new panels also carried in-plane compressive loads to help support the Quiet Spike. Compressive loads are known to reduce panel flutter airspeeds. A nose cone failure could have conceivably led to a Quiet Spike failure and perhaps loss of the aircraft.
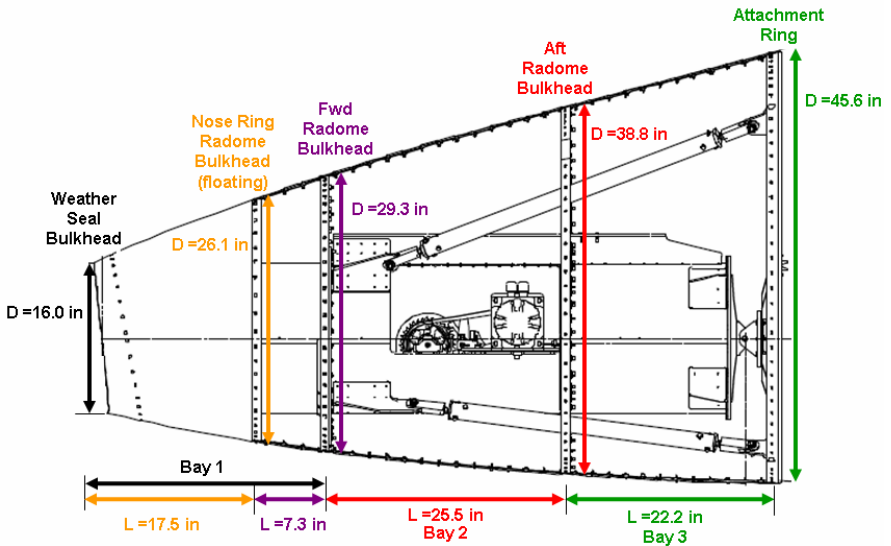
Figure 8. Quiet Spike nose cone dimensions.

With these considerations in mind, tap test comparisons with other F-15B radomes (composite production and metal flight test) were made. It was observed that panels on the Quiet Spike nose cone had much lower natural frequencies and lower structural damping than the other F-15B radomes. Application of panel flutter criteria for flat plates from reference 6 indicated that bays 2 and 3 of the nose cone were potentially susceptible to panel flutter and that bay 1 was marginal for panel flutter. When this panel flutter issue became apparent, Gulfstream engineers modified the nose cone panels by adding flex-core and laminate material inside bays 2 and 3 to build up the effective skin thickness. Also, longitudinal stiffeners were added to the nose ring area of bay 1 to improve the panel length-to-width ratio. These modifications are shown in figure 9.

The modifications were successful in shifting the analysis results for all nose cone bays outside of the panel flutter boundary, as shown in figure 10. Application of the same panel flutter criteria to the nose cone access panels (dark areas in figure 9, left picture) indicated that they were well outside of the danger area and needed no modification. Application of panel flutter criteria for cylinders (reference 7) showed that the combination of material stiffness, length-to-width ratio, skin thickness and

curvature for all three segments of the Quiet Spike skins were sufficient to prevent panel flutter without any modification.

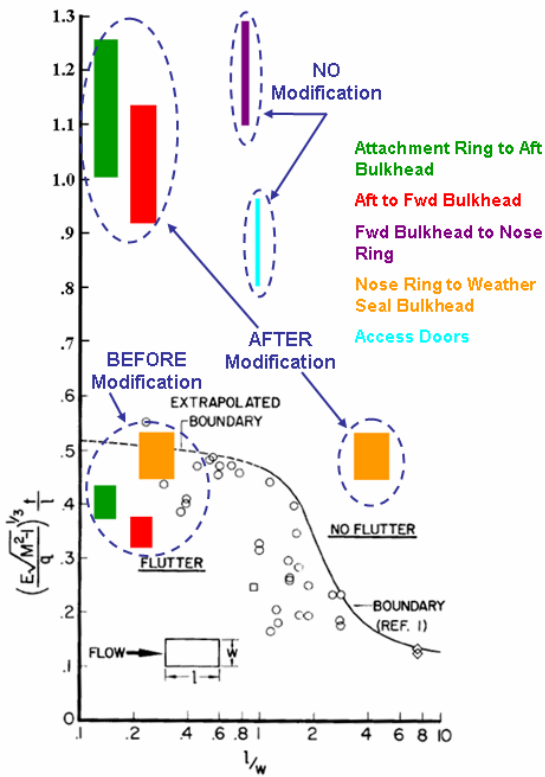Figure 9. Quiet Spike nose cone modifications.

Figure 10. Panel flutter results.

The Quiet Spike flight test program was subsequently flown without a single instance of panel flutter occurring. As it can not be proved that panel flutter would have occurred on the nose cone panels if left unmodified, it is believed that the early attention devoted to this concern allowed a quick fix to be implemented at minimal cost, likely averting this potential trouble or a lengthy delay later during the supersonic phase of the flight testing.

Structural Mode Interaction and Aeroservoelasticity

As a result of the major Quiet Spike modification to the baseline F-15B structure, structural mode interaction (SMI) ground tests were performed on the baseline F-15B and Quiet Spike configurations before flight tests. Unsatisfactory ground SMI test results raised some concern about aeroservoelastic (ASE) stability margins in flight on the Quiet Spike aircraft.

A series of SMI tests were performed to demonstrate a minimum 6db (decibels) of gain stabilization (gain margin without phase crossover) by increasing gain in aircraft control system feedback loops up to 8db. Gains were applied to the aircraft feedback sensor paths in roll rate, pitch rate, yaw rate, normal acceleration, and lateral acceleration in unison (and individually if necessary for individual loop diagnosis). A sinusoidal frequency sweep generator was used as excitation in the feedback paths for open-loop configurations, and pilot stick or pedal raps were used for closed-loop excitation. The aircraft was tested in high fuel remaining (greater than 11,000 pounds) and low fuel remaining (approximately 2000 pounds) conditions on soft tires. Tests involved simulated gear handle up or down at lower (approximately 7 degrees) and higher (approximately 16 degrees) angle-of-attack (AOA). The baseline F-15B did not meet the 6db gain margin minimum, but did have at least 3.5 db of gain margin for all configurations tested and exhibited no SMI inflight.

A series of SMI ground tests were performed on the F-15B Quiet Spike aircraft with the spike fully retracted, fully extended, and partially extended (approximately half way) configurations to measure gain stabilization by increasing gain in aircraft control system feedback loops up to 8db. Gains were also applied to the all the aircraft feedback sensor paths. No lateral-directional anomalies were noted and the 8db stability margin was satisfied for all configurations. In the power approach configuration, no anomalies were noted in the longitudinal axis and the gain margin was at

least 8dB for all spike configurations. However, in the cruise configuration, a very lightly damped pitch oscillation that could manifest itself as a limit cycle oscillation (LCO) (no damping) of the stabilator occurred in the 10 to 13 hertz frequency range with the Quiet Spike fully retracted.

In the cruise configuration with the normal load factor feedback loop present, the critical modal frequencies for the wing-spike-stabilator bending modes were at 10 to 15 hertz and for the fuselage vertical bending modes were at 8 to 10 hertz. Testing showed LCO susceptibility at 16 degrees AOA and very low gain margins at 7 degrees AOA. As a result of these tests, it was decided to clear the aircraft flight test envelope with the Quiet Spike fully extended and limit the AOA to less than 12 degrees with the gear-up. If an LCO occurred in flight the pilot would turn the pitch CAS off and the flight would be aborted.

Extension and Retraction Mechanism Testing

A simulated drag loads test was the first integrated functional test of the direct drive system. This ground test sought to obtain baseline electric servo motor performance data under no load conditions to verify margin available to move the spike under air drag loads, and to verify the drive mechanism and motor performance under simulated air lift and drag loads expected in flight test.

Lift and drag predictions were accomplished both by NASA and Gulfstream through empirical methods, linear analysis, and CFD. The resulting predictions varied between the three methods and thus required the project team to carry high uncertainty values into this ground test. A few test conditions showed predictions of lift in the downward direction, and were used in the drag load testing for conservatism.

All drag loads were applied horizontally aft and all lift loads were applied in the down direction to correspond with aerodynamic predictions. Each servo motor had an electric current limit of 10 amps set as a protection against possible structural damage in the event of a system jam. When this amp limit was reached, a fault was indicated on the spike control panel located in the aft cockpit and power was automatically removed from the motor until a reset could be performed in-flight by the flight test engineer. During the ground test, the left and right motors reached their preset amp limit prior to full spike extension at axial forces of approximately 30-40 pounds (left) and 50 pounds (right). These results provided confidence that all of the extension and retraction test points in the subsonic envelope

would be within the servo motor current limitations. However, the wide uncertainty in aerodynamic predictions indicated that the Quiet Spike system might not be able to overcome drag loads during extension at supersonic flight conditions.

Taxi Tests

Taxi tests were conducted prior to flight to evaluate aircraft bulkhead and Quiet Spike structural loads and dynamics during turns, aircraft accelerations during takeoff (to 100 knots), and aircraft decelerations during landings and during departure end barrier crossing. Tests were conducted with both the Quiet Spike fully retracted and fully extended, and during an extension and retraction cycle while taxiing. These tests cleared the aircraft for taxi speeds up to 30 KGS (knots ground speed) for turns and barrier crossing and for takeoffs and landings. It was noted that structural loads decreased as barrier crossing speed increased. Structural dynamics were measured on the runway by taxiing at a speed that allowed runway concrete junctions to excite the resonant frequency of the Quiet Spike. These tests also allowed a check of aircraft instrumentation. All tests were successfully accomplished and the aircraft was cleared for flight.

Flight Test Plan and Hazard Analysis

Initially, the flight test plan required clearing the aircraft with the Quiet Spike retracted, and then clearing the aircraft with it extended. Extension and retraction points in flight would be accomplished last at selected flight conditions representative of foreseen operational requirements. Much debate occurred about the proper sequence of test point accomplishment. Structural dynamics engineers wanted to start at the highest altitude and slowest speed to build up in dynamic pressure. However, aircraft performance limitations and handling qualities clearance requirements dictated a build up from takeoff to an adequate climb profile to achieve the desired flight conditions. Competing discipline objectives were eventually coalesced into an achievable test point sequence. Figure 11 presents the final sequence of test points adopted for the Quiet Spike envelope clearance.

Because of the concerns raised by the SMI ground tests, the flight testing sequence was changed to fly the spike extended configuration first despite concerns about directional stability at the higher Mach number test

conditions. The spike retracted configuration would only be tested if required for certain objectives and if the project schedule permitted.

Flight clearance maneuvers for a typical flight condition included the maneuvers listed in table 2.

Hazard Analysis

The Quiet Spike was a major modification to the outer mold line of the forward fuselage of the F-15B, essentially increasing the length of the aircraft by a third when fully extended. The extent of the modification combined with the objective to fly at supersonic speeds to Mach 1.8 posed significant hazard concerns and required a systematic approach to understanding, defining, and mitigating the hazards to an acceptable risk level.
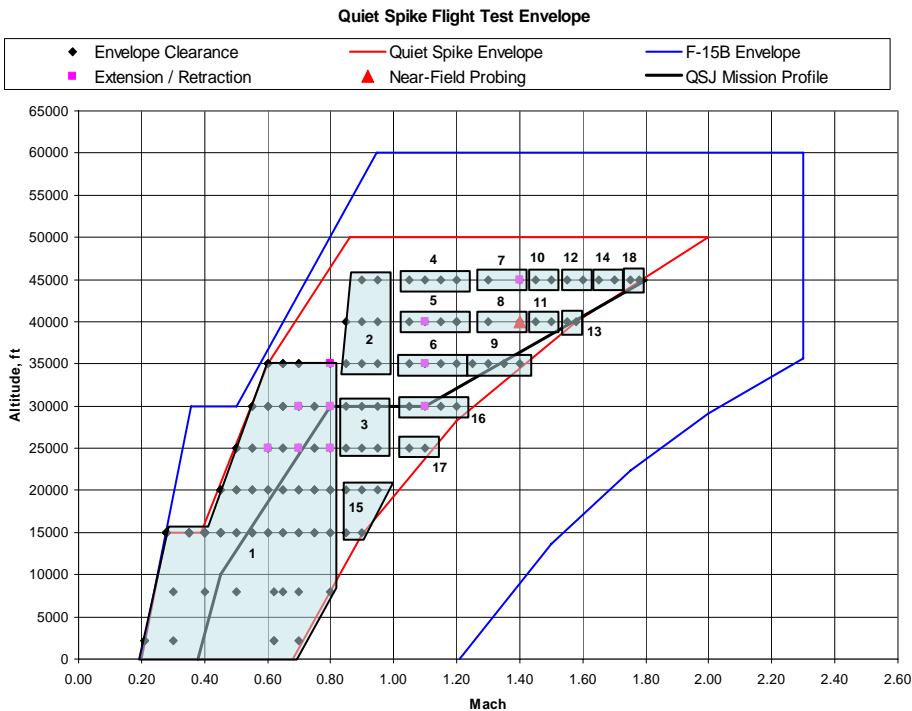

Figure 11. Flight test plan sequence of test points.

Table 2. Flight Test Maneuvers	
Purpose	**Maneuver**
• Structural Dynamics • Structural Mode Interaction	• Pitch and roll raps (control stick) • Yaw raps (rudder pedals)
• Structural Static Loads	• Steady wings level sideslip • Push-over (0.2g), Pull-up (2.0g) • Wind-up turn (2.0g or 3.0g)
• Stability and Control • Flying Qualities • Parameter Identification	• Pitch and roll doublets (3 sizes) • Yaw doublets (3 sizes) • Yaw-roll doublets (3 sizes) • Wings level sideslip sweeps
• Air Data Calibration	• Push-over (0.2g), Pull-up (2.0g) • Constant altitude accelerations and decelerations • Wings level sideslip sweeps • Tower fly-bys

A system safety working group was tasked with identifying potential hazards. The group was lead by an independent system safety engineer and included all the project and discipline leads from NASA and Gulfstream. The standard NASA DFRC hazard analysis process was followed to generate hazards and determine hazard severity and probability for risk assessment.

Significant hazards included: 1) Reduced aeroservoelastic (ASE) stability margins during flight which could cause loss of control of the aircraft; 2) Structural damage or breakup of the Quiet Spike; 3) Excessive structural loads on spike and interface hardware; 4) Structural failure of aircraft radar support bulkhead and forward fuselage; 5) Classical flutter of the Quiet Spike; 6) Loss of stability and control and degraded handling qualities; and 7) Nose gear shimmy during takeoff or landing which could cause excessive structural loads. All hazards identified were well mitigated. Both FAA and NASA standards were used in the design and buildup of the spike. Dynamic and static structural analyses were accomplished. SMI ground testing and ground vibration tests (GVT) were completed. The spike mechanism was tested before flight. Simulation was used to predict aircraft flying qualities. Spike loads during taxi testing were measured. Pre and post flight inspections confirmed spike alignment and integrity. A methodical flight envelope expansion approach provided time for flight

data analysis and formal review before proceeding to the next series of flight test points.

Flight Operations

Test Limitations and Modified Procedures

One method to mitigate the hazards associated with the Quiet Spike experiment and reduce the number of flight test conditions to meet project objectives was to restrict the flight envelope of the aircraft. The aircraft angle-of-attack was restricted to 21 units (approximately 10.5 degrees) for the clean configuration and 23 units (approximately 12 degrees) for the landing configuration. The normal load factor for the aircraft was limited between 0 and 3. The maximum dynamic pressure was limited to 685 pounds per square foot, and the maximum Mach number was limited to 1.8. Additionally, the maximum sink rate for landing was restricted to 5 feet per second (300 feet per minute).

Initially, because of the structural mode interaction ground test results, the aircraft was required to fly with the pitch CAS off whenever the aircraft was in the cruise configuration with the Quiet Spike retracted. Modified takeoff procedures were developed to accomplish takeoff with the pitch CAS on, to turn the pitch CAS off after takeoff, retract the landing gear, and then to fly to the spike extended flight condition of 225 KIAS at 15K feet. Once the spike was extended, the pitch CAS was turned on for flight until preparing for landing. A reverse process was adopted to configure the aircraft for landing. At one point it was suggested that the entire test project be flown with the pitch CAS off, but this was rejected because of poor handling qualities concerns, especially in the supersonic flight regime. The pitch CAS restrictions were removed towards the end of the project when SMI test points were accomplished and no SMI occurred.

Several Quiet Spike unique normal and emergency procedures were developed to address normal spike extension and retraction and various anomalies, spike system problems, structural mode interaction, excessive structural loads caused by maneuvering or turbulence, nose wheel shimmy, and CAS failure. Additionally, two F-15 emergency procedures were revised to account for the Quiet Spike modification during engine problems on takeoff, and landing with the nose gear retracted.

Control Room and Cockpit Operations

The NASA DFRC Mission Control Center (MCC) was configured to provide monitoring of static structural loads, structural dynamics and flutter, Quiet Spike system status, aircraft flying qualities, aircraft stability and control, instrumentation status, and mission control. Routine mission control was augmented by the ability of discipline engineers with access to critical test parameters to provide abort radio calls directly to the aircraft. The control room integrated Gulfstream Aerospace project engineers with the NASA DFRC test team.

The control room monitored approximately 40 safety of flight and approximately 140 mission critical parameters. Engineers in the MCC evaluated the maneuvers in real time for data quality and test point clearance.

The F-15 and chase pilots could accurately determine the position of the Quiet Spike, from fully retracted to fully extended, using paint markings on the top and sides of the Quiet Spike. All test maneuvers were flown in either the R2508 complex (typically within R2515) or within the extended high altitude supersonic corridor with coordination between Los Angeles Center and the Edwards AFB SPORT control.

Quiet Spike Flight Test Results

Overview

The F-15B flew 38 flights during the Quiet Spike test program — 6 baseline aircraft flights and 32 flights in the Quiet Spike configuration. In the Quiet Spike configuration, the first flight was flown on August 10, 2006, with the Quiet Spike retracted and the F-15B landing gear extended for the duration. In order to accelerate the schedule and get the Quiet Spike airborne, a minimal set of monitored parameters were functional. Parameters that monitored extension and retraction of the mechanism were not functional.

Envelope expansion, utilizing a risk reduction build-up methodology, commenced on the second flight of Quiet Spike. Subsonic flight envelope expansion was completed on October 3, 2006, for the Quiet Spike in the extended position. Envelope expansion included numerous maneuvers (table 2) to assess aerodynamics, stability and control, flutter, aeroservoelastic effects, and structural loads.

Quiet Spike entered the supersonic flight regime on October 20, 2006. For 45,000 foot test conditions, all supersonic runs started at 40,000 feet with afterburner initiation at 0.9 Mach or faster, acceleration to supersonic conditions, and a climb to 45,000 feet, not to exceed the cleared Mach or dynamic pressure envelope. This test technique was utilized to avoid any potential engine anomalies associated with F-100-PW-100 afterburner initiation. No engine anomalies were encountered in this project.

Once the envelope was cleared through 1.4 Mach and 40,000 feet, a flight to investigate the near-field shock signature of Quiet Spike was performed. Another NASA DFRC test asset, NF-15B NASA 837, was configured with pressure sensing equipment to probe the shock waves created by F-15B NASA 836 with Quiet Spike installed. The probing maneuvers, with NASA 836 and NASA 837 in formation, were performed on December 13, 2006.

On January 19, 2007, the spike-extended envelope clearance was completed for flight to 1.8 Mach. Directly following spike-extended envelope clearance completion, the test team evaluated the static and dynamic structural envelope to 1.4 Mach with the Quiet Spike in the retracted position.

During the envelope expansion research test flights, the Quiet Spike was extended and retracted at flight conditions of 5,000 to 15,000 feet altitude at approximately 225 KIAS. Following both the extended and retracted envelope clearance to 1.4 Mach, the Quiet Spike transition capabilities were demonstrated with the aircraft at airspeeds to 1.4 Mach.

Baseline Aircraft Testing

Prior to flying the F-15B with the Quiet Spike installed, a series of flights were flown with the aircraft in its standard clean configuration with the YAPS test boom. The purpose of these flights was to provide baseline data for comparison to flight data with the Quiet Spike attached. In addition, these flights were used to calibrate the production air data sensors (pitot-static system and angle-of-attack (alpha) cones) and the new fuselage mounted sideslip angle (beta) vane.

These flights produced a wealth of aerodynamic modeling data, including estimates for control effectiveness, damping and aircraft stability derivatives. Aerodynamic updates were implemented as increments to the baseline aerodynamic model in the simulation, and were included in all

stability and control analysis. For a more detailed description of the aircraft baseline aerodynamic model and the updates see reference 8. Calibration correction curves were created for the production pitot static system, the production alpha cone and the fuselage beta vane. The fuselage beta vane indications were significantly in error as far as absolute value when compared to the YAPS values. Cockpit beta indications on the sideslip angle gauge were estimated to be about twice the actual sideslip angle on the aircraft.

Air Data Calibrations

Due to concerns of air data errors associated with the Quiet Spike, a comprehensive plan for checking air data was created. During initial flight envelope expansion tests, each subsonic test condition was verified by comparing test aircraft HUD indications with chase aircraft airspeed, Mach number, and altimeter readings. Additionally, as the cleared flight envelope allowed, additional pitot-static system tests included tower flyby and constant-altitude accelerations and decelerations. When progressing to supersonic test conditions, the chase aircraft was not available for comparison because of performance differences, and calibrations were accomplished during the incremental envelope expansion using level acceleration and deceleration data. A differential GPS system was used in conjunction with the production pitot static system to create correction curves. These curves were then compared with the curves generated from the baseline flights.

Angle-of-attack and angle-of-sideslip measurements were checked similarly. For angle-of-attack calibrations, POPU (push over, pull up) maneuvers were performed. Angle-of-sideslip calibrations were performed using a wings-level beta sweep maneuver in which the aircraft maintains a wings level attitude using the ailerons while constantly varying sideslip angle from a positive to a negative value using the rudder. These maneuvers were analyzed and calibration curves were created using wind data, data from GPS (Global Positioning System), and INS (Inertial Navigation System) instrumentation.

Despite initial concerns, no significant effects on the air data parameters (pitot static, alpha or beta) were noted during subsonic flight. However, in the supersonic flight regime, the spike noticeably impacted all air data systems. Airspeed errors caused by the spike were on the order of 2 percent at certain Mach numbers. Errors in the production alpha cone were on the order of 1 to 2 degrees because of the spike. Changes in the

calibration curve for the recently installed beta vane were as large as approximately 1 degree.

Stability and Control

Stability and control derivatives of the F-15 with the Quiet Spike were estimated from flight data using piloted doublets and standard parameter estimation techniques (reference 8). During envelope expansion, parameter estimation results were used to check trends, validate simulation studies, and to provide clearance to higher Mach number test points.

Overall, the parameter estimation results were good. Comparisons with baseline data showed that the presence of the spike had little effect on most of the derivatives. In most cases, the differences between the two configurations were within the perceived accuracy of the results. Two of the derivatives expected to change noticeably, the static stability derivatives C_{m_α} and C_{n_β} , were found to change very little.

The pitch damping, C_{m_q} , and yaw damping, C_{n_r} , derivatives changed the most because of the presence of the spike. While pitch damping was always reduced, no discernable trend was demonstrated. The spike had little effect at low subsonic conditions, with the largest change being roughly 25 percent. In the transonic regime, a reduction in damping of slightly over 45 percent was seen, which diminished to roughly 5 percent near Mach 1.6. In general, yaw damping was reduced by 40 to 50 percent in the subsonic region, and 20 to 30 percent in the supersonic region.

The damping derivatives, C_{n_r} and C_{m_q} , were reduced in stability to levels near or slightly beyond the variation evaluated in the simulation analysis. These levels of reduced damping were determined to be acceptable and the subsonic envelope was quickly and efficiently cleared for stability and control concerns.

Two points during the Mach number expansion of the transonic and supersonic flight regimes required more detailed analysis. Figure 12 shows flight test estimated C_{m_q} compared to its region of acceptable variations determined from simulation analysis. The trend projected from 1.2 Mach to 1.4 Mach, which was the next step in upcoming expansion

flights, indicated that variation of C_{m_q} would significantly exceed the acceptable region. Although the projected trend was not considered likely, the simulation was updated for the projected C_{m_q} at 1.4 Mach. Stability margins of the updated simulation were recalculated and shown to be acceptable.

Piloted simulation at this flight condition (1.4 Mach) indicated that in the worst case scenario of a CAS failure, the handling qualities were lightly damped and undesirable, but acceptable for the wings level deceleration task. Figure 13 shows a time history of the piloted evaluation, where the pilot initiates a turn, turns the CAS off and then begins the wings level deceleration. The clearance for the 1.4 Mach test point was conducted without delaying the flight schedule.
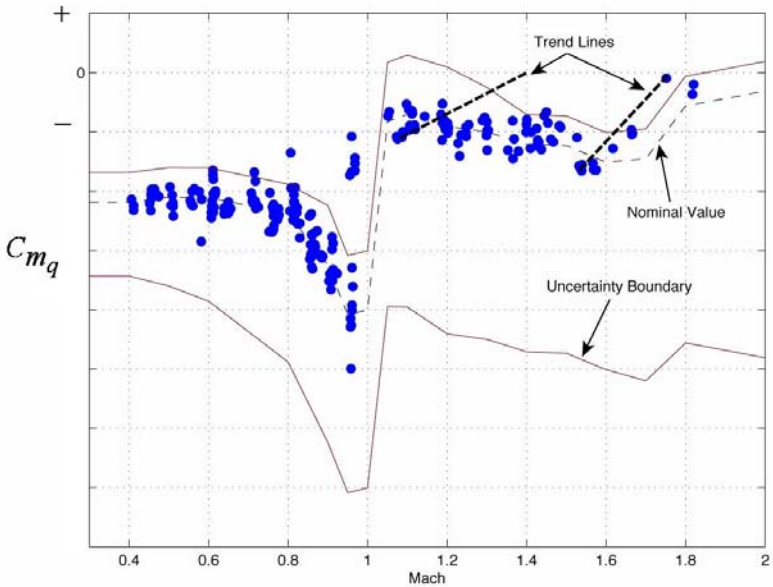

Figure 12. Flight estimated pitch damping derivative, C_{m_q}, with projected trend to 1.4 and 1.8 Mach.

Subsequent flight test data did not validate the projected trend. Instead C_{m_q} stayed relatively constant at the 1.2 value, and stayed within the region of acceptable variations until approximately 1.7 Mach. At Mach 1.7 a significant decrease in pitch damping occurred. The trend was projected to 1.8 Mach, as shown in figure 12, and the same analysis method was repeated as performed for 1.4 Mach. Piloted simulation at this condition again indicated undesirable but acceptable CAS off dynamics. The flight test point at 1.8 Mach was flown and, this time, C_{m_q} was shown to maintain the projected trend. Fortunately, the goal of the program was achieved at Mach 1.8. Little margin was left for expansion to higher Mach numbers because of the destabilizing trend in the pitch damping derivative, C_{m_q}.
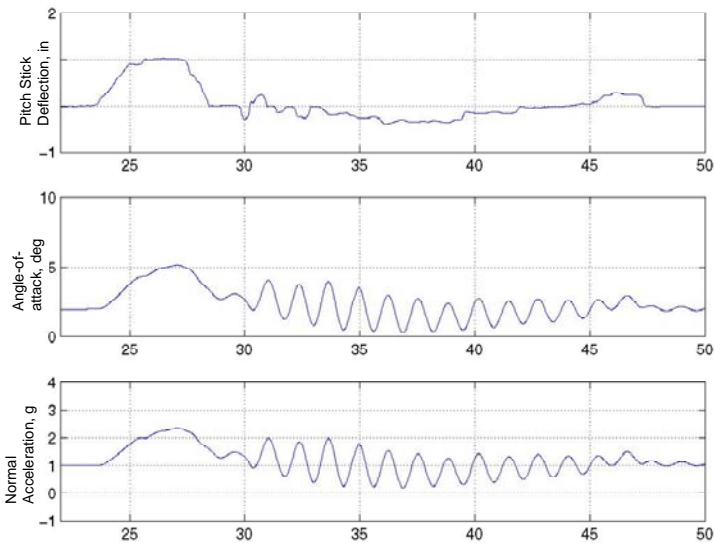

Figure 13. Time history of piloted simulation of CAS off dynamics at 1.4 Mach.

Interestingly, transonic and supersonic $C_{n\beta}$ stayed within its acceptable region. Figure 14 shows $C_{n\beta}$ variations from 0.8 Mach to 1.8 Mach. In the region from 1.2 to 1.3 Mach, $C_{n\beta}$ did show a more rapid destabilizing trend than the nominal F-15. Projecting the trend to 1.4 Mach indicated that $C_{n\beta}$ could reach the minimum level of stability evaluated in the simulation analysis. However, flight test parameter estimation showed the actual trend flattened out by 1.4 Mach, and actually became more stable than the nominal F-15 as Mach increased to 1.8.

The trend in $C_{n\beta}$ estimates did affect how fast the supersonic flight regime was expanded above Mach 1.3. The test plan anticipated Mach number steps of 0.1 in the transonic flight regime to Mach 1.2, and then Mach number steps of 0.2 out to Mach 1.8. However, as a result of the directional stability concerns and the flight data, a more conservative Mach number step size of 0.1 Mach was adopted for Mach numbers of 1.4 to 1.8, with data reduction and $C_{n\beta}$ trend analysis required before proceeding to the next higher Mach number. Details on flight test results can be found in reference 9.

Handling Qualities

Since handling qualities research was not an objective of the project, formal handling qualities evaluations were not conducted during the flight tests. However, brief pilot commentary was collected for typical piloting tasks, approach and landing, and air refueling. Handling qualities were evaluated using open-loop test techniques with the CAS both on and off in the subsonic regime and with the CAS on in the supersonic regime. Closed-loop formation flight was used to evaluate handling qualities for air refueling at representative air refueling conditions.

The flying qualities of the Quiet Spike modified test aircraft were essentially unchanged in the subsonic flight regime from the baseline aircraft. Pitch CAS off operations with the gear retracted were acceptable for the post takeoff climb to the Quiet Spike extension flight condition and reengagement of the pitch CAS. The directional stability of the aircraft at supersonic speeds was of concern from the beginning of the project, but was adequate for the required Quiet Spike testing. The aircraft directional

characteristics were uncomfortable during supersonic wings-level sideslip maneuvers, especially above Mach 1.4, because of the high sideforce experienced and the tendency of the aircraft to remain in a sideslip for several seconds after the rudder pedals were centered due to the presence of lateral acceleration feedback in the yaw CAS. Longitudinal handling qualities were acceptable at supersonic speeds despite a reduction in pitch damping, which was not apparent to the pilot.
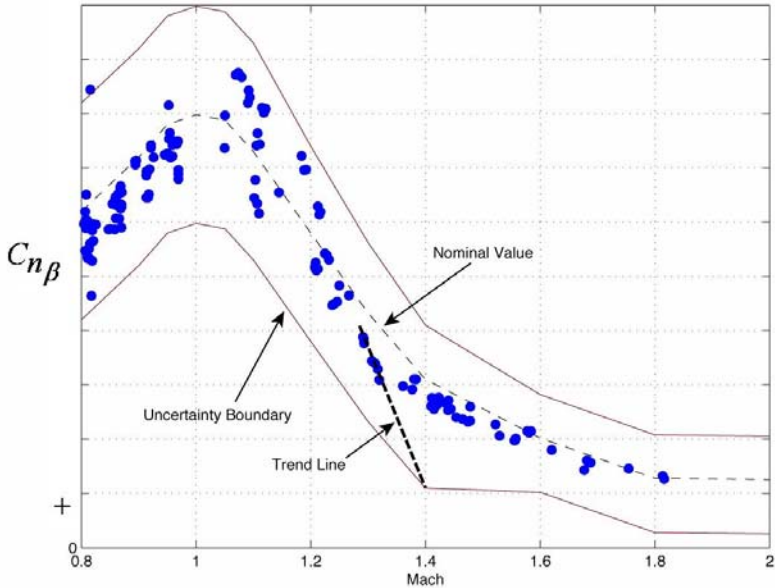

Figure 14. Flight estimated directional static stability derivative, C_{n_β} , from 0.8 Mach to 1.8 Mach.

Structural Loads

In order to monitor the loads on the Quiet Spike throughout the envelope clearance flights, the spike and the attachment structure were instrumented with 37 strain gages. The strain gages measured vertical and lateral bending moments in the spike tubes, were calibrated prior to flight testing and were available for real-time monitoring via telemetry. Numerous maneuvers including takeoff, stick raps, wind-up-turns, large

sideslip maneuvers, speedbrake induced buffet, turbulence and landings were performed to collect the structural response of the spike at different flight conditions. The spike was retracted for all takeoffs and most landings, with the exception of the planned spike extended landing test points, some accomplished during touch and go landings. During takeoff roll and landing roll the aircraft would often experience a nose wheel shimmy frequency near 23 hertz. This shimmy vibration induced spike loads up to 40 percent of Design Limit Load (DLL). Most landings were benign, with the peak loads at or below those loads observed during takeoff and landing rolls. At numerous flight conditions, wind-up-turns (WUTs) were performed and limited to 2g with the exception of the final phase of the program where several 3g WUTs were conducted. The loads developed during all WUTs were below 40 percent DLL with no loads abnormalities observed. The spike structural response was found to be benign during the high beta (steady sideslip) maneuvers which were collected up to 9 degrees beta for subsonic conditions and 1.5 degrees beta for supersonic conditions. Overall, the spike proved to be structurally sound in both the retracted and extended positions through the entire flight envelope.

Structural Dynamics

Both subsonic and supersonic linear flutter analyses were performed prior to flight testing and predicted that the F-15B with the Quiet Spike, both extended and retracted, would be stable throughout the desired flight envelope. Even so, formal flight flutter testing was performed throughout the envelope expansion process, especially with the spike extended. Pitch and roll stick raps as well as rudder kicks were used for structural excitation while Spike responses from numerous accelerometers along its length were monitored via telemetry in Mission Control. Damping estimates were extracted in near real time by the half-power method from power spectral density plots of the two spike tip accelerometer outputs (vertical and lateral) generated from extremely short data records. As expected, the spike's response was nearly always quite low damped but stable and typically ranged between 0.02g and 0.07g. However, at Mach 1.3 the response rose suddenly to 0.12g, then declined to 0.08g at Mach 1.4 and continued to decline further to less than 0.02g at Mach 1.5. This unexpected apparent trend indicated that the spike could flutter, possibly catastrophically, before the aircraft reached Mach 1.6. Reprocessing the recorded raw data post flight gave much the same results but with somewhat less scatter. However, since no physical explanation could be offered, these test points were repeated during the next flight. This time

much flatter damping trends were obtained with no indication of impending flutter. Subsequent flights successfully expanded the flight test envelope out to a final desired Mach number of 1.8 without incident.

Structural Mode Interaction

An ASE analysis was performed after the SMI tests, indicating a potential problem with stability margins in a gear-up configuration, especially with a retracted spike configuration. Flight test clearance was performed with the spike extended to clear the envelope before up-and-away retracted-spike flight. With the spike extended, the aeroelastic modes matched predictions in frequency and damping and the responses were fairly constant across flight condition. Aerostructural response in surfaces or feedbacks was not noted, and the extended spike configuration matched the baseline F-15B fairly well.

After the flight envelope was cleared with the boom extended, spike retracted, gear up, CAS on maneuvers were attempted. The procedure was to start at a minimum acceptable airspeed and altitude with the CAS on, and accelerate with raps at altitude. If an LCO occurred, the pitch CAS would be turned off and testing discontinued at the current altitude. Raps were performed from 0.3 to 0.6 Mach at 15,000 feet every 0.05 Mach, raps from 0.6 to 0.8 Mach at 30,000 feet in 0.05 Mach increments, and raps from 0.6 to 0.8 Mach at 15,000 feet every 0.05 Mach. These conditions were cleared with no problems. The spike retracted, CAS on subsonic envelope was cleared to 0.8 Mach, including a tower flyby, followed by supersonic clearance to 1.4 Mach at 40,000 feet altitude, also with no problems. While the normal load factor response of the aircraft increased with airspeed, the stabilator feedback response decreased due to gain scheduling in the flight control system, resulting in a reduced ASE response with dynamic pressure.

Aerial Refueling Clearance

The F-15B Quiet Spike aircraft was evaluated for handling qualities and aircraft separation distance during aerial refueling maneuvers with the AFFTC KC-135 tanker aircraft. This aerial refueling clearance permitted NASA increased flight efficiency by allowing multiple supersonic test points with minimal test flights. Representatives from AFFTC and NASA completed an initial ground assessment of the expected clearance and agreed to clear a limited aerial refueling envelope similar to that of the current NASA NF-15B aircraft. The F-15B was evaluated in the spike fully

extended configuration to not only demonstrate the worst case condition with the minimum calculated clearance distance between aircraft, but also because of SMI concerns.

This F-15B aerial refueling assessment was completed in two phases. The first phase was a handling qualities evaluation at the pre-contact position and 25 feet aft of the refueling boom. The F-15B aircraft was positioned in the contact uncoupled position and instructed to follow the refueling boom to points on the refueling envelope while evaluating the handling qualities at those various positions. The spike modified F-15B aircraft had similar handling qualities as the baseline aircraft. The F-15B was cleared to contact and stepped through various refueling envelope positions to determine separation clearances. A safety chase aircraft provided estimated clearances between the tip of the extended Quiet Spike and the KC-135 aircraft. The boom operator positioned the F-15B at the fully extended refueling boom length at 40 degree elevation (farthest point from the KC-135) to a middle boom length at 30 degree boom elevation (closest point to the KC-135 in the restricted envelope). These maneuvers were performed at an altitude of 20,000 feet (±200) and airspeed of 275 (±15) KCAS. One test point was completed at 25,000 feet (±200) to ensure that changes in altitude did not affect the aerial refueling operations.

The safety chase aircraft indicated approximately 20 to 25 feet of clearance between the tip of the fully extended Quiet Spike and the KC-135 aircraft at the lower points of the aerial refueling envelope. The chase aircraft reported approximately 10 to 12 feet of clearance when the F-15B was positioned at the 30 degree elevation and middle refueling boom extension (approximately 12 feet). The initial prediction was about 11 feet of clearance at 25 degrees of refueling boom elevation and 6 feet of refueling boom extension. Postflight analysis of photographs showed approximately 18 feet of clearance with the F-15 in the nominal contact position. NASA received a clearance letter with a restricted refueling envelope to conduct aerial refueling with the F-15B Quiet Spike fully extended. All air refueling for this project was conducted with the spike in the fully extended configuration.

Inflight Near-Field Shock Probing

The shock waves produced by the Quiet Spike in flight were predicted to coalesce with the much stronger shocks produced by the F-15B test aircraft at about 1000 feet from the aircraft. This meant that ground

measurements of the aircraft at flight test conditions would not yield data to confirm the shock profile of the test article. In fact, ground measurements were taken using a NASA developed microphone array. These tests confirmed that the shock profile measured at ground level was that of the baseline F-15 aircraft.

In order to verify the operation of the Quiet Spike in the design operational envelope, the NF-15B aircraft was modified with a sensitive pitot tube probe to measure inflight pressure variations at a high sample rate. This technique was previously used to measure inflight shock waves from the SR-71 using an F-16XL probing aircraft as well as the F-5 Shaped Sonic Boom Demonstrator aircraft using an F-15 probing aircraft (reference 4).

The near-field probing flight was accomplished on December 13, 2006. This flight involved five aircraft: The F-15B modified with the Quiet Spike, the NF-15B probing aircraft, an AFFTC KC-135 tanker, and two F-18 chase aircraft. The flight involved three air refueling operations for the two modified F-15 aircraft, each with a restricted air refueling envelope as compared to production F-15 aircraft. Additionally, a total of six supersonic runs to Mach 1.4 in the high altitude supersonic corridor in the Edwards AFB restricted area were conducted. Thirty-one successful data points were collected at separation distances of 100 to 700 feet between the two F-15 aircraft at various lateral locations, as shown in figure 15. Each F-15 was equipped with GPS instrumentation to aid in real-time relative positioning during test maneuvers. Test points were selected to maintain nose-to-tail clearance between the two aircraft at the forward shock of the lead F-15.

Near field probing pressure data confirmed the predicted operation of the Quiet Spike concept, as shown in figure 16. No effort was made to try to predict the pressure profile aft of the forward fuselage of the F-15, and the graph shows less agreement with predictions for the aft portions of the aircraft.
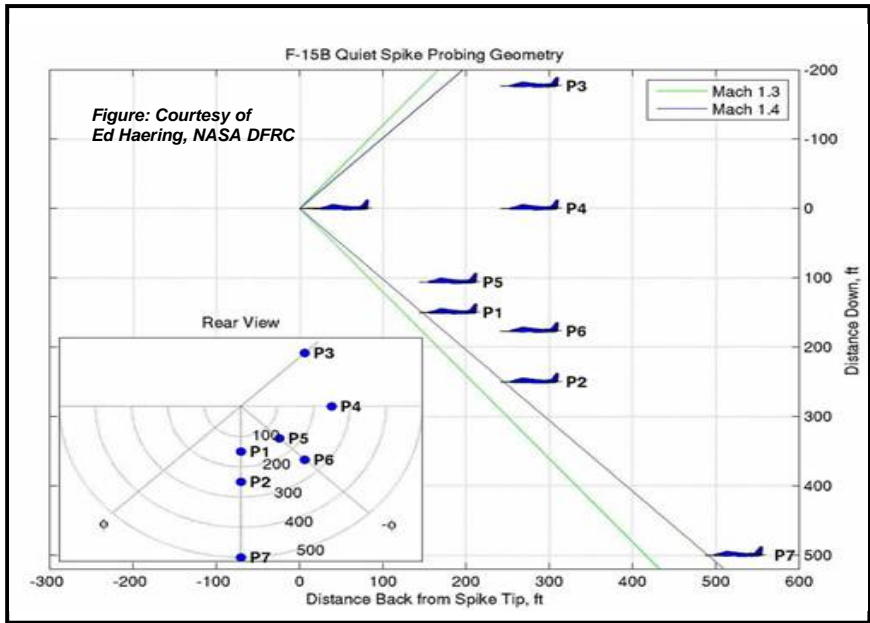
Figure 15. Near-field probing positions around the Quiet Spike equipped aircraft.

Inflight Extension and Retraction Tests

The extension and retraction system was designed to shut down whenever segment 2 (mid segment) reached its full extension or retraction position. This was accomplished with a modified thrust reverser proximity switch. Segment 2 relied on friction to allow segment 1 (forward segment) to come out first. Segment 1 and segment 2 were connected by cables. During certain aerodynamic conditions, the friction was reduced, allowing segment 2 to precede segment 1 extension, prematurely shutting off the system before full extension. By designing a proximity override switch, the rear cockpit operator could override the stop switch and fully extend the spike. Using input from either the pilot, the chase aircraft (using markings painted on the spike), or the control room with real-time instrumentation data, the rear cockpit operator would then stop the spike at actual full extension.

The drag loads testing showed that at certain supersonic test points the spike would not be able to extend because of aerodynamic loading. The

team decided to still attempt extension at these points to verify the ground test data, and the spike always extended, even at the conditions where it was predicted not to extend. The data is still being reviewed, but it appears that reduced friction and or unexpected internal pressurization of the spike contributed to the successful extension at all test points.
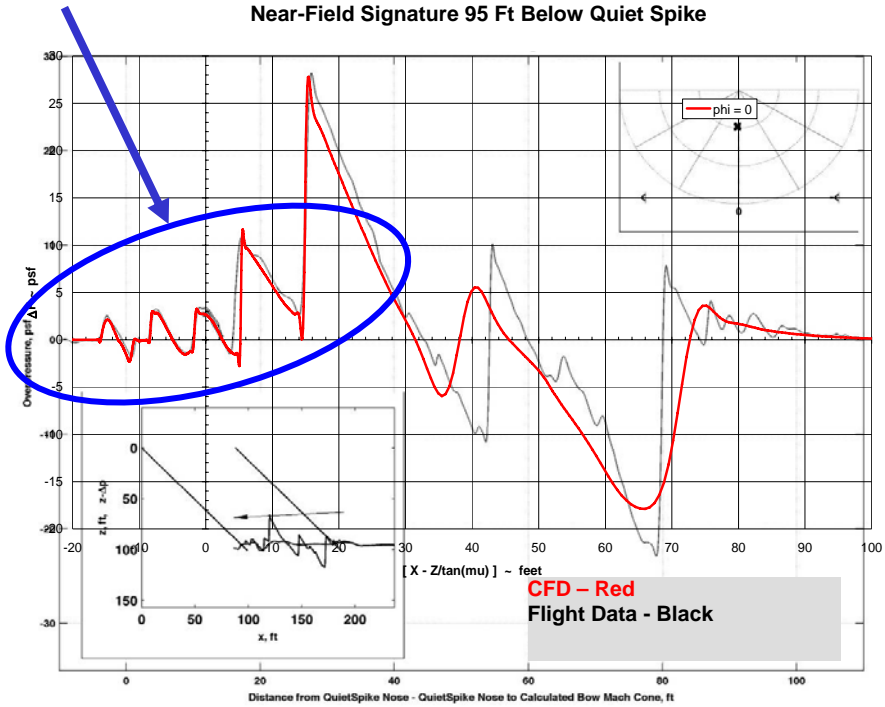

Figure 16. Comparison of CFD shock wave pressure predictions and inflight near-field probing data for Mach 1.4 at 40,000 feet.

Landing Tests

Prior to the start of flight testing, there was considerable concern about the structural loads that would be induced into the aircraft forward fuselage through the Quiet Spike attachments to the aircraft radome bulkhead. To minimize this concern, a maximum landing sink rate of 5 feet per second (300 feet per minimum) was established. Because the F-15B is easy to land, typical sink rates of less than one foot per second were routine. Also, all landings were initially restricted to the Quiet Spike retracted configuration with a premature derotation at 100 KCAS to allow the pilot to

smoothly lower the nose wheel to the runway well before losing longitudinal aerodynamic control power.

However, as experience was gained with the modified aircraft, a desire to look at higher structural loads during landings arose. The first tests involved landing the aircraft with the Quiet Spike retracted at a low sink rate followed by full aerobraking to nose wheel touchdown at about 75 KCAS. These were followed by minimum sink rate landings with the Quiet Spike extended, a premature derotation, and soft nose wheel touchdown. Subsequently, landings with the Quiet Spike retracted and fully extended were accomplished at a low sink rate followed by firm nose wheel touchdown at 100 KCAS and later by full aerobraking to nose wheel touchdown. Finally, higher sink rate touchdowns (between 3 and 5 feet per second) were accomplished with the Quiet Spike both retracted and fully extended, followed by normal aircraft aerobraking and normal wheel braking. While increased structural loads were observed as anticipated, all structural loads and dynamics remained well within established limits (approximately 40 percent of DLL) for both the Quiet Spike and aircraft.

Postflight Inspections

Throughout the test series, the Quiet Spike hardware and F-15B forward fuselage were routinely inspected for abnormalities. Very few anomalies plagued the project through the duration of the project. The most common was retraction cable slack. After the first flight, the right side cable was noted to be completely slack. Some system modifications and adjustments were made, yielding a small amount of positive tension. Throughout flight test, low amounts of negative cable tension sometimes were measured. Particular attention was given to this anomaly. A loose cable could damage critical flight parameters that would be difficult to repair. A flight technique that the team referred to as a "bump retract," usually fixed the low tension situation and provided feedback of positive tension within the system. The short retraction movement (approximately ½ inch of travel) of the Quiet Spike relieved some energy stored within a system spring and provided additional positive tension on the retraction cable.

Periodically throughout testing, laser measurements of the Quiet Spike tip were performed to ensure that the test article was still aligned with the F-15B fuselage axes to within allowed tolerance. These measurements were performed after significant events such as loads calibration ground tests, first taxi, first flight, supersonic flight, and at the conclusion of the

program.   No significant alignment deviations were noted during the project.

Ferry Flight to Savannah, Georgia

Gulfstream Aerospace requested that the Quiet Spike F-15 aircraft be ferried to Savannah, Georgia, for demodification at the plant. A one flight evaluation of the aircraft in the ferry configuration (centerline fuel tank and two travel pods on wing stations) was conducted at Edwards AFB to evaluate aircraft handling qualities and cruise performance at flight level 430 and 0.9 Mach. The aircraft was ferried to Savannah on February 13th and 14th, 2007, with an overnight stop at Kelly AFB, Texas. Upon arrival at Savannah, several passes were made over the runway with the spike retracted and extended prior to the full stop landing with the spike retracted. The aircraft was demodified on February 15th and flown back to Edwards AFB on February 16th with a production radome.

Conclusions

The Quiet Spike flight test project was successfully completed with all primary objectives accomplished. The Quiet Spike structural design was validated at all design flight conditions, including various landing tests with higher than normal sink rates. No structural concerns were noted. The Quiet Spike shock wave pressures were measured during flight and closely matched those predicted by CFD and wind tunnel analysis. No structural loads for the test article or of the attachments to the aircraft were exceeded. Structural dynamics for the Quiet Spike revealed acceptable damping. Despite ground test predictions of structural mode interaction with the aircraft analog flight control system in the pitch axis, no structural mode interaction was encountered inflight. The Quiet Spike modified aircraft exhibited no perceptible changes in handling qualities in the subsonic and low supersonic flight regimes. The pilot perceived a reduced directional stability at Mach numbers above 1.4. Comparison of the directional stability and damping derivatives indicated a small reduction in stability from the baseline aircraft in this flight regime. The Quiet Spike was successfully extended and retracted at operationally relevant flight conditions to Mach 1.4.

Significant Lessons Learned

The differences between FAA and MIL SPEC standards need to be determined. Participating organizations need to agree early in the design cycle upon the standards that will be followed when building flight hardware.

Structural Mode Interaction (SMI) with the flight control system must be considered when structurally modifying an aircraft to avoid instabilities. Results demonstrate that the SMI test, although used as a strong indication of possible stability issues in flight, is not definitive as a flight test predictor. The industry needs to reevaluate how these ground tests are accomplished and develop new procedures to provide more accurate predictive tools. Also, does the SMI change over the life of the aircraft? What is the impact on the airframe of structural upgrades from in the field testing and evaluation on the SMI?

Simple tests are not usually simple. Complications always arise as to procedures. Results which are not well understood can cause unnecessary retesting. Careful preparation can save a lot of time and effort. Ground testing, while essential to perform, is only an indicator of what to expect in flight. The drag loads tests of the Quiet Spike confirm this.

When modifying an existing flight test aircraft, it is important to conduct test flights on the baseline aircraft itself. This provides the true model for flight test results obtained on the modified aircraft. Additionally, these baseline flights provide the test pilot the opportunity to become familiar with the test maneuvers and aircraft handling qualities in the test flight regime. Any questions as to noted differences between the modified aircraft and the baseline can then be attributed directly to the modification, leaving no concern about the fidelity of the baseline aircraft model.

During the Quiet Spike project, flight test was suspended for about three weeks due to the Christmas holidays. Upon return, the next test point scheduled was an envelope expansion point to Mach 1.7. On previous flights, concerns about reduced directional stability at high Mach numbers were noted. While this flight was successfully accomplished, a more prudent approach would have been to plan a less strenuous test profile to give the pilot and test team the opportunity to get back into the testing groove. Don't plan an envelope expansion test to the edge of the

knowledge base after several weeks of down time. Allow the pilots to get back into the air, readying them for the unanticipated.

The Gulfstream and NASA experience working on a joint flight research project was very good. The project took longer than expected to accomplish, but once the flying started, it progressed rapidly and achieved all test objectives. This is directly attributed to all test team disciplines working together effectively to develop a satisfactory test plan, combining points where needed, and quickly modifying plans after review of flight data. No ground or inflight mishaps occurred, attesting to the careful planning and implementation of safety precautions.

References

1. Wolz, R., "A Summary of Recent Supersonic Vehicle Studies at Gulfstream Aerospace, AIAA-2003-0558.

2. Henne, P.A., "Case for Small Supersonic Civil Aircraft", AIAA Journal of Aircraft, Vol. 42, No. 3, May-June 2005..

3. Henne, P.A., Howe, D.C., Wolz, R.R., and Hancock, J.L., U.S. Patent for a "Supersonic Aircraft with Spike for Controlling and Reducing Sonic Boom," March 2, 2004, Gulfstream Aerospace Corporation, Savannah, GA,, Patent No. US 6,698,684 B1.

4. Haering, E. A., Jr., Murray, J. E., Purifoy, D. D., Graham, D. H., Meredith, K. B., Ashburn, C. E., and Stucky, M., Lt. Col., "Airborne Shaped Sonic Boom Demonstration Pressure Measurements with Computational Fluid Dynamics Comparisons," AIAA-2005-0019, 43rd AIAA Aerospace Sciences Meeting and Exhibit, January 10-13, 2005, Reno, NV.

5. McWherter, Shaun, Cheng Moua, Tim Cox, and Joe Gera. "Stability and Control Analysis of the F15-B Quiet Spike Aircraft." NASA TM TBD, 2007.

6. Kordes & Noll. "Flight Flutter Results for Flat Rectangular Panels." NASA TM D-1058, February 1962.

7. Anderson, William. "Panel Flutter of Cylindrical Shells." Final Report – ORA Project 08079, Univ. of Michigan, August 1967.

8. Cumming, Stephen B., "Aerodynamic Effects of a 24 Foot, Multi-Segmented Telescoping Nose Boom on an F- 15B", AIAA-2007-6638.

9. Moua, Cheng M. "Flight Test Results on the Stability and Control of the F-15B Quiet Spike Aircraft." NASA TM (draft), March 2007.

For additional information:

10. Howe, D.C., "Sonic Boom Reduction Through The Use of Non-Axisymmetric Configuration Shaping," AIAA-2003-0929.

11. Howe, D.C., "Improved Sonic Boom Minimization with Extendable Nose Spike", AIAA-2005-1014.

12. Simmons, F. and Freund, D., "Morphing Concept for Quiet Supersonic Jet Boom Mitigation", AIAA-2005-1015.

13. Simmons III, F., Freund, D., Spivey, N. D., and Schuster, L., "Quiet Spike™: The Design and Validation of an Extendable Nose Boom Prototype", AIAA-2007-1774.

14. Spivey, N. et.al., "Quiet Spike™ Build-Up Ground Vibration Testing Approach", AIAA-2007-1175.

15. Herrera, C. Y., and Pak, C., "Build-up Approach to Updating the Mock Quiet Spike™ Beam Model", AIAA-2007-1776.

16. Freund, D., Simmons III, F., Spivey, N. D., and Schuster, L., "Quiet Spike™ Prototype Flight Test Results", AIAA-2007-1778.