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Nacelle Integration To Reduce the Sonic Boom of Aircraft Designed To Cruise at Supersonic Speeds

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Nacelle Integration To Reduce The Sonic Boom Of Supersonic-Cruise Aircraft

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SUMMARY

An empirical method for integrating the engine nacelles on a wing-fuselage-fin(s) configuration has been described. This method is based on Whitham theory and Seebass and George sonic-boom minimization theory. With it, both reduced-sonic-boom as well as high aerodynamic efficiency methods can be applied to the conceptual design of a supersonic-cruise aircraft. Two high-speed civil transport concepts were used as examples to illustrate the application of this engine-nacelle integration methodology: (1) a concept with engine nacelles mounted on the aft-fuselage, the HSCT-10B; and (2) a concept with engine nacelles mounted under an extended-wing center section, the HSCT-11E. In both cases, the key to a significant reduction in the sonic-boom contribution from the engine nacelles was to use the F-function shape of the concept as a guide to move the nacelles further aft on the configuration.

INTRODUCTION

The conventional location for engine nacelles on a supersonic-cruise aircraft is under the wings. This is the arrangement seen on the United States' XB-70, the English-French Concorde, and the Russian Tu-144, references 1 to 3. It is desired because the engine inlets are in a favorable flow field under the wing where the shock losses from the nacelles can be recovered through nacelle-wing interference lift. Most conceptual high-speed civil transport (HSCT) aircraft studied in subsequent years followed this engines-under-the-wing practice. References 4 to 10 document but a few of the configurations that have appeared during the time period when the Supersonic Transport (SST) Program and the follow-on Supersonic Cruise Aircraft Research (SCAR) Program funded studies of design, performance, maintenance, and marketing problems.

When the engine-nacelle location was changed, it was usually for a specific reason. One such reason was the reduction of the aircraft's sonic-boom on the ground. Sonic-boom minimization theory, reference 11, and sonic-boom reduction methods, references 12 to 14, showed that ground overpressure noise could be reduced by careful shaping of the aircraft's geometry. These methods, however, assumed that the aircraft's components had areas that were smooth and continuous. It was found that engine nacelles did not meet this criteria, so they had to be treated differently. In this paper, the reasons for moving the engine nacelles aft to reduce sonic-boom are analyzed and discussed. The conceptual aircraft in these discussions were those instrumental in discovering and isolating nacelle-integration effects on sonic boom, as well as subsequent conceptual aircraft whose unconventional engine-nacelle positions would enable them to cruise supersonically with reduced ground overpressure.

SYMBOLS

C_L	lift coefficient
$C_{L,CRUISE}$	lift coefficient at beginning of cruise
F(y)	Whitham F-function of variable y
h	altitude or separation distance, ft
M	Mach number
W	aircraft weight, lb
x	longitudinal distance along model signature, in
y	effective length along the longitudinal direction of the aircraft or concept

BACKGROUND

The impact of nacelles on the shock systems from conceptual aircraft was first observed during wind-tunnel measurements of pressure signatures from the Mach 2 and the Mach 3 theory-validation wind-tunnel models of reference 15. These were *1:600 scale* models of conceptual aircraft designed with the methodology documented in references 16 and 17 as well as methodology reflected in the wind-tunnel models and pressure-signature measurements described in reference 18. A three-view sketch of the Mach 2 concept is shown in figure 1.

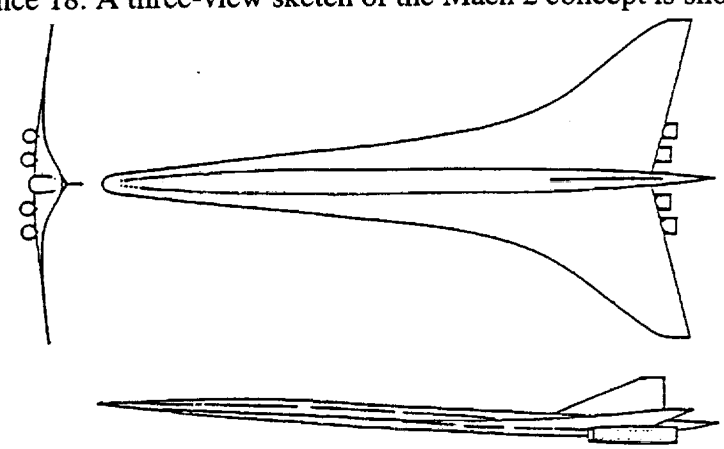

Figure 1. Mach 2 low-boom theory-validation concept.

During the wind-tunnel tests, this model generated a pressure signature which had an unexpected strong shock between the nose and tail shocks as seen in figure 2.

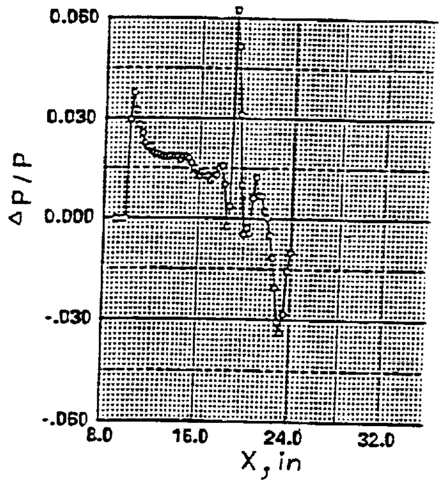

Figure 2. Pressure signature from the Mach 2 wind-tunnel model: M = 2.0, h = 6 in, and $C_L = 0.068$; nacelles on.

The model's nacelles were thought to be a possible source of the shock, so they were removed and another pressure signature, figure 3, was measured.

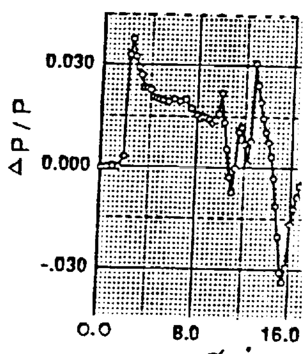

Figure 3. Pressure signature from the Mach 2 wind-tunnel model: M = 2.0, h = 6 in, and $C_L = 0.068$, nacelles off.

Comparisons of figures 2 and 3 showed that the unexpected strong shock observed in figures 2 was, as suspected, caused by the engine nacelles. However, the shock should not have been present since the Mach 2 and Mach 3 models had been designed with the latest methods, references 16 and 17, which should have accounted for these nacelle disturbances.

A methods analysis and re-evaluation revealed that the original methodology was based on assumptions not completely fulfilled on real wind-tunnel models or real aircraft. These idealized assumptions concerned the fineness ratio and inlet-lip angles of the engine nacelles: nacelle diameter/length ratios of 1/10 or more, and inlet-lip angles of 1.0 degree or less. Nacelle diameter/length ratios were actually closer to 1/8 and inlet-lip angles were in the 3.0 to 4.0 degree range. The aerodynamic volume of the nacelle (integral of the nacelle cross-section area minus the inlet area along the length) was usually a small contribution to the total equivalent area of the aircraft. However, a lip angle of 3.0 to 4.0 degrees generated a strong shock and an abrupt "jump" in front of the nacelle F-function because the *inlet-lip radius is not zero* as it is on the nose of a slender body of revolution. Similarly, the area gradient at the start of the nacelle-wing interference-lift distribution had a linear component which introduced a similar "jump" in front of the nacelle-wing interference-lift F-function. The analysis and its results were presented in reference 19 where it was shown that: (1) sharp-lip-angle nacelles would generate undesirable flow-field shocks if the nacelles were positioned by low-drag rather than by low-boom criteria; and (2) the nacelles generated these strong shocks under choked-flow or unchoked-flow conditions. So a modification was made to the design and analysis method: equivalent areas would be summed and used to calculate a combined-area F-function only if each area component started with zero area and had smooth and continuous derivatives at their origins; F-functions for components like engine nacelles would be calculated separately, and then combined with F-function from the components with smooth and continuous area distributions to obtain an aircraft F-function.

APPLICATION OF MODIFIED METHODOLOGY

The modified method for predicting sonic-boom overpressures and designing low-boom conceptual aircraft seemed theoretically and empirically correct, but wind-tunnel tests were necessary for validation. To achieve this objective, new aircraft concepts were designed, references 20 to 22, and *1:300 scale* wind-tunnel models were built. The concepts were designed with the high-aerodynamic efficiency approach and methods of reference 23. They also incorporated the results from the most recent low-boom technology studies. The desired goal was to determine whether mission requirements and low-boom constraints could be met with aircraft concepts whose gross takeoff weights were similar to those without sonic-boom reduction features that were designed by United States aircraft companies. Mission characteristics were determined by weights and performance codes similar to the code in reference 24. Sonic-boom characteristics were predicted with Whitham theory during the design process or with Computer Fluid Dynamics (CFD) methods for comparison with data from the wind-tunnel tests.

Two of the three conceptual aircraft, references 20 and 21, had engine nacelles in the usual under-the-wing location where they generated both nacelle-volume and nacelle-wing interference-lift disturbances. The third concept, the HSCT-10B, reference 22, had the engine nacelles mounted on the aft-fuselage where they generated nacelle-volume, but not nacelle-wing interference-lift disturbances, in the flow field. Large flow-field disturbances from the engine nacelles would be readily observed in the measured pressure signatures from the HSCT-10B model if the design methodology was inadequate or was improperly applied when the nacelles were integrated with the wing-fuselage for reduced sonic boom. Such data would be helpful when the complete body of wind-tunnel test data was interpreted.

The HSCT-10B concept was designed after an analysis of wind-tunnel data from the previously-mentioned Mach 2 low-boom theory-validation concept, figure 1. Similar in length, but with 6.25 percent less span, it was designed to have low sonic-boom characteristics at a Mach number of 1.8 rather than 2. There were other performance-based design differences as well. The HSCT-10B was designed to cruise at Mach 2.4 over water and Mach 1.8 over land. The Mach 2 theory-validation concept had the engine nacelles under the wings, but the HSCT-10B had its engine nacelles mounted behind the center-section trailing edge on the aft fuselage. The Mach 2 concept had slightly-notched wing with an area of 15,000 ft^2, but the HSCT-10B had a moderately-notched wing with an area of about 10,500 ft^2. A three-view sketch of the HSCT-10B concept is shown in figure 4.

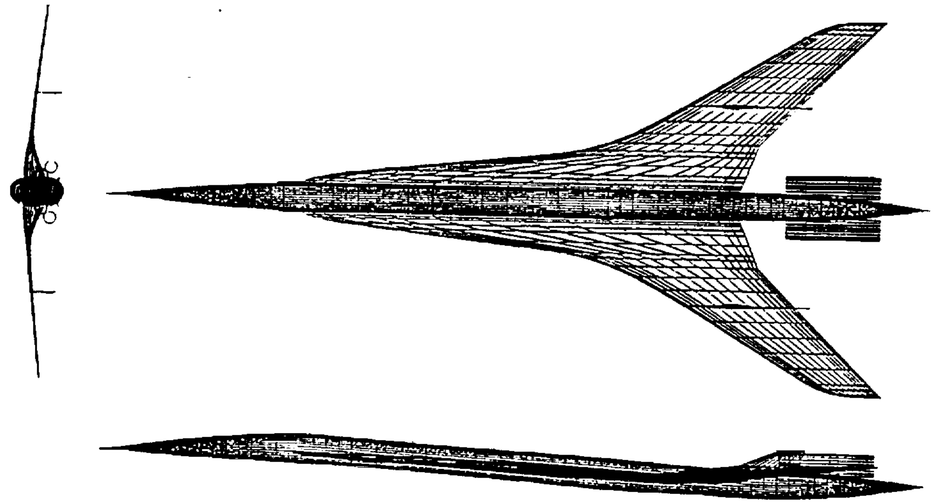

Figure 4. Three view of the aft-fuselage engine nacelle concept, the HSCT-10B.

The HSCT-10B wind-tunnel model had the sting integral with the fuselage. Strain gages were recessed in the model sting to form a balance-sting support so that lift and pitching moment could be monitored during the measurement of flow-field overpressures. This arrangement permitted a smooth transition between the model and the sting support, but it meant that the area aft of the fuselage altered the shape of near-field pressure signatures.

WIND-TUNNEL TEST DATA AND ANALYSIS

The HSCT-10B wind-tunnel model produced pressure signature data that were both encouraging and disappointing. With the model at half the cruise lift coefficient, the top of the measured pressure signature was markedly flat and level. This was the desired shape that was expected from the modified design, analysis, and nacelle-integration methods employed during the design process. As the lift on the wind-tunnel model was increased, a slight "ramp" started to form across the top of the positive-pressure section of the signature. As cruise lift was neared, the aft end of the "ramp" erupted into a pressure disturbance which quickly grew to shock levels as full cruise lift was reached. The appearance and strength of this shock was not expected. However, these pressure signatures, with both large and small engine nacelles, somewhat resembled the shape and features of the pressure signatures from the Mach 2.7 low-boom wind-tunnel models whose data was reported in reference 18. In the following sections, samples of these pressure signatures from the HSCT-10B model will be presented. They were measured through a range of C_L from 0.5 $C_{L,CRUISE}$ to full $C_{L,CRUISE}$. The practice of using varying lift had been used before in previous wind-tunnel pressure-measurement tests with references 18, 25, and 26 being typical though not an exhaustive set of examples.

<u>HSCT-10B Concept Model.</u> The two measured pressure signatures in figure 5 and 6 are from wind-tunnel tests, reference 27, of models derived from the HSCT-10B concept shown in figure 4. They were measured at a Mach number of 1.8 and at a distance of 24 inches with the model at a $C_L = 0.0511$, which was a $C_L/C_{L,CRUISE}$ ratio of about 0.5.

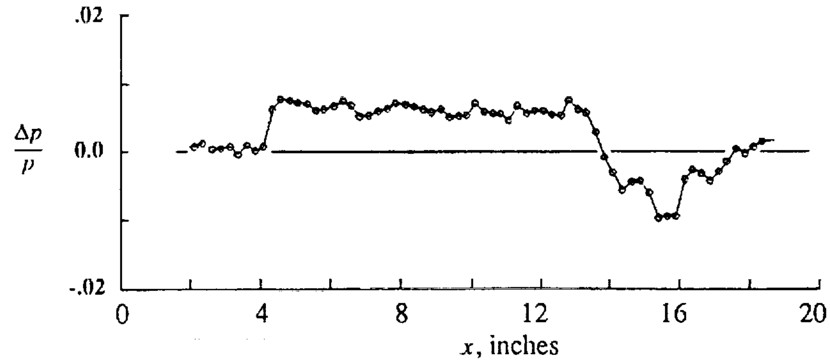

Figure 5. Pressure signature from the HSCT-10B at M = 1.8, C_L = 0.0511, and h = 24 inches; small nacelles.

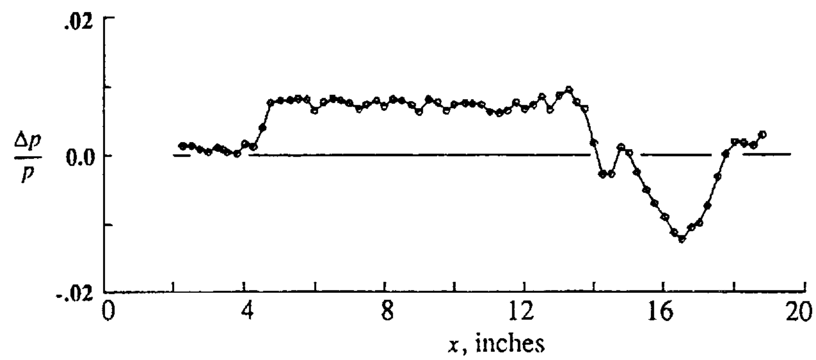

Figure 6. HSCT-10B pressure signature: M = 1.8, C_L = 0.0511, and h = 24 inches; large nacelles.

Both positive-pressure sections of the pressure signatures are virtually identical in shape, length, and magnitude although the large nacelles were 19-percent longer and 39-percent wider than the small nacelles. However, the C_L was only half of $C_{L,CRUISE}$. At this lift condition, the top of the pressure signatures is virtually flat without any indication of wing-fuselage junction, wing leading-edge crank, or nacelle shocks.

When the C_L was increased to 0.1022, the cruise lift coefficient, the pressure signatures in figure 7 and 8 were recorded.

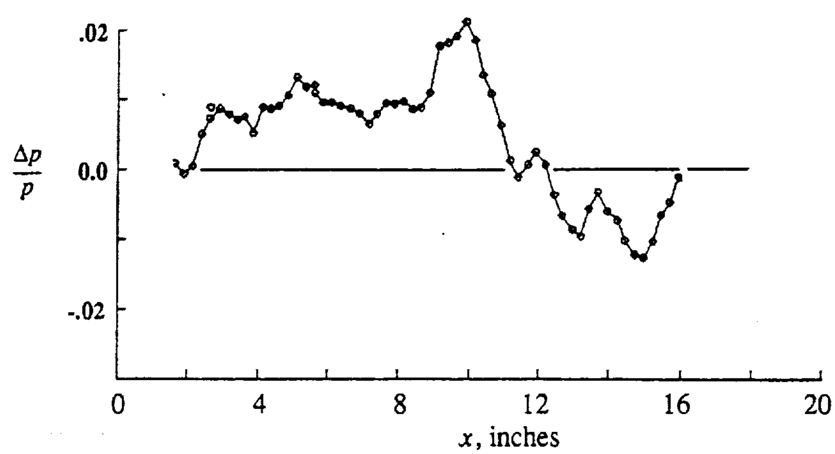

Figure 7. HSCT-10B pressure signature: M = 1.8, C_L = 0.1022, and h = 24 inches; small nacelles.

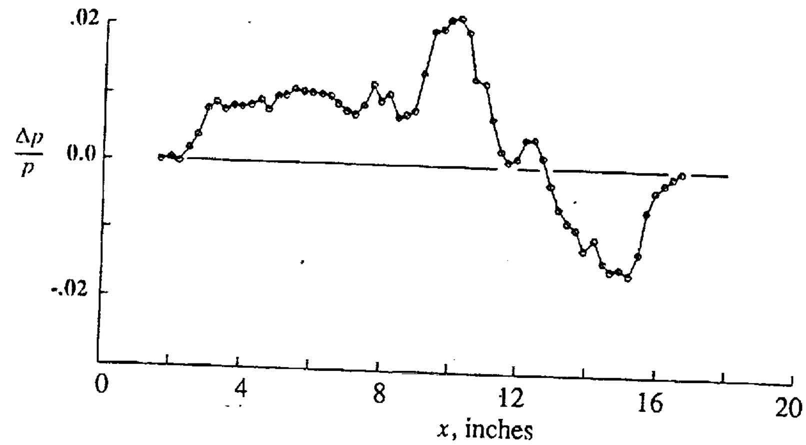

Figure 8. HSCT-10B pressure signature: M = 1.8, C_L = 0.1022, and h = 24 inches; large nacelles.

Again, both positive-pressure sections of the pressure signatures were virtually identical in shape near the front with an additional strong shock (due entirely to wing lift) positioned before the expansion to the tail shock. These changes in signature shape, from figure 6 to figure 8, over a range of lift coefficients, $C_L/C_{L,CRUISE}$ of 0.50 to 1.0, are shown in figure 9.

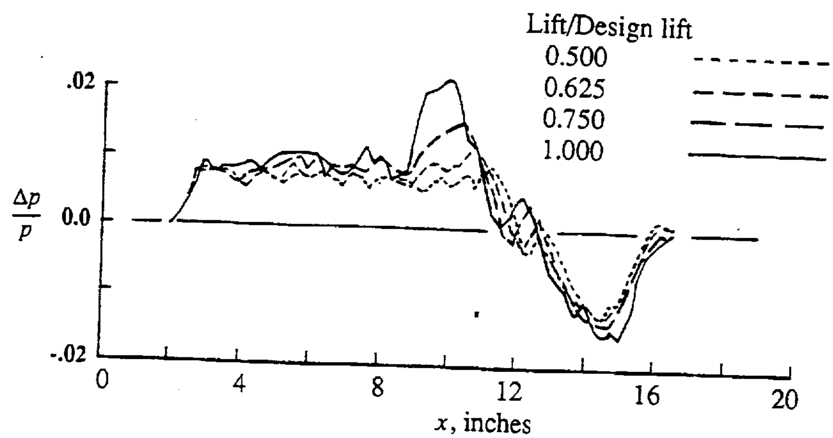

Figure 9. HSCT-10B pressure signatures: $C_L/C_{L,CRUISE}$ ratios of 0.50, 0.625, 0.75, and 1.0; M = 1.8, h = 24 inches, large nacelles.

Since the wing leading edge contour on the HSCT-10B planform was purposely made smooth and continuous, the growth and strength of the lift-induced shock was a source of concern. This rapid growth in flow-field disturbance was the result of a relatively small increase in angle of attack. The positive-pressure segment on the signature in figure 5, $C_L/C_{L,CRUISE}$ = 0.5, suggested that, at the low lifting pressures across the wing upper and lower surfaces, the equivalent areas and summation of F-functions represented the model's low volume and lift disturbances reasonably well. With increasing lift, an ever larger pressure perturbation due to lift formed until, at the designed-cruise lift coefficient, a strong shock, rather than a flat-topped pressure trace, signaled the end of the pressure signature's mid-section ramp and the beginning of the expansion leading to the tail shock. This lift-induced disturbance grew into a strong shock over a range of about 1.5 degrees in angle of attack which corresponded to an increase in equivalent area-due-to-lift from 400 ft^2 to 800ft^2.

The growth and behavior of this lift-induced disturbance suggested that it was due to near-field effects. If this hypothesis was correct, the observed extra shock was an imbedded shock that would decrease in strength rapidly before it could move forward to coalesce with the nose shock. The "ramp" section of the signature will lose its "roller-coaster" appearance and would approach the shape of the desired ground signature. However, further wind-tunnel tests at larger separation distances would be required to check this hypothesis.

The pressure signatures in figure 5 and 6 showed no large shocks from either the small or the large engine nacelles, while the pressure signatures in figures 7 and 8 showed almost identical shocks when the lift on the model was increased through the same range. These results were the basis of a conclusion that the engine nacelles had been successfully integrated into the wing-fuselage of the HSCT-10B concept and that nacelle-integration methodology could successfully account for nacelle volume disturbances. Since only the small engine nacelles were used in the design of the HSCT-10B, the carry-over to the large engine nacelles must be considered fortuitous.

There was no time available to begin a new design that would test the complete nacelle-integration methodology. A "boom-softening" study was undertaken to reduce the sonic boom of a configuration without employing the configuration tailoring described in reference 11. This study, then, became an opportunity for employing and theoretically evaluating the full capabilities of the Langley nacelle-integration methodology.

METHOD APPLICATION TO A "BOOM-SOFTENED" CONCEPT

The conceptual aircraft shown in figure 10 was designed as part of the "boom-softening" study reported in reference 28.

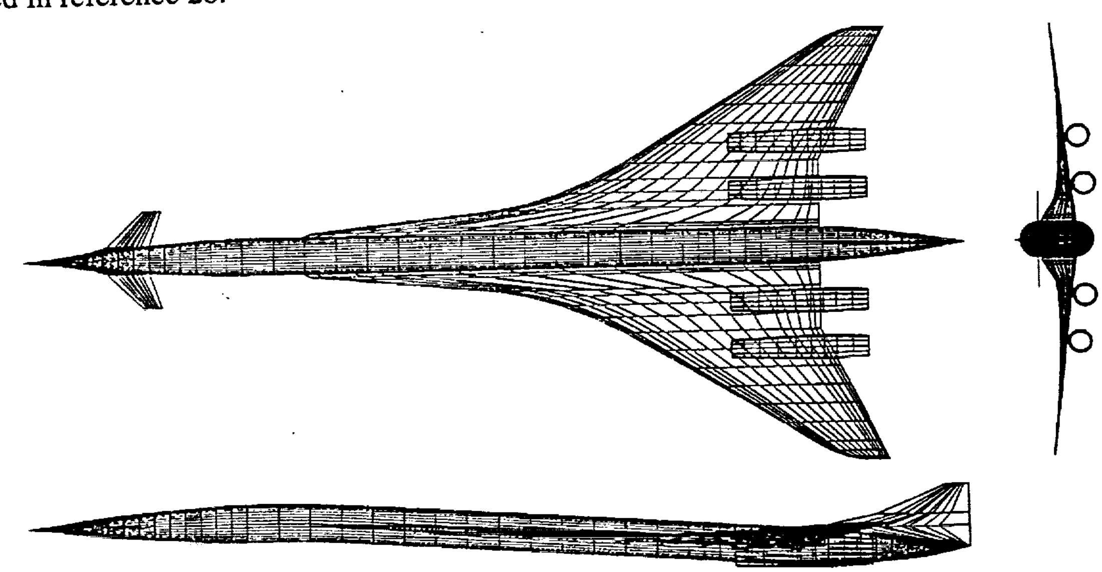

Figure 10. Three view of the "boom-softened" arrow-wing concept, the HSCT-11C.

It differed from the baseline McDonnell-Douglas concept mainly in two ways: (1) its planform had an extended and curved leading edge to "soften" the sonic boom without drastically increasing the wing area and the gross takeoff weight; and (2) the configuration was given a canard, rather than a horizontal tail, for takeoff and landing operations.

The design Mach number for the HSCT-11C was 2.4, the cruise Mach number specified of all the "softened-boom" study concepts. Figure 11 shows the complete F-function of the HSCT-11C.

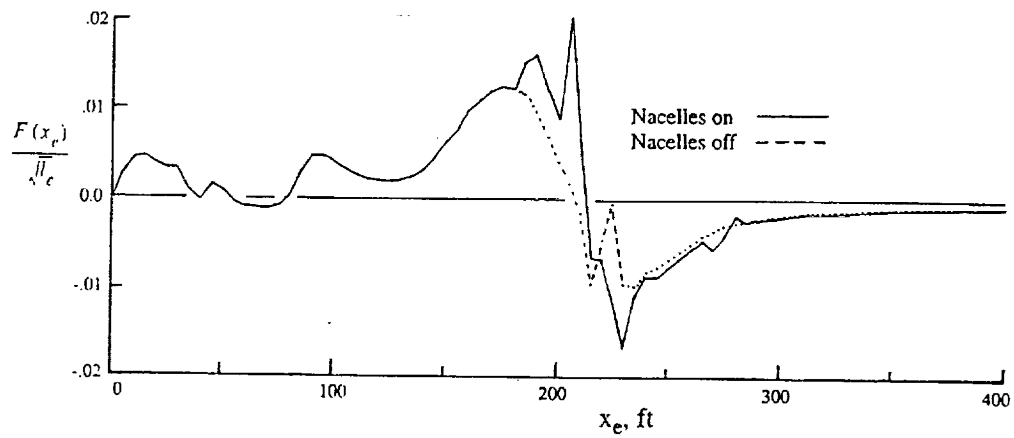

Figure 11. F-functions of the HSCT-11C concept at M = 2.4 and W = 684,400 lb.

The location of the engine-nacelle disturbances, both volume and interference lift, are readily apparent on these summed F-functions. In figure 12, the predicted ground pressure signatures, nacelles on and nacelles off, are presented and compared for the HSCT-11C at cruise Mach number and 56,850 ft.

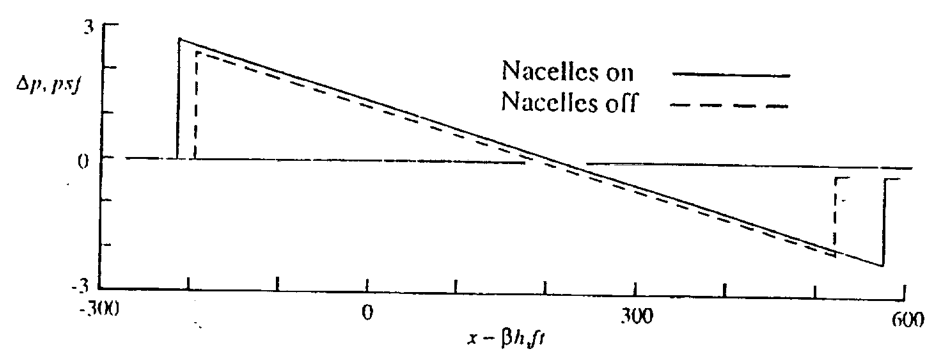

Figure 12. Predicted ground signatures from the HSCT-11C at M = 2.4, W = 684,400 lb, and h = 56,850 ft.

There is a 0.3 psf increment between the nacelles-on and nacelles-off condition which is noticeable even on this non-low-boom-tailored configuration. If the engine nacelles could be moved further aft, their disturbances would be superimposed on the F-function's expansion region and considerably reduced in its effect on the nose-shock strength. The nacelles could be moved further aft by extending the central wing section; an idea modeled after that feature on the Russian Sukhoi S-51 conceptual aircraft, reference 29, which is shown in figure 13.

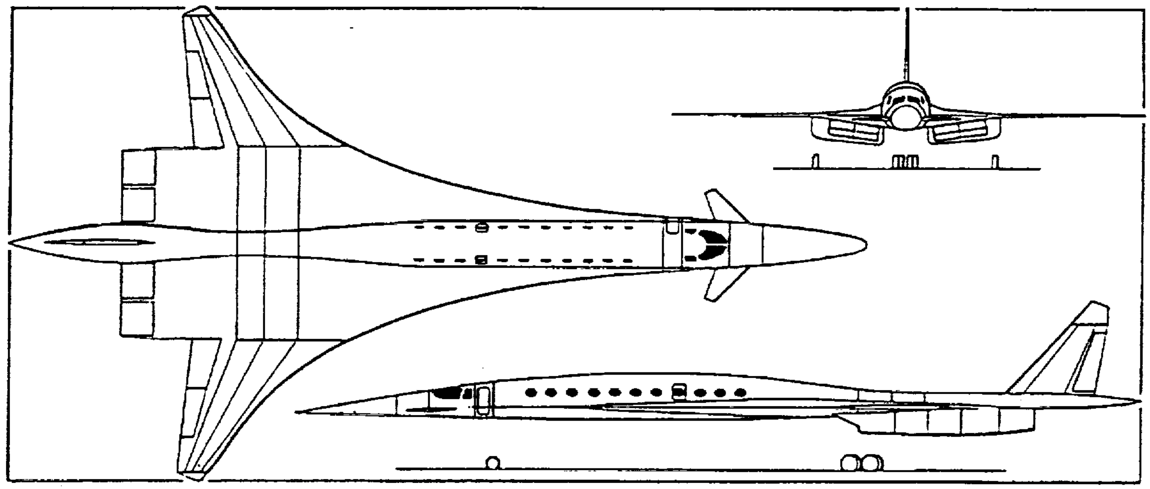

Figure 13. Three-view of the Sukhoi S-51 conceptual aircraft.

This modification to the wing planform of the HSCT-11C was employed as a "softened-boom" feature on the HSCT-11E. With it, the wing-mounted engine nacelles could be moved aft so their lip-shock disturbances should not add to the strength of the nose shock. The canard on the conceptual HSCT-11E, as on the HSCT-11C, was used only for takeoff and landing. A three view of the HSCT-11E concept is presented in figure 14.

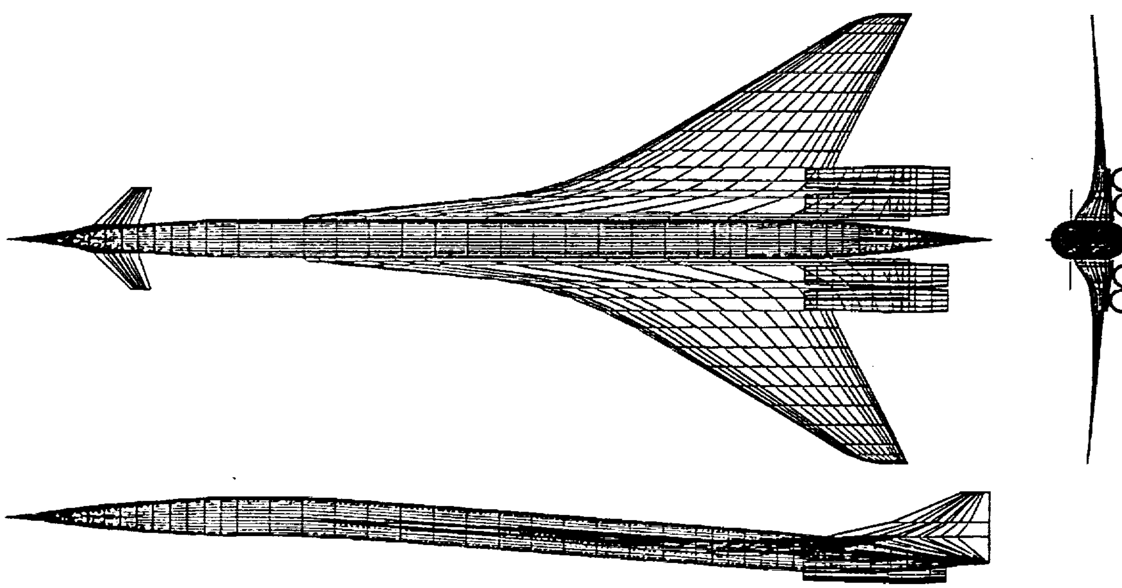

Figure 14. Three view of the HSCT-11E concept (the modified HSCT-11C).

With the engine nacelles shifted to this aft location, the combined nacelle volume and interference lift disturbances are also moved aft on the concept's F-function, as seen in figure 15.

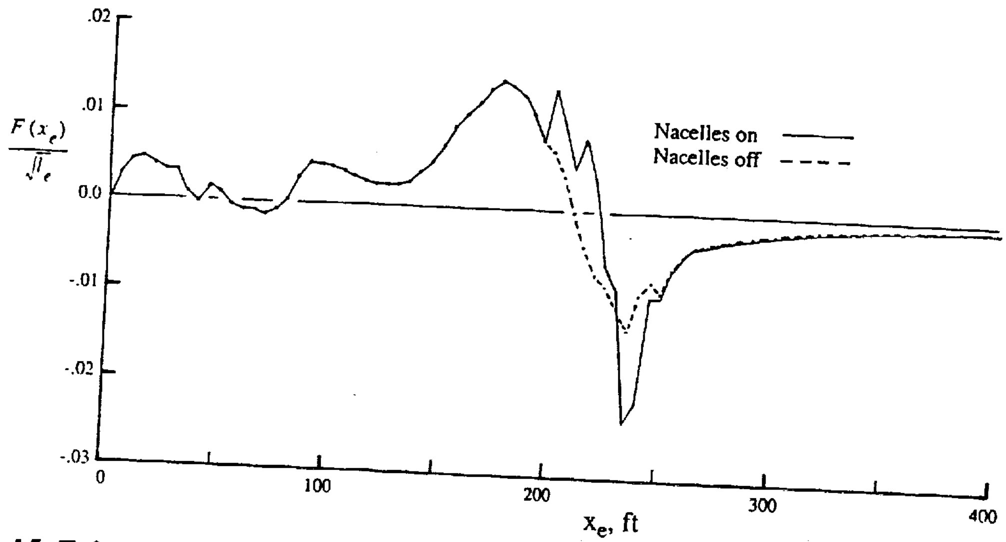

Figure 15. F-functions of the HSCT-11E concept at M = 2.4 and W = 696,000 lb.

Predicted pressure signatures from the HSCT-11E concept, with and without nacelles, were obtained from the F-functions in figure 15. These pressure signatures are presented and compared in figure 16.

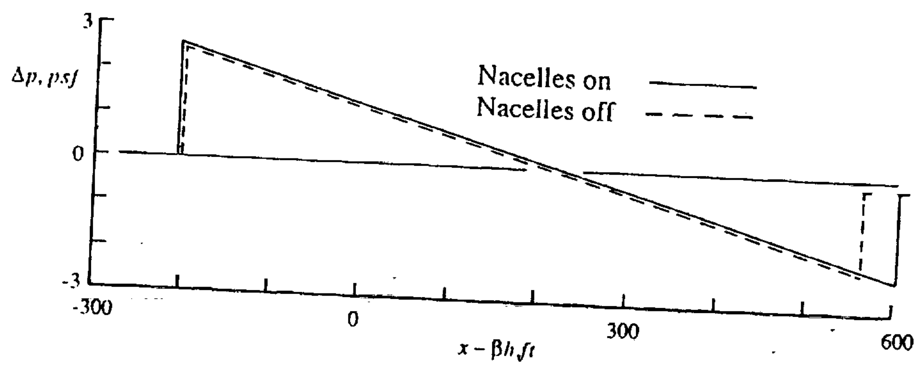

Figure 16. Predicted ground signatures from the HSCT-11E at M = 2.4, W = 684,400 lb, and h = 56,850 ft.

Although shifted aft over twenty feet, the nacelles still add a small incremental engine-nacelle volume and interference lift disturbance to the strength of the nose shock. Moving the engine nacelles further aft would have helped, but this would also have imposed an larger weight load on the trailing edge of the wing's extended center section. However, the shape of the F-function in figure 15 indicated that the wing planform shape and lifting length were the major contributors to the nose-shock strength problem. If equivalent-area tailoring were applied to the concept's volume and lift distribution by further alterations to the wing planform, the nose shock could be reduced and the present location of the engine nacelles would not aggravate the reduced sonic boom obtained by the use of low-boom methodology. Meanwhile, the extra inboard chord length increased the available volume for fuel and landing gear stowage If the wing thickness/chord ratio was kept constant, there was additional spar depth for support of the engine nacelles. However, there was an aerodynamic-performance decrement to be accepted since wing area was added while the span remained constant. Moreover, the additional wing area and volume would mean an increase in the configuration's gross takeoff weight.

CONCLUDING REMARKS

An analytical and empirical technique for integrating the engine nacelles to a wing-fuselage-fin configuration has been described. The technique was based on a more-complete application of Whitham sonic-boom theory and sonic-boom minimization of Seebass and George, and was developed to remedy the shortcomings of the previous method for analysis of sonic-boom characteristics which was developed during the 1960's and 70's. Previous methods assumed that engine nacelles slender with smooth and continuous area distributions, but the new technique made no such assumption and permitted the application of low-boom methods along with high aerodynamic efficiency methods to the analysis and configuring of a supersonic-cruise conceptual aircraft during all stages of preliminary design.

Two HSCT concepts were used as examples to illustrate the application of this engine-nacelle integration method: (1) a concept with engine nacelles mounted behind the wing on the aft-fuselage, the HSCT-10B; and (2) a concept with engine nacelles mounted under wing center-section extensions, the HSCT-11E. In both cases, the key to reducing the flow-field disturbances from the engine nacelles was to move them behind the wing where they would be in a "Mach-sliced" or area-ruled expansion region, where the wing lift was reaching its maximum value.

Mounting the nacelles behind the wing on the aft fuselage removed the interference-lift disturbances and helped shift the center of gravity rearward, but it would place the nacelle inlets in the upper-surface flow fields of the wing and the fuselage. It would also impose a large weight and thrust loading on the tail section of the fuselage. Extending the wing center section so that the engine nacelles could be mounted further aft under the wing moved both the nacelle volume and the interference lift disturbances closer to the desired expansion region on the conceptual aircraft's F-function. Additional benefits were extra wing volume available for fuel, landing gear stowage, and nacelle support structure. However, these advantages were obtained at the expense of extra wing area that reduced overall aerodynamic efficiency, and wing volume that would probably increase the gross takeoff weight.

Both the Mach 2.0 theory-validation concept and the HSCT-10B were, theoretically, low-boom conceptual aircraft. However, if the "boom-softened" HSCT-11E would have been given low-boom area-rule tailoring, it could have become an aircraft concept with engines in the under-the-wing location that possessed reduced- or low-boom characteristics. Nevertheless, both concepts, the HSCT-10B and the HSCT-11E, demonstrated that low-boom technology and nacelle-integration methodology along with high aerodynamic performance efficiency, innovative structural efficiency, and advanced-composite materials could be included in the process of preliminary conceptual-aircraft design. The HSCT-10B and the HSCT-11E concepts are most likely not the only possible configurations that could achieve low-boom or "softened sonic-boom" status. Since the canard on the HSCT-11E concept was intended only for takeoff and landing, both concepts were flying wing configurations during the supersonic-cruise segment of the mission. It is likely that there are canard-wing or wing-horizontal tail configurations, with the canard and the horizontal tail carrying positive lifting loads, that might be achieve reduced- or low-boom flight during supersonic cruise. In either case, the keys to achieving a low-boom conceptual aircraft design would include the successful integration of engine nacelles on a wing-fuselage configuration that also has the potential for high aerodynamic efficiency at cruise and low speeds, and low structural weight.

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13. ABSTRACT ***(Maximum 200 words)***
An empirical method for integrating the engine nacelles on a wing-fuselage-fin(s) configuration has been described. This method is based on Thitham theory and Seebass and George sonic-boom minimization theory. With it, both reduced sonic-boom as well as high aerodynamic efficiency methods can be applied to the conceptual design of a supersonic-cruise aircraft. Two high-speed civil transport concepts were used as examples to illustrate the application of this engine-nacelle integration methodology: (1) a concept with engine nacelles mounted on the aft-fuselage, the HSCT-10B; and (2) a concept with engine nacelles mounted under an extended-wing center section, the HSCT-11E. In both cases, the key to a significant reduction in the sonic-boom contribution from the engine nacelles was to use the F-function shape of the concept as a guide to move the nacelles further aft on the configuration.

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