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October 2003

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Summary

Pressure signatures generated by the wind-tunnel model of a business-jet concept were measured at a Mach number of 2, at separation distances of 9.5 and 18 inches, and at $C_L/C_{L,CR}$ ratios of 0.5 and 1.0. An analysis of the data showed that the engine-nacelle disturbances were just as difficult to "hide" in the flow-field expansion region of a supersonic-cruise business jet as they were in the same flow-field expansion region of a 300-passenger supersonic-cruise transport. So, while the beginning-cruise weight was lower, the reduced lift resulted in a shallower expansion leading to the formation of the tail shock. This result was the basis of the conclusion that it was more, not less, difficult to tailor the concept's geometry for sonic boom overpressures that were half those required of the much larger transport aircraft. In spite of this result, however, the predicted strength of the nacelle shock in the ground signature was so low that it would probably be unnoticed by the observer.

Introduction

A supersonic-cruise business jet (SBJ) concept was designed at the Langley Research Center to aid in assessing the scope of supersonic-cruise technical problems. These special technical problems were associated with applying low/reduced-boom methods and aircraft technologies to the design of supersonic-cruise vehicles that were considerably smaller than the Supersonic Transport (SST) or the High Speed Civil Transport (HSCT); vehicles that had been the subject of intense study from the late 1960's through the 1990's. It was thought that due to its reduced size and weight, a low-boom SBJ would be easier to design than its HSCT counterpart.

A wind-tunnel model was derived and built from the geometry of the SBJ concept. Pressure signatures generated by the model in the wind tunnel were measured at the design Mach number and used to assess the applicability of existing design and analysis methods.

In this report, pressure signatures generated by the Langley Low Sonic Boom Business Jet Wind-Tunnel model and measured in the Langley Research Center's Unitary Plan Wind Tunnel are presented and analyzed. The results of the analyses were used to determine the level of success in achieving the desired design goals for this type of configuration.

Nomenclature

A_E	equivalent area, ft^2
b	wing span, feet
C_L	cruise or takeoff lift coefficient
$C_{L,CR}$	cruise lift coefficient
$F(y)$	Whitham F-function of parameter y, $ft^{1/2}$
h	cruise altitude, ft
l_e	effective length of the aircraft, ft
M	cruise Mach number
p	ambient pressure, psf
Δp	overpressure in the aircraft's flow field, psf
W_c	aircraft weight at start of cruise, lb
W_{eff}	aircraft weight used to calculate a low-boom F-function and equivalent areas, lb
x	distance along the longitudinal direction, ft
x_e	effective distance along the longitudinal direction, ft
y	spanwise direction or Whitham F-function effective length parameter, ft
β	Mach number parameter defined by $(M^2 - 1.0)^{1/2}$
ξ	length to end of constant $F(y)$ section on a hybrid Whitham F-function, ft
η	ratio of F-function "ramp" slope to the acoustic signal slope
λ	length of the positive section of the low-boom F-function, ft

Conceptual Configuration

The low-boom features on the business-jet concept, reference 1, were guided by the sonic-boom minimization theory of Seebass and George, reference 2. This minimization theory was a refinement of an initial minimization work of Jones, reference 3, based on the pioneer flow-field prediction research of Whitham and Walkden, references 4 and 5.

These theories along with experimental evidence were the basis of McLean's conclusions, reference 6, which noted that special tailoring of the aircraft's geometry could extend the benefits of pressure-signature shaping farther into the aircraft's supersonic flow field than previously suspected. Subsequent studies, reference 7 for instance, applied these ideas to early low-boom transport concepts. Refinements in methods and applications (references 8 to13 are typical) followed, and were in place during the HSCT concept design studies. All these low sonic-boom design methods, fuselage-tailoring methods, and sonic-boom analysis techniques were available and employed to design the Langley low-boom business-jet concept.

The preliminary design of the Langley business jet concept had the following low-sonic-boom and mission objectives:

Range	=	4000 nmi
Cruise Mach Number	=	2.0
Number of Passengers	=	10
Number of Crew	=	2
Maximum Nose/Tail Shock Overpressure	=	0.5 psf or less
Number of Engines	=	2

Beginning-cruise weight was estimated using the method of reference 14. This estimate required an initial wing planform and its performance characteristics, the mission objectives, and the propulsion system's cruise performance. From a beginning-cruise altitude, the cruise Mach number, and a beginning-cruise weight, the desired ground overpressure was estimated.

Supersonic-cruise aerodynamic performance characteristics of lift, drag, and pitching moment were obtained by using the methods and codes described in references 15 to 17. The method of reference 18 was used to obtain nacelle F-functions. An independent code was developed and used to obtain estimates of the configuration skin friction drag. These analysis tools, as well as those previously mentioned were used to design the Langley low-boom business jet concept shown in figure 1. Low-boom inputs, equivalent area distribution (without nacelles), and the low-boom F-function of the Langley low-boom concept are found in Appendix A.

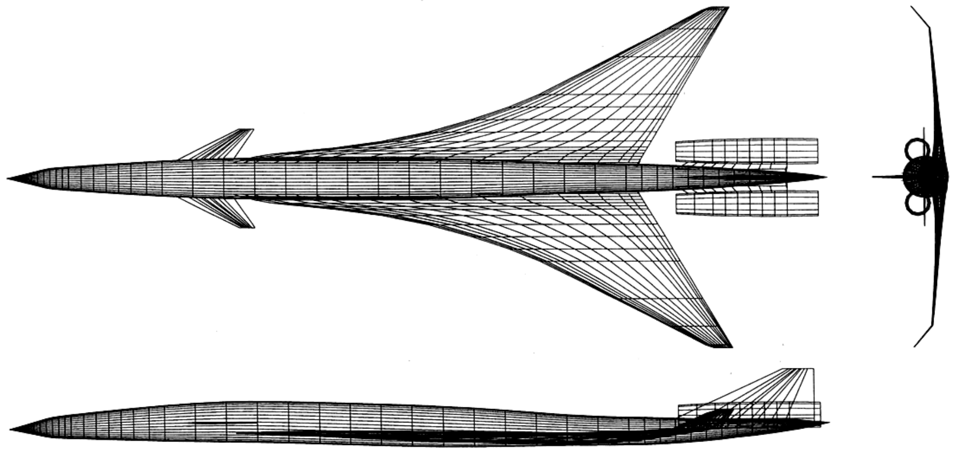

Figure 1. Three-view drawing of the Langley concept.

Wind-Tunnel Model

The wind-tunnel model which would be used to generate pressure signatures was derived from the design of the Langley supersonic-cruise low-sonic-boom business jet concept. A scale factor of 1:100 was used to obtain the model from full-scale dimensions. The Langley low-boom wind-tunnel model is shown in figures 2 and 3.

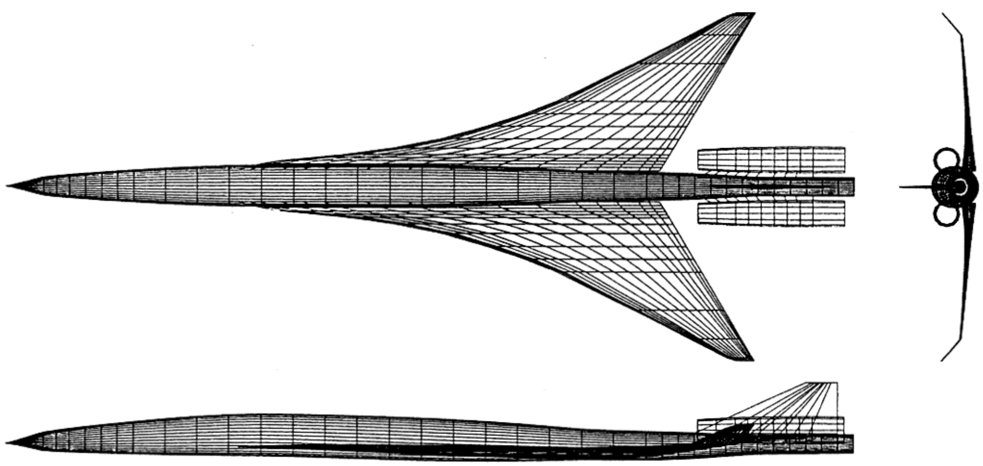

Figure 2. Three-view sketch of the Langley low-boom wind-tunnel model; small nacelles.

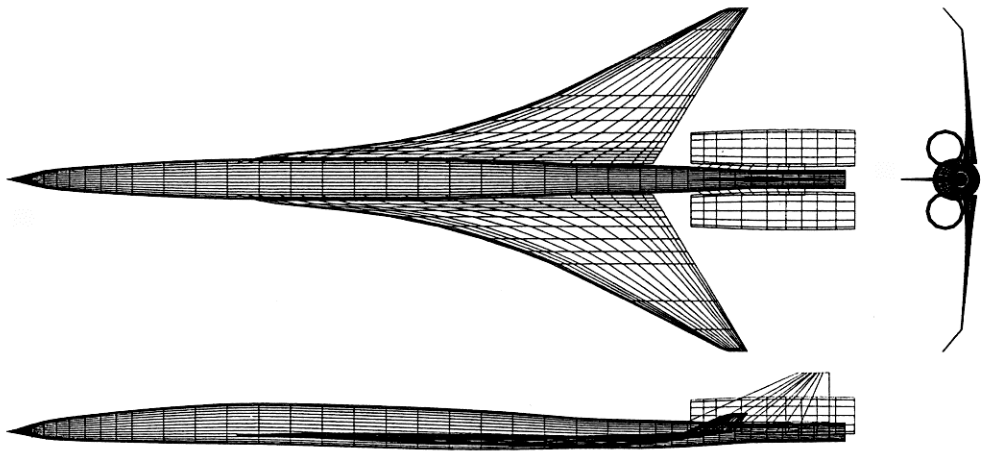

Figure 3. Three-view sketch of the Langley low-boom wind-tunnel model; large nacelles.

Two different nacelles were built for the same wing/fuselage/fin/nacelle strut model. They represented the nacelles required for engines having two bypass ratios. The inlet of both nacelles are at the same longitudinal station, but the larger nacelle's lateral position was changed so that the nacelle strut span was the same for both nacelles. These permitted the evaluation of the disturbances from nacelles of engines incorporating different technology developments, different noise-suppression techniques, and/or different life-expectancy requirements.

Only the model and the cylindrical section aft of the fuselage are shown in figures 2 and 3. The cylindrical aft fuselage replaces the body closure on the full-scale configuration and blends into a tapered sting-balance which extended the integrated model-sting-balance to 32 inches in length. This tapered sting-balance section is not shown so that configuration features can be easily seen in the figures. Note that the canard on the full-scale concept was not on the wind-tunnel model. Pressure signatures were to be measured at several angles of attack (several levels of lift) and the canard was to carry zero lift during supersonic flight. To maintain the canard at zero lift on the model, a canard attitude adjustment mechanism would have been needed necessitating undesired model complexity or manual adjustment for each lift setting.

The canard volume was not replaced with fuselage volume to keep the fuselage from being "lumpy" where the canard was located. This meant that the concept's Whitham F-function would not be smooth along the section between the nose "spike" and the onset of wing lift as if the canard were in place. However, the changed equivalent areas could be input to the prediction codes for obtaining a predicted pressure signature of the model's nose, forebody, and forward strake where the disturbances were mainly from volume (ANALYSIS section). Configuration dimensions and qualities which were scaled by a factor of 1:100 are found in Appendix B.

Wind-Tunnel Test Section and Test Matrix

The wind-tunnel model was mounted on an angle-of-attack mechanism which permitted remote control of the lift on the model during the measurement of pressure signatures. The angle of attack mechanism, in turn, was connected by a sting to the main lateral and longitudinal motion strut in Test Section No. 1 of the Langley Unitary Plan Wind Tunnel. Thus, both model lift and separation distance could be changed by remote control during the test runs.

A side-view schematic of this model-probe arrangement is shown in figure 4.

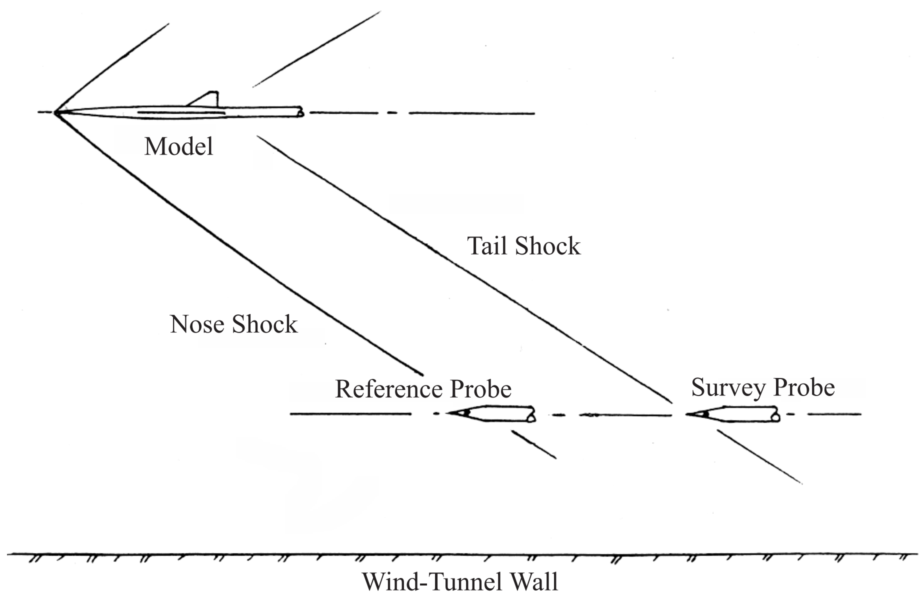

Figure 4. Side-view schematic of model and measurement probes in the test section.

The reference and survey probes were cylindrical with a 4 degree vertex angle conical tip. Each tip had two, opposed, 0.035 inch diameter orifices. Both were mounted on masts which kept them outside the wind-tunnel-wall boundary layer. The orifices of the survey probe were set normal to the plane formed by the survey probe and the model centerline.

The matrix of pressure signatures generated in the flow field under the model and measured with a Statham differential pressure gage at a Mach number of 2.0 is shown in figure 5.

Separation Distance, in.	Lift/Cruise Lift	Nacelles
9.5	1.0	Large
18.0	1.0	Large
9.5	0.5	Small
18.0	0.5	Small
9.5	1.0	Small
18.0	1.0	Small
9.5	0.5	Off
18.0	0.5	Off
9.5	1.0	Off
18.0	1.0	Off

Figure 5. Separation distances, lift ratios, and type of nacelles during test.

The Lift/Cruise Lift ratio, $C_L/C_{L,CR}$, was 1.0 for a model lift of 6.72 lb. This value was obtained by multiplying the full-scale lift by 1:10000 (scale factor squared), and then by the ratio of wind-tunnel to free-stream dynamic pressures. An additional lift increment was estimated and applied to correct for wing downwash effects on the sting-balance. The pressure signatures were measured at the two design and off-design lift levels so that the effects of lift versus volume contributions to flow-field disturbances could be identified and studied on a concept of this size and type.

Measured Pressure Signatures

There were two primary areas of interest in the pressure signatures measured from the Langley wind-tunnel model. The first area of interest was how well the model-generated pressure signatures met design expectations, and the second was the relative flow-field disturbance effects of the two different-size nacelles. These two topics will be discussed in the following sections.

Analysis of Pressure Signatures

The sonic-boom design and analysis methods employed to obtain the business-jet concept and its wind-tunnel model evolved through research and wind-tunnel experimentation from the theories of Whitham and Walkden, reference 4 and 5. These are inherently far-field in form while pressure signature development in the environment of the wind tunnel test section where the pressure signatures are measured is near field. However, the nose and forward fuselage section generate only volume disturbances, and the initial section of the wing strake is mostly volume with a very low lift component. So, if the forward section is very slender, it is possible to employ Whitham-Walkden theory to obtain a tentative prediction of this part of the near-field pressure signature. Figure 6 shows a comparison of measured and Whitham-theory predicted pressure signatures at Mach 2, $C_L/C_{L,CR}$ = 1.0, and a separation distance of 18 inches.

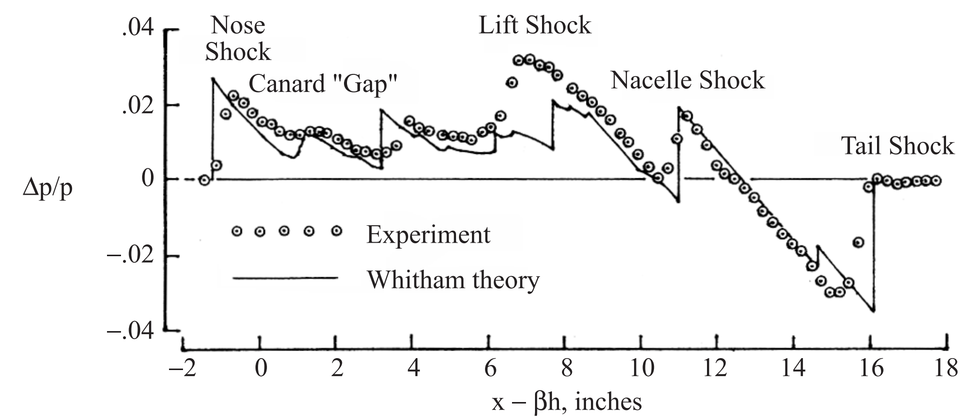

Figure 6. Comparison of measured and predicted pressure signatures. M = 2, $C_L/C_{L,CR}$ = 1.0, *h* =18 inches, small nacelles.

The predicted pressure signature is longer than the measured signature which is normal for Whitham theory predictions. Agreement between predicted and measured signatures along the first 7 inches of signature length is fairly good. However, both the predicted nose and canard "gap" shocks are ahead of the corresponding measured pressure rises, and the expansion aft of the nose shock is over-predicted. Serious differences between the predicted and the measured signatures are found where the wing volume and lift begin to grow rapidly. The single measured lift-induced shock is stronger and is further forward than the two weaker predicted shocks. This is typical of Whitham Theory-predicted near-field signatures of lifting wing-body models whose equivalent areas due to lift exceed those from volume by a factor of two or more. At this near-field distance, under-wing pressure disturbances are disproportionately stronger and have shorter propagation distances than above-the-wing pressure disturbances so they exert a larger influence that they would from a further distance.

The predicted nacelle shock strength and location agrees well with that of the measured signature. Both nacelles are located above and aft of the wing, so their disturbances do not interact with the wing and the wing lift. However, the nacelles are in the flow field disturbed by the upper wing surface. From the good agreement between predicted and measured nacelle inlet-lip shock, it would appear that the air crossing the inlets has nearly free stream velocity. So, on this model, the nacelles behave very much like two separate bodies flying in formation with the wing-fuselage-fin. Note that the nose and nacelle shocks have nearly the same strength. So, in spite of being in an aft position on the fuselage, the nacelle shocks are readily seen on the pressure signature.

The Whitham theory prediction of the ground pressure signature at a Mach number of 2 and a cruise altitude of 53,000 feet is presented in figure 7.

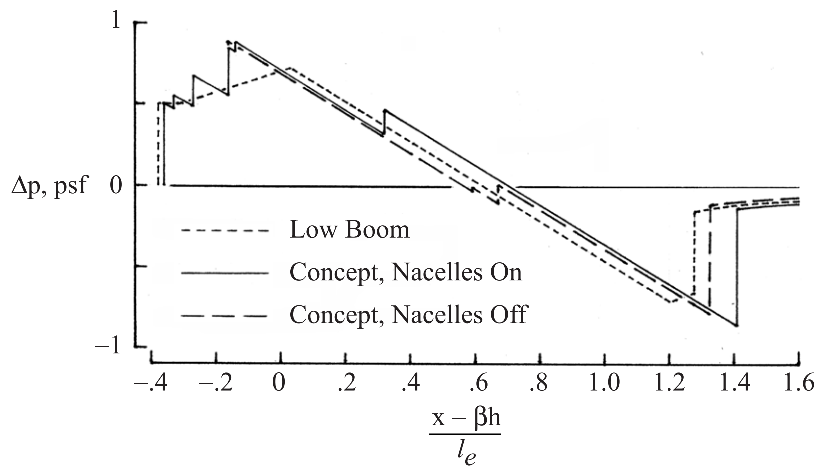

Figure 7. Predicted ground signatures from the business jet concept. M = 2, h = 53,000 ft.

The nacelle shock is located along the expansion, and before the tail shock. The extraneous “ramp” shocks probably resulted from too coarse a fuselage description and possibly, insufficient low-boom tailoring of the fuselage areas. These “ramp” shocks did not appear in the near-field pressure signatures of references 11 and 19. The models in these references had much higher fineness ratio fuselages, and the corresponding concepts were HSCT-size vehicles.

Relative Disturbances From the Different Nacelles

The second area of interest was the relative effects of large and small nacelles on the pressure signature. In figure 8, three signatures generated by the model with large nacelles, small nacelles, and no nacelles are presented for comparison.

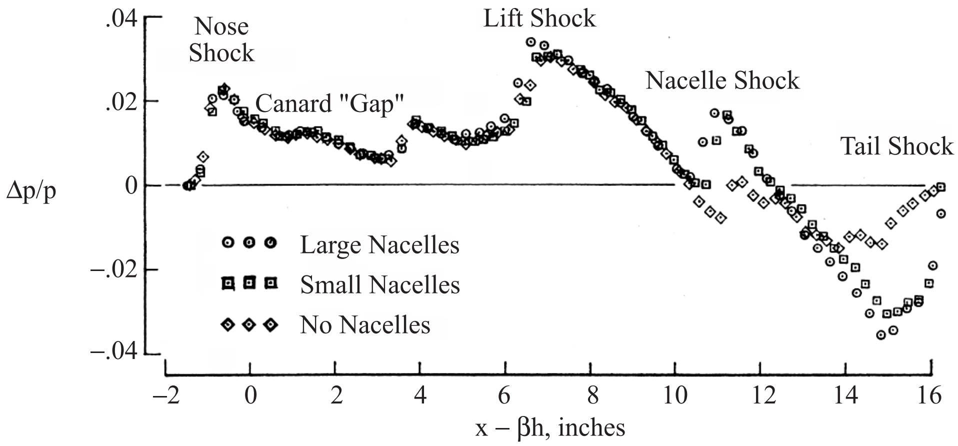

Figure 8. Comparison of pressure signatures at h = 18 inches, M = 2, $C_L/C_{L,CR}$ = 1.0.

Just behind the nose shock is a short shallow expansion followed by a low-strength shock. These features are due to the absence of the canard which had to be omitted from the wind-tunnel model geometry. Nacelle inlet-lip shocks are easily seen on the two pressure signatures from the model with large and small nacelles. Although there is a marked difference in nacelle diameters and lengths, there was very little difference in their inlet-lip shock strengths and locations. The small nacelle-location shock on the signature from the model with no nacelles was due to the nacelle struts which were left in place when the nacelles were removed. Aft of the inlet, expansion fields generated along the length of each nacelle added to the tail shock strength. However, the relative magnitudes of the pressures in the aft region of the three signatures makes it relatively easy to isolate and identify the nacelle volume effects.

These pressure signatures in figure 8 demonstrated that for a supersonic-cruise vehicle the size of a SBJ, nacelle shocks and disturbance effects are just as, if not more, difficult to mask as they are for vehicles in the HSCT size range. Because the lift-to-volume ratio is less on a SBJ, there is a shallower F-function expansion than on the F-function of the larger heavier HSCT. So, the pressure “jump” from the nacelle inlet lip has a smaller “valley” to “hide” in.

While there is a minimum sonic boom theory for the shaping of the configuration’s forward 75 to 80 percent, there is only empirical theory for minimizing nacelle effects. References 11 and 20 suggest a nacelle location in the expansion field of the concept’s F-function, and this idea was used on the SBJ concept. Beyond coupling this idea with the use of a small inlet diameter and a shallow inlet lip angle, there are no other theoretically and experimentally- validated methods for controlling and reducing the tail shock in a manner similar to that of the nose shock. This is an area open for study.

A third area of interest was the relative effects of the volume and lift on the shape of the signature. A comparison of two pressure signature generated by the model, without nacelles, at Mach 2 and separation distance of 18 inches is presented in figures 9.

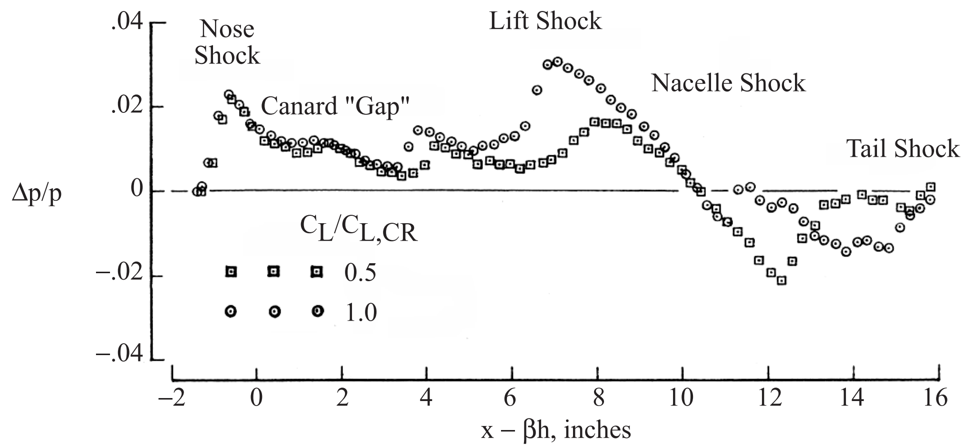

Figure 9. Comparison of two wind-tunnel model pressure signatures. M = 2, *h* = 18 inches, no nacelles, $C_L/C_{L,CR}$ = 0.5 and 1.0.

The nose shock and forebody disturbances have the same shapes and strengths at both levels of $C_L/C_{L,CR}$. Differences between the two pressure signatures appear aft of the canard location where the wing lift begins. For $C_L/C_{L,CR}$ = 1.0, the lift-induced shock is forward of, and stronger than, the lift-induced shock for $C_L/C_{L,CR}$ = 0.50. The same observation is true for the respective shocks off the trailing edges of the wing and aft fuselage. These shock locations differ because of the difference in angle of attack required to achieve the two lift levels.

Results

Pressure signatures generated by a Langley wind-tunnel model of a SBJ concept have been measured in test section of the Unitary Plan Wind Tunnel at a Mach number of 2, separation distances of 9.5 and 18 inches, and at $C_L/C_{L,CR}$ ratios of 0.5 and 1.0. An analysis of the data showed that the disturbances from the nacelles were just as difficult to submerge in the flow-field expansion region of a supersonic-cruise business jet as they were in the same flow-field region of a 300-passenger transport. The lower beginning-cruise weight of concept resulted in a shallower expansion following the peak in volume and lift before the development of the tail shock. From this perspective, the task of designing low-boom characteristics into the concept's geometry has not been made easier simply because there has been a reduction in concept size and weight. In spite of this, however, the strength of the nacelle shock in the ground signature was predicted to be so small that it would probably go unnoticed to the observer.

Concluding Remarks

The measured and predicted pressure signatures of the Langley wind-tunnel model showed that reducing the size of the supersonic-cruise, low-sonic-boom vehicle from HSCT to SBJ size did not make it easier to meet low-boom requirements. Three factors were involved: (1) the desired overpressure limits, which were reduced from 1.0 psf to 0.5 psf; (2) the mission range, which was still long at 4000 nautical miles; (3) propulsion and materials technology, which had changed very little during the intervening years.

Decreasing the overpressure limits added to the conflicts between choices to achieve high aerodynamic efficiency and compromises to achieve low sonic boom. Specifically, the need for both high aspect ratio, 1.9 to 2.1, and long lifting length resulted in low wing loadings and/or penalties in structural weight.

A mission range of 4000 nautical miles meant that the concept was a flying fuel tank as well as a high-speed conveyance for 10 business passengers. This affected the design by requiring the fuselage to be long enough to carry crew, passengers, baggage, and most of the volume for the fuel tanks. While low-sonic-boom characteristics were helped by this design feature, the weight penalties accumulated with each foot of length added. However, to maintain trans-Atlantic and/or two-jump trans-Pacific capabilities, this much range was required.

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Appendix A

Low-Boom Parameters for an Equivalent-Area Distribution and the Corresponding F-function on the Langley, Supersonic-Cruise, Low-Boom Business-Jet Concept

Mach Number, M = 2.0
Beginning-Cruise Altitude, h = 53,000 ft
"Nose-Bluntness" Length, y = 6.0 ft
"Flat-Top" Section of F-Function, $\xi - y$ = 10.0 ft
Beginning-Cruise Weight, W_c = 88,457.0 lb
"Low-Boom, Equivalent-Area" Cruise Weight, W_{eff} = 92,809.4 lb
Effective Length, $l_e = l_{ep}$ = 111.0
Ground Overpressure, Δp = 0.5 psf
η = 0.35
Ground Reflection Factor, RF = 1.9

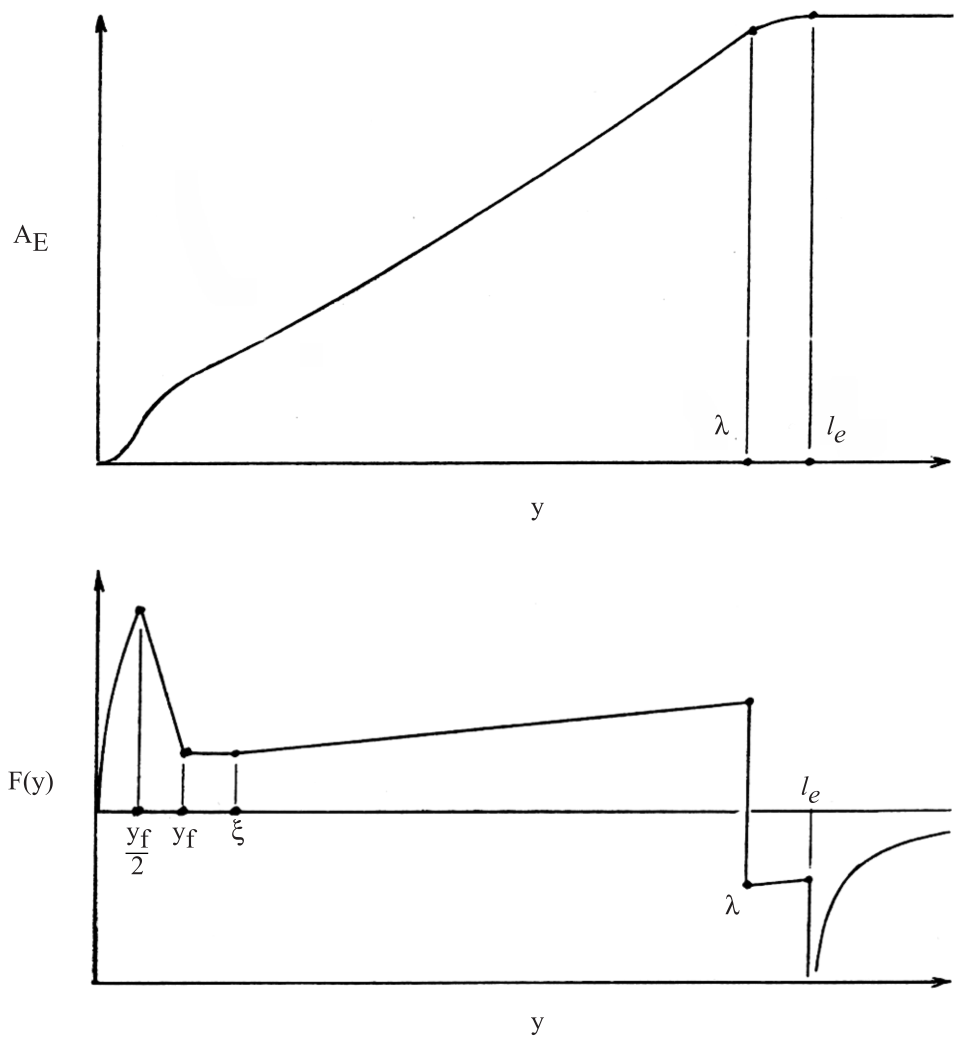

Figure A.1. Equivalent area and F-function calculated from cruise data.

Appendix B

Characteristics of the Langley low-sonic-boom supersonic-cruise business jet which were scaled by 1:100 to obtain the wind-tunnel model.

Span, ft	55.0
Length, ft	132.5
Wing Area (reference), ft^2	1,560.25
Wing Mean Aerodynamic chord, ft	42.00
Wing Aspect Ratio (projected area)	1.93
Fin Area, ft^2	109.0
Canard Area (projected), ft^2	90.0
Cruise Mach Number	2.0
Beginning Cruise Weight, lb	88,497.0

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14. ABSTRACT

Pressure signatures generated by the wind-tunnel model of a Business-Jet Concept were measured at a Mach number of 2, at (lift/cruise lift) ratios of 0.5 and 1.0, and at separation distances of 9.5 and 18 inches. Analysis of the pressure signature data showed the engine-nacelle disturbances were as difficult to "hide" in the flow-field of a 10-passenger cupersonic-cruise business jet as they were in the similar part of the flow-field of a 300-passenger supersonic-cruise transport. This result indicated that it was more, not less, difficult to tailor the business-jet concept's geometry for sonic boom overpressures that were half those required of the much larger transport aircraft.

15. SUBJECT TERMS
Sonic boom; Wind-tunnel tests; Measured pressure signatures; Low-boom business jet

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