Low-Boom SR-71 Modified Signature Demonstration Program

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Abstract

A flight program using the SR-71 airplane to validate sonic boom technologies for High-Speed Commercial Transport (HSCT) operation and potentially for low- or softened-boom design configurations is described. This program employs a shaped signature modification to the SR-71 airplane which is designed to demonstrate computational fluid dynamics (CFD) design technology at a full-scale HSCT operating condition of Mach 1.8 at 48,000 feet altitude. Test plans call for measurements in the near-field, at intermediate propagation altitudes, and through the more turbulent boundary layer near the Earth surface. The shaped signature modification to the airplane is comprised of added cross-section areas on the underside of the airplane forward of the wing and engine nacelles. Because the flight demonstration does not approach maximum SR-71 altitude or Mach number, the airplane provides more than adequate performance and maneuver margins for safe operation of the modified airplane. Probe airplane measurements in the near-field will use fast response pressure sensors. Far-field and ground-based boom measurements will use high response microphones or conventional sonic boom field recorders. Scope of the planned demonstration flights also includes ground level measurements during conditions which cause minimal signature distortion and conditions which cause high distortion of the signature.

Outline

- Introduction
- Justification
- Flight test objectives
- Demonstration test approach
- Modified signature flight test plan
- Measurement requirements
- Discussion
- Summary

INTRODUCTION

Air traffic-routing plans for large supersonic passenger aircraft consider that ground level sonic boom strength may be too large to allow regular flight routes over populated areas. Thus, supersonic routes used by the Concorde and those envisioned for second-generation "High-Speed Commercial Transport" (HSCT) aircraft are essentially restricted to over-water segments. This restriction extends the travel time required for many city pairs and thereby reduces the utilization (mileage) rate for each airframe. Intercontinental service to inland cities would be faster and the overall return on airframe investment would be greater if supersonic speeds could be used on overland routes. However, supersonic operation over most populated areas is not likely to be allowed for current baseline HSCT designs because they would produce boom over pressures on the order of 3.0 pounds per square foot (psf) at cruise (Mach 2.4) and somewhat higher in the Mach 1.2 to 1.4 region during the accelerating climb and decelerating descent. To alleviate this problem, recent airplane design studies developed configuration concepts that could be used to reduce boom annoyance levels (refs. 1 and 2). These modifications of the configuration cross-section area and lift distributions would reduce the initial overpressure rise. The resulting shock pattern at ground level would not be as large and sharp as the N-wave usually produced at the ground by aircraft at high cruise altitudes.

Flight tests to demonstrate low-boom design capability by modifying existing airframes have been proposed for the BQM-34E remotely piloted vehicle (RPV, the "Firebee," Teledyne Ryan Aeronautical Co., San Diego, CA, refs. 3 and 4) and the manned Mach 3 SR-71(Lockheed Corporation, Burbank CA) reconnaissance airplane (refs. 5 and 6). An important reason for testing the viability of low-boom design concepts is provided by route performance trade studies (ref. 7) which indicate that reduced boom configurations using a cruise Mach number of 1.8 for sensitive overland corridors and 2.0 over oceanic routes would reduce travel time for many city pairs and increase airframe utilization rates relative to conventional configurations using 0.9 Mach overland and 2.4 Mach over oceanic route segments. Moreover, the ability to serve additional cities would improve the return on fixed investment costs by increasing the production run. Thus, successful demonstration of the computational fluid dynamics (CFD) technology to predict the near-field boom signature and to design supersonic configurations which produce low-annoyance boom signatures at ground level could allow expansion of supersonic HSCT flight to a number of additional overland route segments. Since low-boom characteristics require major differences in airframe configuration, accurate assessment of their potential is important before HSCT pre-production design specifications are finalized.

Introduction

- **Demonstrate low-boom, shaped signature technology in flight**
- **Acquire in situ, near-field signature measurements to validate low-boom design technology**
- **Examine signature formation and initial coalescence characteristics**
- **Evaluate state-of-the-art computation tools for sonic boom propagation**
- **Document sonic boom distortion caused by Earth turbulent boundary-layer effects for shaped and N-wave signatures under quiet and turbulent conditions**

JUSTIFICATION

Unique merits of the plan to demonstrate low (or reduced) boom design technology with the SR-71 include the (1) large, essentially full-scale HSCT capability for the signature modification evaluation, (2) demonstration test condition would be at a realistic flight altitude and Mach number for HSCT cruise, (3) test altitude permits propagation evaluation over a conservatively long propagation path to the ground, (4) measurements at intermediate altitudes would scale directly to the actual HSCT operating condition, (5) SR-71 performance margins can support a wide range of experimental modifications and aerodynamic conditions within the HSCT altitude envelope. The plan incorporates measurements of near-field signature formation, coalescence, aging over long propagation paths and turbulent distortions through the ground layer. These measurements will serve to assess CFD near-field prediction, establish the capability for state-of-the-art propagation codes and illustrate the effects of Earth turbulent boundary-layer and signature shape. As such, the design technology enabled by the SR-71 demonstration will support sonic boom impact assessment for standard planforms as well as for low-boom configurations. It will substantiate, and most likely improve, the technologies needed to address boom sensitivity concerns for both overland and over-water routes. The primary driver in the choice between reduced boom and conventional HSCT configurations is likely to be future national and international standards for maximum over-pressure metrics and exposure rates over various population zones and natural habitats. Hence, the ability to formulate recommendations and negotiate favorable route agreements will hinge on expert first-hand skills in the sonic boom technical areas.

Significant resources in research program dollars, intellectual effort, CFD development and wind-tunnel testing have been directed at improving traditional boom prediction tools during recent years (ref. 2). State-of-the-art improvements for boom propagation prediction appear to center on rise time as influenced by oxygen and nitrogen molecular absorption. Sound attenuation by water vapor is also indicated by some investigators. Turbulence effects have been explored experimentally using shocks produced by sparks in the laboratory and by using parameterized boundary-layer characterization with previous field study data. Adequate field data for empirical validation of these new refinements in boom signature propagation and boundary-layer distortion have not been acquired for their use in the significant decision-making processes that face the HSCT.

Delay of the real atmosphere experience at HSCT flight conditions, which brings the above refinements to maturity, increases program risk and cost penalties. Outside interests (other agencies, other countries and environmental groups) will continue to periodically bring confrontation on sonic boom issues to the table. If the High Speed Research (HSR) Program is ready with mature, demonstrated boom technology, the program risks attending these confrontations will be minimized. If test and demonstration of the boom technology elements are delayed, the costs needed to maintain the current technological position on the learning curve will increase, or capabilities for accomplishment at a later date will decrease. Decreased capability could result from human and technical attrition because of several factors. First, inadequate career phasing can fail to provide the needed expert personnel. Second, in the face of pressing decision-making situations, the lack of adequate expertise easily leads to over-reaching assumptions, or perhaps worse yet, to technical apathy and misdirected attention. The element of human attrition is particularly critical for several reasons. Sonic boom technologies span several areas of expertise. Personnel retention is difficult since levels of program support vacillate from "some" to "nearly none". Present capabilities rely strongly on empirical experience and "engineering art" as practiced by only a few experts. New theoretical formulations are not quickly validated in flight nor rapidly assimilated as permanently established engineering practices.

JUSTIFICATION (cont'd)

A large part of the existing national ability can be attributed to NASA HSR Program efforts at Langley Research Center, Hampton, Virginia. These efforts have brought together broad interdisciplinary expertise from government, industry and academia. Note that these disciplinary areas are thinly staffed and, that historically, industry has not internally maintained more than one or two of the requisite skills in any given corporate entity at any given time. Continuation of the national team activity is the least costly way to provide the critical expertise necessary to deal with future challenges to supersonic fleet operations.

Sonic boom technology is and will continue to be a competitive element for national and international acceptance of supersonic passenger aircraft design and operation. Low-boom concept technologies could be established as a potential HSCT enhancement factor for overland route segments. Moreover, the U.S. sonic boom technical ability will be one of the HSCT make-or-break issues for environmental review of routes over water and sparsely populated areas.

Justification

- **Reduced boom overland flight segments will increase HSCT utilization rate and airframe production run.**
- **Flight-demonstrated technology will be applicable to soften boom strength for conventional Mach 2.4 HSCT planforms.**
- **Critical expertise in sonic boom technologies cultivated from the 1960's to 1990's can be sustained for application during the HSCT era - 2000 to 2020.**

FLIGHT TEST OBJECTIVES

The modified signature demonstration using the SR-71 will address four goals:

1. Demonstrate a shaped sonic boom waveform (non N-wave signature) at the ground.

2. Validate the CFD code capabilities for design of shaped near-field sonic boom signatures.

3. Evaluate the abilities of state-of-the-art tools to predict shaped signature propagation from cruise altitude to mid- and low-altitudes.

4. Obtain empirical data for shaped signature (non N-wave) propagation through the Earth boundary layer under quiet (stable, low wind) and turbulent (convective, windy) conditions.

The ultimate test of low-boom design technology is for the sonic boom waveform generated by the test airplane at HSCT cruise conditions to reach ground level without coalescing into the classic N-wave form with its large, strong, sharp rise to maximum overpressure at the leading-edge. Instead, it is desired that the shaped signature would reach ground level with a smaller leading-edge pressure rise followed by a gradual pressure rise ramp, or a "flat-top" segment, before producing the maximum boom overpressure. Such shaping of the boom decreases the annoyance to humans and the startle effect on other animals. The SR-71 flight capability provides an especially conservative demonstration of low-boom technology because it can reach HSCT flight conditions. Its relatively shorter length (approximately 100 feet vs. 300 feet for the HSCT) gives a longer propagation in terms of altitude-to-fuselage-length (h/l) scaling units. The SR-71 bow to inlet distance allows the shaped signature to have a ramp with the rate of pressure increase representative of that desired for the full-scale HSCT (ref. 6).

Near-field validation of CFD code design ability requires in situ measurement of the sonic boom overpressure signature that is close to the generating aircraft (approximately 100 feet). Evaluation of signature propagation tools requires in situ measurement in the near-field (roughly 100 to 1000 feet) below the generating aircraft and at mid- and low-altitudes to examine coalescence, signature aging caused by molecular absorption of acoustic energy, and distortion caused by atmospheric perturbations.

Flight Test Objectives

- **Demonstrate shaped boom waveform at ground level**
- **Validate CFD design codes with in situ near-field measurements**
- **Evaluate propagation codes and coalescence behavior**
- **Observe boundary-layer induced distortions for N- and non N-wave signatures**

DEMONSTRATION TEST APPROACH

The three main areas of the low-boom demonstration program include design and fabrication, flight test operations, and sonic boom measurements and data analysis. Industry, NASA, and the science community will conduct the program.

A modification to the cross-sectional area of the SR-71 forebody is being designed by industry (ref. 6). The design uses CFD in an iterative process. Area is added to achieve a desired signature shape. Then, the resulting local aerodynamics and near-field signature shape are evaluated. The primary flight condition for design of a low-boom HSCT is taken to be Mach 1.8 at 48,000 feet pressure altitude. Interest also exists in boom softening for a conventional HSCT planform at a cruise speed of Mach 2.4. However, additional fabrication costs are entailed for demonstration at the higher Mach number. Thus, this paper emphasizes the Mach 1.8 low-boom demonstration.

The SR-71 airplane manufacturer completed structural design for the low-boom modification using preliminary loft lines. Final design, fabrication, and installation will allow functional access to the service bays, operation of the landing gear, and removal of the modification to return the aircraft to its original flight configuration.

Flight test responsibilities center on the NASA Dryden Flight Research Center where the SR-71 is presently operating. These responsibilities include flight safety and flight readiness reviews, flight test engineering, aircrew preparations, and data acquisition. The CFD analysis of the final low-boom modification design will be accomplished independently by industry, NASA Langley Research Center, and NASA Ames Research Center. Aerodynamic margins will be examined on the basis of CFD results and flight simulation. If any performance or safety concerns are identified, wind-tunnel tests using a model of the modified SR-71 will be conducted. Data analysis and evaluation will be shared with HSR Program participants in industry, academia, and NASA.

Demonstration Test Approach

- **Modification loft design and CFD aeroloads conducted by Douglas**
- **Structural aircraft modification design conducted by Lockheed**
- **Low-boom modification fabrication and installation by Lockheed**
- **Research flights using modified SR-71, probe aircraft, and ground measurements at Dryden**
- **Data analysis by HSR Contractors, Langley, Ames, and Dryden**

MODIFIED SIGNATURE FLIGHT TEST PLAN

Flight operations will involve the modified SR-71 airplane, instrumented probe airplane, and safety chase. The SR-71 will generate the modified sonic boom signature in steady flight at Mach 1.8 and 48,000 feet similar to the previous flight tests (ref. 8). The instrumented near-field probe airplane will probe forward from a position behind and below the SR-71. The probe aiplane can keep the SR-71 in view, even as the SR-71 bow shock is crossed. This is possible since the bow shock cone sweeps backward from the airplane to allow a longitudinal gap between the probe airplane nose below and the SR-71 tail above. Next, the probe airplane will drop back and reposition itself for another pass. During near-field signature sampling, the relative speed between the aircraft is expected to range up to 25 fps. Significantly higher rates would be expected to increase the time needed to reposition as well as decrease safety margins. Plans call for 12 good near-field probes: 3 each at altitude separations of 100, 200, 500, and 1000 feet below the SR-71.

Ground-based signature measurements will be accomplished by overflying an array of sonic boom recorders. To cover the signature variations caused by naturally unsteady atmospheric conditions, six passes are planned for calm or low-signature-distortion conditions which are most likely during morning hours. Another six passes are planned for conditions when the typical N-wave signatures would be more strongly distorted by atmospheric turbulence and winds. An additional six passes are anticipated for "off-design" test points at other Mach-altitude combinations. Supporting measurements will include rawinsonde measurement of the atmospheric wind, temperature, and humidity profiles from Edwards AFB, California, near the flight time. Detailed atmospheric boundary-layer characteristics at the sonic boom array will be measured by tethersonde and ground-based acoustic probes (SODAR) to document wind and temperature profiles and fluctuations in the boundary layer.

Signature measurements during propagation at middle and low altitudes above the Earth turbulent boundary layer will be obtained with subsonic platforms using sonic boom recorders or microphones with equivalent dynamic characteristics.

Modified Signature Flight Test Plan

- **SR-71 maintains Mach 1.8 and constant altitude**
- **Probe airplane positions below and aft, then moves forward**
- **Probe airplane passes bow shock, drops back and repeats**
- **Both aircraft use differential Global Positioning System (GPS)**
- **Signature measured with short-coupled, high-response total and static pressure sensors**
- **Mid-field, far-field, and ground signatures measured with boom recorders, microphones, or narrow range differential pressure sensors**

MEASUREMENT REQUIREMENTS

Near the signature-generating airplane, the overpressures are relatively large and decrease rapidly with distance as the Mach cone propagates away. Therefore, to validate computed pressure fields near the airplane, adequate precision must be used for the in situ pressure measurements and the distance between the generator and the probe aircraft. A table of measurement quality goals is given below.

In the near-field region of interest, the maximum overpressure ranges from approximately 20 percent to less than 2 percent of the flight altitude ambient pressure. In terms of operational absolute pressure transducers used for pressure altitude, these overpressures become 2 to 0.2 percent of the full- scale range. Thus, the goal for overpressure accuracy of 5 percent calls for sensor stability and resolution reaching 0.01 percent of transducer full scale. Measurement risk will be reduced by implementing high-response probes for static and total pressure. In addition, absolute pressure transducers may be augmented with differential transducers referenced to nominal pressure reservoirs for increased resolution and redundancy. Relative aircraft positions will be obtained with differential GPS on each airplane (ref. 8). Precision ground-based tracking radar will provide backup data for each airplane.

Measurement Requirements

Parameter	Tolerance
SR-71 test condition, Mach number	0.05
SR-71 test point pressure altitude, ft	150
Relative separation distance, percent	5
Overpressure accuracy, percent	5
Minimum damping ratio	0.7
Minimum natural frequency, Hz	50
Minimum sample rate, sps	100

DISCUSSION

The proposed modified SR-71 sonic boom flight test program represents a highly comprehensive demonstration of sonic boom technologies. This program presents the first opportunity to explore the propagation of shaped signatures with in situ data documentation in the airplane near field, at mid-field, through the Earth boundary layer, and at ground level. These near-field data will validate wind-tunnel and CFD techniques. These techniques are the primary tools for HSCT evaluation during the airplane design stage. Wind-tunnel measurements and CFD data are restricted to flow near the body of the aircraft because of practical limitations in wind-tunnel dimensions and CFD grid point density (or computational cost). Thus, the near-field, in-flight data will validate assumptions used to bridge the gap between local aerodynamics and specification of initial conditions for boom propagation codes. Signature measurements at middle and ground levels will provide data for evaluation of boom propagation code abilities to account for atmospheric absorption and rise time characteristics which impact annoyance statistics. Demonstrated skill in the state-of-the-art for these technologies is crucial to low-boom design decisions and vital to environmental impact clearance for conventional HSCT planforms.

Flight operations planning and safety reviews will thoroughly consider impacts of the modification on aircraft structural integrity, performance, and flight control. Structural design of the cross-sectional area modification for the Mach 1.8 test point has been approached using a safety factor of 2.25. Aerodynamics results from a preliminary design indicate minimal change in pitching moment. Final design CFD will be confirmed independently by analysis codes at NASA Langley Research Center and NASA Ames Research Center. The resulting aerodynamic characteristics will be used in the flight simulator to examine airworthiness of the modification. Any performance factors or stability and control anomalies with the potential to compromise flight safety will be evaluated using further CFD and wind-tunnel tests.

Discussion

- **Proposed SR-71 modified boom signature demonstration would validate design and propagation technologies for application to the HSCT.**
- **Go-ahead for the SR-71 modification was deferred because of budget decreases and ongoing design rework.**
- **Current emphasis is redirected toward signature coalescence and propagation issues.**

DISCUSSION (cont'd)

A final design for the SR-71 modified boom signature demonstration has not been completed. Budget reductions and program redirection indicate that a go-ahead is not imminent. In the interim, independent approaches to low-boom CFD design are emerging (ref. 9). These approaches may provide additional confirmation of or optimization to the proposed SR-71 modification.

Sonic boom flight research and field study needs can be grouped into four phenomenological areas: (1) the local boom signature aerodynamic formation processes within approximately three body lengths or six span distances below the airplane, (2) the signature feature coalescence region in which higher pressure shock zones overtake lower pressure zones, (3) molecular interactions which exert frequency dependent acoustic absorption, and (4) focusing and distortion caused by maneuvers and atmospheric perturbations. A major thrust of the proposed SR-71 modified signature demonstration addresses the ability of CFD techniques to account for signature formation during the design phase of an aircraft. Some discrepancies between CFD, analytical methods and wind tunnel test data in this region are not adequately understood. Because of programmatic constraints, attention to these areas may be deferred in favor of field measurements to examine the coalescence phenomena which result in the N-wave signature shape. Initial suggestions for signature coalescence flight test points are listed below.

Recommended Coalescence Test Point Objectives

- **Measure signature at 4 separations from near-field to N-wave formation**
- **Accomplish for three Mach numbers between 1.2 and 2.4**
- **Emphasize lightweight, high dynamic pressure, low altitude conditions**
- **Spot-check heavy high altitude conditions at two Mach numbers**
- **Spot-check signature coalescence above the airplane at two Mach numbers and two separations**

SUMMARY

Sonic boom technologies are a critical element in the United States High-Speed Civil Transport (HSCT) efforts. In fact, these technologies could easily be make or break factors with respect to such issues as (1) environmental acceptance for over water and overland routes, (2) precise discrimination between boom strength from U.S. HSCT designs and those of competing countries, (3) realistic negotiations of specific routes and supersonic approach corridor distances, and (4) assessment of domestic and foreign low-boom design proposals. The proposed SR-71 modified boom demonstration offers a timely opportunity to ascertain whether state-of-the-art technologies for computational fluid dynamics (CFD) design techniques and boom propagation prediction codes can move from the drawing board to practice in full-scale flight.

At HSCT altitudes and Mach numbers, the SR-71 has a broad flight envelope. At given altitudes, its speed range extends a full Mach number. At fixed Mach numbers, its altitude envelope is approximately 20,000 feet thick. This envelope provides a broad capability for the safe conduct of flight experiments that entail additional weight and drag. Other test bed vehicles either lack in size, speed range, and reliability or use mixed compression inlets which can not represent anticipated HSCT configurations as well as does the SR-71 (at Mach numbers from 1.6 to 3.0). Similar capability is not anticipated in future aircraft or in HSCT prototypes because of their requirement for increased mission optimization.

The SR-71 ability to flight test design techniques, propagation prediction codes and signature distortion all together in the real atmosphere at essentially full-scale HSCT conditions represents a highly cost-effective and timely use of program resources.

Remarks

- **SR-71 is the most "*experimenter friendly*" test bed for Mach numbers between 1.8 and 2.4 anticipated to be available over the next 20 years**
  - **Payload margin**
  - **Flight endurance**
  - **Speed altitude envelope**
- **HSCT prototype financial commitment requires demonstrated technology maturity**
- **Partial or fragmented sonic boom expertise could very likely be an "HSCT *Show Stopper*" in the environmental-political arena**

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