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Supersonic Transport Optimization to Mach 4

Dennis M. Bushnell
Langley Research Center, Hampton, Virginia

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Langley Research Center
Hampton, Virginia 23681-2199

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INTRODUCTION

There are several companies (e.g., Virgin Galactic, Boom, Spike, Aerion, and Hermeus) currently developing supersonic transports [refs. 1, 2], and Space X is studying application of its large rocket to point to point travel on the home planet [ref. 3]. The current and historical safety record of rocket launches is failure on the order of every 100 launches, some 1000 times more accident prone than current subsonic air travel [ref. 4]. Application of rockets to point to terrestrial travel will probably require serious attention to improving flight safety. There are also some who are working on Mach 4-level airbreathing high supersonic Mach number transports. The knee of the efficiency curve for point-to-point travel on a body the size of the Earth is on the order of Mach 4 to 5, hence the interest in that Mach number range [ref. 5].

For several decades (1920s to 1960s), the development trend of commercial aviation was higher and faster, culminating in the 707 class of conventional takeoff and landing (CTOL) transports (and subsequent derivatives). This extraordinary marriage of the swept wing and jet engines revolutionized long-haul passenger transport and supplanted steam ships, trains, and more recently, even eroded the lower end of the long-haul transport spectrum, buses. The higher and faster trend was halted in the '70s by a combination of economic reality and environmental concerns. The next logical step beyond the 707-class aircraft would have been a supersonic transport (SST). Such an aircraft nominally cruises in the Mach number 2 to 3 range and would represent a revolutionary development in long distance transport. An early version of such an aircraft, the Concorde, while a technological marvel for its time, was not economically viable, and only a small number were produced and operated. Many of the problems associated with SST class aircraft, both economical and environmental, are traceable in a major way to shock waves. These problems include high drag (and associated low lift-to-drag ratio/range), sonic boom, and higher material temperatures. Depending upon the subsonic comparison, SSTs typically burn some three to seven times more fuel per passenger-mile than subsonics. The U.S. SST program was canceled in the early '70s in an era of (a) general technological antipathy, (b) rising fuel costs, and (c) environmental sensitivity/concerns.

Today there is a resurgence of interest in civilian supersonic long-haul aircraft. Probable reasons for this are the emergence of the Pacific Rim as an ever-increasing major economic entity and technology advances. The subsonic CTOL flight times associated with passage between some of the major Pacific economic players is on the order of 12 hours or greater, which is fostering the application of immersive presence, digital reality (aka tele-travel) for many purposes as a substitute for physical travel. The Pacific application of an SST is more technologically demanding in that longer range is required than for many Atlantic flights. Additional technological problems or boundary conditions imposed upon an SST for operation include: (a) ozone depletion and upper atmospheric pollution concerns including water, CO_2 and NOx (b) sonic boom, and (c) sideline noise along with uphill econometrics. Fortunately, several technologies have developed to a considerable degree since the last large-scale SST studies including: variable cycles, supersonic through-flow fan [refs. 6, 7], engines with higher turbine inlet temperature and staged combustion, lightweight, higher temperature materials, flow control including automatic load alleviation and laminar flow control, and improved shaping methodologies to reduce sonic boom. However, even with currently projected technology levels, the development of an economically viable SST will be a formidable task. We are not starting from a surfeit of performance. The major SST metrics include:

- Weight which affects take off noise, sonic boom, range, fuel burn, and payload fraction
- Sonic boom and takeoff noise
- Drag, lift to drag (L/D), fuel burn, range
- Emissions/Climate (CO_2, NOx, water, cirrus, ozone, black carbon)
- Cost/econometrics compared to subsonics
- Propulsion efficiency/fuels with regard to performance and emissions
- Safety including radiation

The present report will consider the frontiers of these metrics and their synergistic interactions and suggest approaches for overall vehicle optimization.

AERODYNAMICS, DRAG REDUCTION AND FLOW CONTROL [refs. 8 and 9 and refs. therein]

There is an especial need for improved aerodynamic performance. Improvements in L/D would be extremely significant, given the small payload fractions inherent in SST design, while a factor of two increase in L/D would literally be revolutionary and alter the entire economic viability issue. The lower supersonic Mach number SST L/D is on the order of 10 (without the inclusion of many real vehicle influences). The Concorde value was on the order of 7. Values greater than 16 have been proffered [ref. 10]. The performance requirements for a Mach 4 or so high supersonic transport are greater, due to the increased wave drag. However, the higher altitude (90K ft vs. 60K ft) is efficacious for sonic boom. The near lack of atmospheric particulates reduces the cirrus cloud warming impacts of water emissions (with the exception of interplanetary dust and meteoroid fragments).

The benefits of sizable drag reductions would alleviate several of the environmental and economic concerns. Reduced fuel requirements associated with drag reduction results in lower weight, which could provide benefits in terms of reduced: (a) sonic boom, (b) sideline noise, and (c) pollution, (d) as well as reduced initial and direct operating costs. Obviously, supersonic aircraft optimization concepts would also be of interest for possible application in various military arenas such as supercruise fighters, artillery rounds, supersonic cruise missiles, tactical and strategic missiles, and (military/civilian) low-Earth-orbit launch vehicles, both airbreathing and non-airbreathing.

The drag breakdown of a typical supersonic transport design [refs. 11, 12] is on the order of 1/3 skin friction (assuming no pressure drag associated with flow separation and neglecting trim drag). It is also 1/3 wave drag (volume wave drag and wave drag due- to-lift (DDL)) and 1/3 vortex DDL. At high supersonic Mach numbers, wave drag percentage is greater and the others less. Thus far, the major drag reduction efforts for SST class aircraft have concentrated on wave drag reduction, a vital issue and the newbie for supersonic transports, and friction drag reduction. The search and research for supersonic drag reduction for one component of drag can result in increased drag for another component such as the increased surface area (increased skin friction, as well as weight/structure penalties) associated with many favorable interference concepts for wave drag reduction. Addressing the supersonic aircraft drag reduction problem from an overall viewpoint using the full arsenal of available and emerging technologies would allow such ancillary penalties to be minimized. Favorable synergisms are possible in some cases.

Drag reduction is required during both supersonic and subsonic (overland) operation unless sonic boom issues are solved with regard to overland flight. Fuel is approximately one half of the gross weight [ref. 13], and the weight of the fuel reserves required for exigencies is on the order of the payload. Subsonic drag reduction, especially vortex or DDL reduction on such typically low-aspect-ratio configurations, may have particularly large net benefits. For SSTs, a l% drag decrease corresponds, approximately, to a 5% increase in passenger payload. Of possibly critical importance and particular interest are drag reduction techniques employing the maturing technologies of flow control of various types (e.g., LFC, flow separation control, and vorticity/turbulence control), and nonlinear flow phenomena via CFD. Supersonic aerodynamics was historically dominated to a remarkable degree by ideas, theories, targets, and design methodologies that are directed to avoid nonlinear effects. More accurate theories have predicted drag less than those given by linear aerodynamic theory. Major future performance improvements for transports could result from various types of flow control devices including passive shock-boundary-layer interaction control, LFC, and variable camber wings.

Viscous Drag Reduction

Roughness Minimization - Roughness drag per se is not always included in conventional systems studies, but was certainly present on all of the supersonic cruise aircraft produced thus far. Roughness at supersonic speeds is particularly worrisome due to the increased element drag caused by element shock wave formation. Concomitant with supersonic flight is aerodynamic heating and elevated temperature levels which produce thermal stresses that can be larger than those induced by aerodynamic or mass loading. Design approaches to alleviate these thermal stresses such as tiles, joints, shingles, corrugations, etc., typically result in various types of surface (drag increasing) roughness. Non-smooth aircraft surfaces not only increase drag directly, but are also responsible for promoting early transition; smooth surfaces are an enabling condition for supersonic laminar flow control. Fortunately, as in the subsonic LFC case, contemporary materials and fabrication techniques appear to be capable of surfaces of sufficient smoothness to minimize direct roughness drag, delay transition, and promote LFC. The lower near-wall density at supersonic speeds usually allows a less stringent physical smoothness criteria than the corresponding subsonic case. Viscous drag reduction via roughness minimization is both achievable, and probably essential, for a viable SST.

Transition Estimation and Delay – The ability to estimate transition location on SSTs is much improved compared to the Concorde design time frame due to: (1) development of advanced flow stability theories (along with utilization of the advancements in flow field CFD), (2) invention and development of high speed quiet tunnels, (3) high quality flight LFC and transition experiments, and (4) the realization (by inference) that the background disturbance levels in both flight and quiet low-disturbance wind tunnels, are similar. These developments have enabled the extension and application of the eN method into high-speed flows and transition initiated by each of the four major linear instability modes (TS, crossflow, GortIer, and Mach 2nd mode) with a precision (for transition estimation), which can be on the order of 20% or better in transition

Reynolds number/location. This compares to a historical uncertainty of an order of magnitude or more. This transition estimation technique parameterizes transition location as a function of the multitudinous variables which affect the mean flow, and in particular, the streamwise variation of these parameters, as well as allowing specification of conditions required to delay transition. As in most flight situations, this capability is limited to cases where background disturbances are low and much of the disturbance amplification leading to transition is linear and occurs in the absence of transition induced roughness. Such a transition estimation capability can be utilized, along with smooth surfaces, to design for transition delay for drag reduction, and thus provide limited natural laminar flow over the vehicle nose and other components. The technology can also be applied in conjunction with suction to delay transition (i.e., depending upon body design, roughness, etc., significant transition delay and concomitant drag reductions are possible using active systems). General guidelines include: (a) avoidance of parameter ranges which produce large disturbance amplification rates such as adverse pressure gradients and bleed (injection), (b) avoidance/minimization of instability modes which have large amplification rates such as Gortler and crossflow, and (c) avoidance of bypasses such as roughness. As an example, the transition Reynolds number of a 2D body can be on the order of 50% greater than the axisymmetric case at high speeds.

Laminar Flow Control - Laminar flow control or LFC is used herein to refer to transition delay via active control as opposed to transition delay by aerodynamic shaping (i.e., natural laminar flow). For supersonic aircraft, the usual LFC techniques of choice are suction and wall cooling. The wall cooling approach has been demonstrated by the Russians up to Reynolds Numbers of 34 x 106 at supersonic speeds [ref. 14], but the technique is limited to: (a) nonhypersonic aircraft and (b) regions of small crossflow as cooling does not significantly dampen the crossflow instability and destabilizes Mack 2nd (hypersonic) modes. Supersonic suction LFC is an extremely powerful technique, particularly for crossflow dominated regions (which are endemic on the typically highly swept SST configurations). The net benefits (after allowing for the suction and ducting penalties) are greater than 50% of the skin friction drag. Research in the 1960s by W. Pfenninger and his group at Northrop demonstrated that the technique works [ref. 15] (using suction through multiple closely spaced slots) up to the limits of the ground facilities employed, which were on the order of 25 million Reynolds Number for swept wings and 50 million for axisymmetric bodies. The success of these tests is remarkable in that they were conducted under the extremely adverse conditions of high unit Reynolds number (stringent smoothness tolerance) and high free-stream noise (radiated nozzle wall turbulent boundary-layer noise, present in all nonquiet supersonic/ hypersonic tunnels). Basically, supersonic suction LFC is aerodynamically feasible and the validity of the technique is further bolstered by the record of successes produced by subsonic LFC and natural laminar flow control research. This does not mean that supersonic suction LFC is in hand. In fact, considerable research is required such as attachment region and porous/perforated suction surface physics including effective 3-D roughness induced by the discrete suction as well as laminarization for juncture regions to avoid sizable loss of laminarized surface area on low-aspect-ratio (supersonic) wings from direct fuselage turbulence contamination. Additional research also includes system optimization studies such as minimization of suction drag penalty, the extent to which passive bleed can be used for LFC suction and supersonic flight suction experiments at appreciable Reynolds number to determine real world maintenance and reliability issues including heated air handling, and duct seals (i.e., the known key issues are primarily flight and systems related). Of particular concern are the destabilizing influences of various disturbance fields generated by usually turbulent and discretely rough fuselage radiated noise onto the wing LFC surfaces. Even weak waves produced by fuselage joints would oscillate (and thereby create a dynamic radiated disturbance) due to the fuselage boundary-layer turbulence. Techniques to minimize suction losses include improved suction pressure recovery, passive bleed, and approaches to reduce crossflow. Also of concern is the compatibility of LFC with leading edge thrust. What is particularly intriguing concerning supersonic LFC are the large potential benefits, not only for drag directly but also reduced radiation equilibrium surface temperature and the resizing benefits.

Turbulent Drag Reduction - The benefits of lowering the turbulent skin friction drag without resorting to LFC are much less than for the LFC case (10 to 15% of the friction drag vs. 50 to 80% for LFC). However, the techniques are more robust than LFC and, in the context of the payload sensitivity of SST designs to the level of zero lift drag, are considered worthwhile pursuing, particularly as a complement to LFC for nonlaminarized body acreage. The premiere approach is the supersonic application of riblets, small flow aligned grooves on the surface which are now state-of-the-art in subsonic flows following several successful flight experiments. The fundamental mechanism for riblet drag reduction involves utilization of large transverse friction forces near the surface (within the groove, forced by the groove presence) to increase the viscous sublayer thickness. The benefit of riblets is on the order of 8% of the turbulent skin friction. The alignment of the grooves is not critical (to within approximately 15 degrees to the local flow) and their performance does not seem to be degraded by small pressure gradients. Studies of riblets in supersonic flows indicate similar performance as in the subsonic case. The presence of a riblet-containing film on the surface also reduces roughness drag via surface smoothing and the necessarily micro-porous film converts the usual pressurized fuselage air leakage drag increase into a skin friction reduction.

The second approach of choice for supersonic turbulent skin friction reduction is slot injection, tangential downstream surface injection of low momentum fluid to reduce the wall shear levels. The key to the success of this approach is the provision or availability of a low-loss source of injectant. Simply using ram air is much too inefficient. Two possible sources of such low-loss air are LFC suction air and engine bleed air. The former can be used on the wing, downstream of the laminar flow region, to both reduce skin friction on the order of 10% or greater (depending on the quantity of air available, e.g., the extent of the suction laminarized region providing the air). Engine bleed air can also be used due to the resultant boundary layer thickening which reduces wing trailing-edge shock drag. This latter effect is in contravention to the low-speed case where thicker trailing-edge region boundary layers produce larger pressure or form drag. In the supersonic case, the increased displacement thickness can reduce closure wave drag. Engine bleed air, that is air passively bled from inlets/compressor section to control flow separation, can be applied locally to reduce the external nacelle skin friction drag. The estimated benefit from reference 16 is on the order of 35% of the nacelle friction drag, thereby partially mitigating the effects of the inlet bleed, which can amount to as much as 3 to 5% of total airplane drag. Considerably more speculative, and applicable only in the nose region or locally depending upon the detailed design, is the concept of using the large debilitative influence of convex longitudinal curvature upon wall turbulence to yield a net skin friction reduction. Research on this concept, even for the subsonic case, is still in the early stages, but there is evidence that convex longitudinal curvature will appreciably reduce turbulent skin friction, and that the affect can last on the order of 50 boundary-layer thicknesses downstream. Whether such an approach can yield a net benefit, considering the possible adverse effects on wave drag, remains to be seen.

The remaining possibilities for reducing turbulent skin friction are obvious and depend upon the specific design. One such technique is sheer size, using Reynolds number, due to the well-known reduction of skin friction coefficient with increasing length of Reynolds number due to boundary layer thickening. There is also a favorable influence of increased wall temperature upon skin friction level, produced primarily by the resultant reduction in near wall air density. This is in contrast to transition delay where wall cooling is required (at supersonic speeds) to reduce drag. Thus far in this discussion the emphasis has been upon reduced skin friction coefficient. What is fundamentally required is reduced wall shear stress. Alternate methods to accomplish this, besides reducing skin friction coefficient, are to reduce wetted area and local dynamic pressure. The former can be accomplished via use of active load alleviation and/or replacement of separate control surfaces by flap systems located on the necessarily elongated lifting surfaces (incorporated into the Concorde and TU-144). Thrust vectoring (enabling use of smaller controls) and planform tailoring for higher CL values can also be used. The latter can be detrimental to other components of drag (e.g., DDL, wave drag) and hence becomes part of the overall tradeoff process.

Another somewhat radical approach for reduced wetted area is some type of two-stage aircraft, either actual (e.g., takeoff requirements met via a stage that separates and flies back) or ersatz such as midair refueling or ski jumps on takeoff runways. Reduced dynamic pressure is provided as a by-product of higher Mach number regions of the flow. Higher local Mach numbers produce not only a dynamic pressure reduction but also a reduced skin friction coefficient level. This again is in contravention to the low-speed case where a higher Mach number increases the skin friction level through increases in velocity. An additional viscous drag reduction issue is optimal design of intersection regions to avoid the high local skin friction which can be associated with necklace or horseshoe vortices. Numerical solutions indicate that simple fillets of adequate size can obviate the formation of such highly organized intersection region vortex flows. The design precept for such fillets is continuous surface curvature.

As with all of the optimization approaches discussed herein, many of these viscous drag reduction possibilities are probably worth at least some further research to determine their applicability and performance for particular configurations. These devices/approaches have associated with them various systems penalties, usually including structural, parasitic drag, or power consumption, and therefore their use is a function of overall system design issues. The possible penalties in the supersonic case could be aggravated by parasitic wave drag, but a decision as to whether or not to employ them should be based upon at least a cursory configuration optimization design study. As a final comment in this section research is underway on a plasma flow control approach that appears to be capable of sizable net drag reduction, TBD.

Vortex Drag Due to Lift Reduction

Classical Approaches - Vortex DDL reduction is particularly critical for SST designs in both the cruise and takeoff/landing phases of the flight. Classical linearized theory indicates that elliptic loading, increased aspect ratio/span, and lower CL values with reduced weight are the primary means by which vortex drag can be reduced. For the large sweep angles associated with low wave drag, supersonic designs increasing aspect ratio/span beyond a certain point becomes inefficient due to increased wetted area/skin friction drag, and structural penalties unless variable sweep or oblique wing (especially spanloader) approaches are utilized. The cranked delta planform is a useful compromise between low and high-speed performance. Even in the variable sweep case with the wing swept back for cruise, the aspect ratio is still low for high-speed operation. Although, for lower speed efficiency the aspect ratio is significantly enhanced by unsweeping the wing. The wetted area problems are addressable via both trailing edge notching (e.g., using arrow wings) and laminar flow control. The structural problem is possibly addressable via strut bracing [ref. 10], although detailed supersonic design studies employing the latter are not yet extant. Reducing CL typically results in a structural penalty and, thus, becomes part of the overall design trades. However, reduced weight via friction and wave drag reduction will synergistically reduce vortex DDL. The effective aspect ratio of supersonic configurations is considerably less than for subsonic CTOL long-haul transports and, therefore, performance may benefit appreciably from various nonclassical approaches to vortex DDL reduction. The application of various techniques other than increased aspect ratio for vortex DDL reduction has not been significantly addressed thus far in high-speed cruise aircraft system studies. However, some authors considered thrust vectoring for CL reduction, especially for higher Mach numbers [refs. 17, 18]. In the remainder of this section, various approaches which might be tried will be mentioned. While some of these approaches can be directly applied, most require considerable further research, even for the subsonic case, and some may not yield any net drag reduction at all.

Non-Planar Vortex Sheet Approaches - Relaxing the assumptions of classical linear theory (i.e., closed body, no energy addition, planar vortex sheet, etc.) provides alternative DDL reduction possibilities, aside from the usual ones already mentioned. In particular, use of non-planar lifting surfaces (e.g., distributing the lift vertically through various approaches such as upswept tips) can provide reductions in vortex DDL This approach is related to the winglet case which is discussed in the next section. Natural observations (e.g., morphology on Avians [flyers] or Nektons [swimmers]) may relate to the DDL reduction problem and in particular to the production of non-planar vortex sheets. The first of these is the swept-back tapered tips seen on many fliers and swimmers. When wings with such tips are placed at incidence, the lift is distributed vertically toward the tip. Also termed sheared tips, there may be a measurable benefit associated with this bionic observation. Other interesting bio morphologies, which require investigation, include serrated trailing edges, leading edge bumps, and the curious tip of the shark caudal fin, where a trailing-edge near-tip cutout has a hinged flap, forming a combined swept back, notched, and winglet-like fin tip arrangement.

Energy/Thrust Extraction from Tip Vortex - The vortex, which forms at and downstream of the wing tip, is due to the upwash from the lower surface high-pressure region. This region rotates part of the lift vector into the drag direction and is the cause of vortex DDL. As aspect ratio increases, a smaller percentage of the wingspan is influenced by this flow and, as stated previously, the DDL is reduced. A characteristic feature of this vortex formation is flow which is at an angle to the free stream. Devices can therefore be inserted into this flow to produce/recover thrust and/or energy from this tip flow. This (simplistically) is the fundamental rationale behind at least four devices which reduce vortex DDL. These devices include tip turbines for energy extraction, winglets and vortex diffuser vanes. The vortex diffuser vane is supported by a spar behind the wing tip to allow the tip vortex to concentrate before intercepting it. Of particular interest and effectiveness with regard to wing tip devices for vortex DDL reduction are C tips.

These devices work quite well, producing, on the order of 5% to 15%, vortex DDL reduction at subsonic/transonic speeds (depending upon wing design). Major issues of concern include structural, penalties, possible use as control devices, and for the high-speed case, associated wave drag.

Alteration of Tip Boundary Condition(s) - These DDL reduction techniques are based upon either eliminating the tips altogether or injecting mass in the tip region. Eliminating the wing tips can be accomplished either via ring wings or joined wings and tails. Injecting mass at the tip is accomplished either via tip engines, tip blowing, or various types of porous tips. The tip engines and tip blowing result in sizable DDL reduction. The tip blowing is especially intriguing as the required mass flow could possibly be obtained via wing leading-edge ingestion (passive bleed), and the blowing could be used to tailor for the production of, and be modulated to excite, virulent instabilities in the tip vortex at landing/takeoff for amelioration of the wake vortex hazard problem.

Wave Drag Reduction

As mentioned in the introduction, the formation of, and losses associated with, shock waves at supersonic speeds is probably the major core problem of SST design (along with the all-pervasive ozone and other high-altitude pollution issues). Shock waves cause additional drag due to both volume and lift and are responsible for one of the major impediments to a successful SST design-sonic boom. Therefore, minimization of wave drag has, historically, been the focus of SST drag reduction research. Both volume wave drag reduction and wave DDL reduction are included in this section. It should be noted that the performance of many of these approaches is limited by the real flow effects of flow separation and the suggestions in the section on flow separation control are included herein to allow full advantage to be taken of these various inviscid wave drag reduction approaches.

Classical Approaches to Wave Drag Reduction - Several of the zeroth order approaches to wave drag reduction for supersonic cruise aircraft are extensions into the supersonic regime of transonic techniques optimized via linear theory, including wing sweep and area ruling. Detailed implementation is different at high speeds in that large sweep angles are required for subsonic (i.e., normal Mach number) leading edges. Such wings, however, have the added advantage of distributing the lift vector lengthwise (also, the forward portion of the fuselage is cambered and lift is carried over onto the fuselage) and providing for leading-edge thrust. Linear theory is also used to optimize wing twist/camber/warp to minimize DDL. Strut-braced wings could allow use of both highly swept and extreme arrow configurations to reduce both volume wave drag and wave DDL as well as wetted area/viscous drag. Other classical approaches include increased effective body length/thin sections (to reduce shock strength) and gradual (even approximations to isentropic) compression, the latter of especial interest for inlets. Simplified theories have been employed to provide various locally optimized solutions using these approaches including the R. T. Jones skewed wing. CFD/nonlinear methods have been applied to the supersonic optimization problem. Classical nonlinear flow drag reduction techniques include use of nose spikes (either physical or shock alteration via forward fluid/particle/energy injection) on blunt-nosed bodies and base blunting. The former is incorporated into the design of the C-4 and D-5 trident missiles and has been further improved via attendant mass addition in the separated flow region formed in the nose region to obviate/alter the separated flow reattachment shock systems. A blunt base reduces the strength of the base recompression shock and, as mentioned previously, the favorable influences of base blunting can be mimicked by boundary-layer thickening/displacement thickness effects through, for example, slot injection. Also, nose blunting can provide a drag reduction due to overexpansion. As stated previously, many of these classical techniques have been applied over the years to the SST design problem with considerable success, producing L/D values of 0 (10), some 50% greater than Concorde performance. As discussed subsequently in the present report, these classical methods can probably be improved upon significantly through the use of flow-separation control.

Wave Drag Reduction via Favorable Interference - There are two fundamental approaches to wave drag reduction: (1) weaken the shock wave initially, during its formation process (or substitute a series of weak shocks for a single stronger one), or (2) utilize the initial shock wave, via reflection/interaction, to create favorable interference, either for body drag reduction or lift, or both [ref. 19]. Favorable interference approaches were recognized early on and considerable effort, primarily theoretical, was expended in evaluating and optimizing various techniques. Realizations of favorable interference include: (a) ring wings and various segmented versions, (e.g., parasol wing), (b) multiple bodies (e.g., fuselages and/or control surfaces and fuselages), and (c) propulsion system interaction. For nonlifting bodies, the (nonlifting, i.e., symmetric) ring wing can cancel, in much the same way as a supersonic Busemann bi-plane, the volume wave drag of a body, at the expense of increased wetted area, weight, etc. From reference 20, "very significant drag reduction (on the order of 50%) can be obtained even with simplified ring wing-body combinations." In addition, beneficial interference effects are only gradually reduced as the Mach number varies from the design Mach number as the angle of attack is increased. For the lifting case, the parasol-type wing is more efficient with the favorable wave interference, providing both partial cancellation of the body and/or nacelle volume wave drag and an efficient lifting surface..

In the multiple body case, wave interactions/favorable interference is used to raise the pressure over the rearward portions of adjacent bodies, providing a thrust component to partially cancel the volume wave drag in a similar fashion to the (nonlifting) ring wing. Favorable propulsion system wave interactions can be of two types. In one approach, extensively used in SST design, the nacelle flow fields are used as a multiple body to provide thrusting pressure fields, particularly effective on M wings which are also interesting in and of themselves. In addition, the nacelles can also provide lifting forces on adjacent wing surfaces. The other favorable interference propulsion interaction is highly speculative. The basic concept is to reflect body shocks off of the engine exhaust flow back onto the afterbody (i.e., utilize the exhaust flow as a multiple body). Unfortunately, in many cases there appears to be very little reflection occurring, even if the engines are placed on the body in correct juxtaposition for such a favorable interaction to occur. It would be interesting to determine whether the engine exhaust flow profiles can be altered/tailored to provide for appreciable shock reflection back onto the body. The application of favorable interference for shock wave drag reduction would be facilitated by: (a) flow separation control (to control extraneous flow fields induced by shock-boundary layer interactions) and (b) active controls/morphing surfaces to ensure/maximize optimal wave positioning. From reference 11, the benefits of parasol-type wings can be on the order of a 20% increase in L/D compared to a conventional optimized wing. For nacelle interaction, favorable interference can essentially cancel the nacelle wave drag.

Speculative Wave Drag Reduction - In addition to the approaches already discussed, there are several other possibilities that could be studied for the wave drag reduction problem. These include: (a) serrated/zig-zag bodies, (b) use of focusing lasers/ion or other beams to increase the effective body length, (c) increase upper surface share of lift, and (d) use of passive bleed. The fundamental idea for the serrated body case is to create a series of very weak shocks. The fundamental problems, for a 2-D or axisymmetric realization, are the viscous induced difficulties of (probably unsteady) separated flows and attendant increased wave drag. Possibilities for mitigating the flow separation problems include a 3-D shingle design, which might be crudely visualized as being similar to a pinecone or artichoke. Such a 3-D geometry, combined with some further flow separation control, could possibly result in an overall benefit. Focused and possibly pulsed beams (e.g., lasers, etc.) could be studied to attempt to turn the flow ahead of the body, thereby extending the effective body length. The energy saved by sharpening the flow field and reducing the wave drag is 30 times the energy required to point the shock on a blunt body [ref. 21]. At supersonic speeds, a significant portion of the lift (more than current practice) could be carried on the upper surface, thereby possibly reducing the wave DDL from the lower surface wave systems. The problem here appears to be upper surface flow separation (See the next section on flow separation control.). According to Becker, "The low-pressure side thus emerges as a key consideration in the L/D problem" [ref. 22]. Another concept, passive bleed, allows a reduction in body flow deflection and, hence, weakens the body shock systems. The technique is much studied for transonic wing application (with possible direct application to subsonic leading-edge high-speed wings) for mitigation of off design wave drag and shock induced separation.

Separated Flow Control

Traditionally, separated flow control, either active (e.g., blowing, suction, etc.) or passive (e.g., vortex generators) has been viewed as primarily a local after-the-fact fix to design problems or for high lift. The conventional view is that separated flow should be avoided as much as possible through mitigation of imposed pressure gradients. This approach (restricting the imposed pressure gradients) has yielded good, but perhaps not optimal, designs, in that the large pressure drag increments associated with separated flow are avoided. The design restriction that separated flows must be avoided (rather than actively or passively controlled) has, especially in the supersonic case where shock waves can impose tremendous local pressure gradients, perhaps unduly penalized several drag reduction approaches. That is, the anticipation and mitigation of viscous flow effects or separation has restricted the extent to which in viscidly-predicted benefits can be realized. Experiment has shown that many of the benefits of leading-edge sweepback are not attained in practice because of separation of the flow over the upper surface of the wing. In fact, according to Bertin “Successful configurations have attached flow over the wing upper surface, unsuccessful wings exhibited vortex dominated flow, strong shocks, and large regions of separation” [ref. 23]. Obvious examples where flow separation control may allow the accrual of greater benefits include: (a) greater leading-edge thrust on subsonic leading-edge wings, (b) increased lift increment from the upper surface, (c) increased fuselage lift and camber (reduced wave DDL), (d) increased favorable wave interference effects from multiple bodies including propulsion modules and displaced wings, and (e) improved isentropic compression surfaces. The fundamental suggestion is straightforward: incorporate flow separation control into cruise designs to allow accrual of the maximum wave drag reduction benefits available from inviscid considerations. This suggestion includes both supersonic and subsonic operation. In the low-speed case, cruise LFC suction and separated flow control systems could perhaps be used for high lift.

The basic approaches to flow separation control are well known: (1) remove the near-wall low momentum fluid, (2) add momentum/energize the near-wall region, or (3) impose a wall slip layer. Removal of near-wall low-momentum fluid can be accomplished via suction, which can be active or passive (bleed) and either local or distributed, or via boundary-layer diverters including swept shocks at high speeds. Energizing the near-wall region can involve either adding energy from an external source (e.g., blowing, steady, or pulsing), redirecting energy from the external flow to the wall region (e.g., vortex generators, either jets or bodies, augmented turbulence including shock-induced amplification), and adding near-wall momentum through increased wall density via surface cooling. Effective wall slip regions can be established using various types of small-scale grooves or moving walls. The use of flow separation control for cruise as suggested herein has obvious problems associated with systems penalties for the control technique. These problems include positioning of the control devices for off- as well as on-design performance and possible interference with smoothness requirements for laminar flow control. In this regard, the use of intelligent walls may be useful, especially if those walls use distributed sensors to detect incipient separation. Considerable synergisms between the various flow control and drag reduction techniques (e.g., flow separation control) are possible as discussed in the next section. Techniques possibly well suited to the high-speed flow separation control problem include passive porous walls and vortex generator jets as well as conventional bleed for high-pressure regions.

Flow Control Design Synergisms

The most obvious benefits and synergisms from successful drag reduction approaches occur because of the opportunity to resize the supersonic cruise aircraft. In particular, a smaller required fuel load for an aircraft with a large fuel fraction and small payload fraction can have dramatic influences upon other drag components (e.g., smaller size yields smaller wetted area/friction drag, smaller volume diminishes wave drag, and lower weight reduces CL/DDL). Also, a reduced weight reduces sonic boom, the size/weight of takeoff gear, and sideline noise. This is a major reason why the recent resurgence in SST activity is in smaller, business aircraft. Vortex DDL reduction would be especially beneficial for subsonic operation and landing in that required fuel reserves (and their additional weight, which is currently the order of the payload) could be reduced. Wave drag reduction techniques applied to the engine inlets may also increase propulsion efficiency. Use of suction LFC could also provide suction for flow separation control/high lift during takeoff and landing, with subsequent utilization of suction mass efflux for vortex generator jets over aft portion of airfoil to augment/replace flap systems. Alternatively, the efflux could be used to control lee-side vortices or vortex flap systems for vortex lift augmentation or ejected from the wing tips for DDL reduction. Also, suction LFC could provide: (a) low-loss air for slot injection for skin friction reduction, (b) drag reduction during subsonic overland flights (to meet sonic boom restrictions), (c) reduced wetted surface penalty for struts and other devices employed for favorable interference wave drag reduction, and (d) strut-braced wings for drag due-to-lift reduction and wave drag reduction (higher sweep). At high supersonic speeds, thrust vectoring should be beneficial for lift production, thereby reducing DDL, wing size, and weight and friction drag. Thrust vectoring for control can also reduce trim drag and obviate the need for the empennage weight and drag.

EMISSIONS/ CLIMATE/FUELS

There is increasing concern worldwide regarding climate change and the deleterious impacts of aviation upon such. This section considers the SST specific implications and options with regard to climate, an arena which was very complicit in the cancellation of the last U.S. SST program. The usually considered first order aviation emissions for chemical fuels are CO_2, water, NOx, and black carbon among others [ref. 24]. The effects of these are different in many aspects for SSTs vice subsonic transports due to their increased cruise altitudes and some five times greater emissions than subsonic aircraft. SSTs up to Mach 3 cruise, depending upon Mach number, cruise at 50K ft at 60K ft. For Mach 4, the altitude increases to some 90K ft. These altitudes are in the ozone band (nominally 50K ft to 110K ft). Protective ozone depletion is an SST climate related impact additional to the usual aviation climate forcing/warming issues. At 90K ft, there are fewer in situ particulates (e.g., interplanetary dust and meteoroid debris) to form cirrus clouds than at 50K to 60K ft.

Impacts of Water Emissions – Overall, water makes up almost 95% of the greenhouse gases causing climate forcing/warming [ref. 25]. Water forms hydrogen oxide and destroys ozone [ref. 26]. Water forms cirrus clouds on particulates from the propulsion system which reduce the IR escaping the planet. Water is a positive feedback, storing heat. Water induced climate forcing from aircraft is still being assessed. Thus far, there has been little consideration of SST water emission effects nor how to mitigate such. Water emissions for SSTs were, however, recently addressed in ref. 27, where their effects appear to be benign.

CO_2 – The CO_2 effects on climate forcing are well known/publicized. CO_2 is the major emission issue currently under consideration for SSTs.

Impacts of NOx – NOx destroys ozone in the ozone layer and is a current SST emission under consideration.

SST Climate Solution Spaces

Prospective CO_2 solutions – The fuels that are CO_2 curative include solar hydrogen and methane, ammonia, and biofuels (either no CO_2 (hydrogen, ammonia) or ambient CO_2 used in production/a circular renewable (e.g., methane, biofuels)). Hydrogen fuel has increased volume and drag issues.

Prospective NOx solutions – staged combustion, lean burn/quick quench, other combustion/combustor modifications. More research is needed but considerable progress has been made.

Prospective water solutions – All of the CO_2 solution fuels produce water and hydrogen produces 2.55 times as much water. Currently in development is an alternative to fuel combustion for aircraft - electrics. If lithium-air class batteries are developed with a 10ish times lithium-ion energy density, a suitable electric propulsion system is developed (e.g., electric motors to drive compressors, superlative inlets, electric heating), advanced (two times) aero developed/utilized, along with advanced (two to five times) materials (nano printed for superb microstructure or composites), then there could exist a solution to CO_2 and water. Batteries will going forward be increasingly charged by renewables/ green electricity, which now provide approximately 28% of electric generation, a percentage that is growing rapidly.

PROPULSION

For Mach numbers 3 and less, the current propulsion approach is turbofan engines. For Mach 4 and higher, air turbo ramjets are more efficient. Then there is the possibility of electrics going forward. The variable cycle turbofan, along with other engine designs, are under study and some are under development for the usual SST less than or equal to Mach 3 range. A major design issue is meeting both cruise performance and takeoff noise. In the 90s, the NASA High Speed Civil Transport Study worked this issue by adding a large mixer ejector which increased much the weight of the aircraft and reduced thrust. An alternative, not pursued except in academic research, was to inject liquid water jets (producing droplets) into the turbulent mixing regions responsible for much of the jet takeoff noise. The purpose of the water droplets was to reduce the intensity of the turbulent noise sources, as opposed to the mixer-ejector whose purpose was to reduce the jet exhaust velocity by mixing with ambient air. The water injection approach therefore utilized a very different physical noise reduction mechanism and, as the water was injected aft, added to thrust instead of reducing it as the mixer-ejector had. Also, the water weight was expelled during takeoff, and therefore did not have to be carried throughout the flight as was the case with the heavy mixer ejector.

For the high supersonic Mach 4 cruise case, the ramjet cycle is more efficient but needs to be boosted to the Mach 2.5-3 range for takeover. From an integrated vehicle design point of view, the integrated air turbo ramjet has less weight. The design utilizes rotating machinery until ramjet takeover, where the air is then ducted through the integral ramjet flow path. Ramjets usually utilize an isolator section in the inlet to produce a cleaner flow in the combustor. This isolator section adds weight and flow separation control in the inlet is efficacious, allowing reduction in the length/weight of the isolator. Supersonic airbreathing engines generally utilize inlet bleed for flow separation control, which produces appreciable vehicle drag and affects engine performance. There is a possibility that small surface bumps in the internal inlet shock impingement regions might, via production of smaller 3-D separated flow regions, result in lower losses (TBD). Also, endothermic fuel approaches could provide performance improving regeneration and improved cooling capacity. Mixing enhancement would improve the overall ramjet metrics. Approaches include multiple velocity inflections in the injected fuel streams, shocks/adverse pressure gradients, and fuel injector stream interactions. The overall propulsion efficiency could possibly be improved by collection and regeneration of the aerodynamic heating into the airframe.

Electrics for Supersonics [ref. 28]

Advantages of Electric Propulsion:

- Regenerative energy recovery during descent and landing
- Battery heat production could be utilized for cabin heating, deicing, or regeneration via thermoelectric generators
- Higher altitude operation feasible
- Reduced cooling drag
- Quieter
- Reduced vibration
- Fewer inspections
- No engine flameouts or restarts
- No fuel explosions during crashes
- Power train efficiency greater than 90%, nominally twice or greater than IC and GTE chemically fueled propulsion
- Much lower energy costs
- No power lapse with altitude at high temperatures
- High reliability
- High efficiency over most of the power envelope
- Up to six times motor power to weight compared to combustion engines
- Reduced maintenance
- Far fewer parts
- Less expensive
- Higher torque
- No vehicle emissions
- Distributed, scalable propulsion

Electric propulsion for SSTs could involve a quite different approach from that for fueled aircraft. Instead of a combustor and a turbine to drive axial flow compressors, very light weight and very efficient electric motors would drive them. The initial stages of compression could involve supersonic through flow compressors. Rather than combustion providing the cycle enthalpy increase, electrics from batteries or fuel cells would provide such, with thrust produced via subsequent flow expansion out the nozzle. Such engines should be more efficient than GTEs. To further increase efficiency, the heat produced by the motors and heat into the airframe could be regenerated and used to produce additional electricity to propel the aircraft. There are a plethora of extant energy conversion approaches to enable this including thermal electrics, pyroelectrics, sterling cycle heat engines, etc.

Electric propulsion for SSTs is in an early research stage, with ideation and R&D optimization required. It is particularly needed for propulsion cycles and boundary layer control (including for shock-boundary interactions to increase compressor stage loading and to obtain favorable shock wave interference), minimization of shock losses in the inlet, along with further work on supersonic through flow fans and possibly morphing blades. Major additional technologies are required to enable electric SSTs. These include approaches to reduce the required energy levels, the power the electric supply would have to provide via, for example, two times L/D and five times materials. Extant concepts/research suggest those are possible. The other requisite technologies involve the electric supply which includes batteries and fuel cells, the prime potential electrical energy sources. Even when considering two times L/D and five times plus materials and the increased efficiency of SST electric propulsion, current batteries have over an order of magnitude too low an energy density and weigh far too much. What is needed is success in the current research efforts to develop viable lithium air class batteries, which have the requisite energy density. Argonne has demonstrated the requisite number of discharge cycles. There is much ongoing effort regarding such breakthrough batteries. The fuel cell issues involve the aircraft weight increase (versus the decrease when burning fuel) associated with fuel cell operation via addition of atmospheric oxygen.

MATERIALS

There are many reasons to press for lighter effective materials for advanced SSTs. These include reduced weight/increased range, opportunity for systems of systems level vehicle resizing/optimization, and reduced internal secondary radiation produced by incident space radiation. At 50 to 90K ft, there is appreciable space radiation as are above much of the protective sensible atmosphere. Peak neutron flux in the atmosphere is at 50K- 60K ft. There are advanced high temperature composites, including carbon based and metal materials, which proffer a compendium of availability, cost, utilization reliability, and capability. At MIT, Prof. Schuh [ref. 29] has produced high temperature metals with up to five times better properties via printing at the nano scale to produce superb material microstructure. His technique reduces dislocations and grain boundary issues that lead to cracking and other issues. Boron nitride nanotube-based composites are discussed for some 900 degrees C and possess radiation protection properties. The historical material is titanium. The high temperature alloys are nickel and titanium-based including nickel aluminide. Printing manufacturing is reducing costs.

SST CONFIGURATION OPTIONS [ref. 28]

The greatest efficiency improvements are usually available from aircraft configuration optimization at the systems of systems level in the context of synergistic combinatorials of propulsion, structures/materials, dynamics and control and aerodynamics.

Advanced configuration SSTs come in five major categories: (1) unswept, (2) thin natural laminar flow wings, (3) parasol wing with favorable interference, (4) multistage aircraft, and (5) yawed wings and the Pfenninger symmetric extreme arrow strut braced wing [ref 9]. The multi-stage approach usually involves a stage which includes the capability to get off the ground with acceptable noise and high lift and then separates and returns to the airfield. The portion of the aircraft that lands at the end of the flight weighs far less, allowing carriage of lighter weight gear and high lift systems during cruise. In-flight refueling is another multi-stage aircraft option. The asymmetric yawed wing approach uniquely provides a low supersonic Mach number option that is nearly boomless and extremely efficient.

Of these, the Pfenninger extreme arrow strut braced wing appears to have greatest SST potential, essentially doubling the Concorde L/D of approximately 7.3. The best NASA did in the HSCT/HSR program of the late 90s was an L/D in the range of 9.5. The Pfenninger designs proffer values in the range of 14 to 16+. The extreme arrow wing minimizes wave drag due to lift and wing wetted area as well as providing a credible span for vortex drag minimization. The short wing chord aids suction laminar flow control. There are mid-wing fuel canisters for favorable wave interaction and load alleviation with the possibility of natural laminar flow on the forward regions of the fuel canisters and the fuselage. Several approaches utilized to optimize the truss braced CTOL design can also be applied to this SST. They include gear weight reductions via automatic landings, parachutes for refused takeoff, and c-wing tips to reduce DDL.

There is also a bi-directional configuration concept that alters vehicle flight direction for subsonic vs. supersonic operation with high L/D [ref. 30]. Beyond all these options is an extreme possibility utilizing double favorable shock wave interference. Consider a double fuselage with the facing sides configured Busemann biplane style to cancel the volume wave drag. Each fuselage has a parasol wing pylon. These pylons support an arrow parasol wing, which profits from lift produced by the fuselage nose shocks and fuselage thrust from reflection from the wing onto their afterbodies. This is an exemplar of combinatorial, unconventional aircraft configuration ideation.

At high supersonic Mach numbers, utilizing thrust vectoring for lift starts to become interesting. At low speeds this is detrimental, but at hypersonic speeds it can reduce thrust requirements by some 20%. The difference is the decreased shock wave drag. At high supersonic speeds, thrust vectoring for lift can reduce wave drag and required aero lift, therefore drag due to lift, and reduce wetted area, lower angle of attack and reduce weight. Its use at Mach 4 needs to be evaluated.

With respect to sonic boom, the configuration is key to minimization. What is needed is a long, slender configuration designed to keep the shocks generated by the various vehicle piece parts from coalescing, maintaining the near field shock separation as far into the far field as possible. Also efficacious with regard to boom reduction is reduced weight, higher altitude, and diffuse shock systems. Issues with regard to boom level include possible doubling due to atmospheric caustics and maneuvering. Also, in addition to the people effects of boom, there are building/structural impacts, especially with regard to the low frequency components of the boom spectra. These are difficult to tailor/reduce.

SUMMARY – SUGGESTED SST OPTIMIZATION APPROACHES UP TO MACH 4

Configuration – Conceptually, the Busemann biplane configured double fuselage with arrow parasol wing for maximum favorable shock wave interference may be a near optimum configuration, however, it requires further study. Next in line with regard to performance is the Pfenninger extreme arrow strut braced and the bi-directional configurations, followed by a parasol wing approach. These are proffered to provide some 25% to a factor of two plus improved aerodynamic performance.

Flow Control – At high Mach number, thrust vectoring for lift and control should be studied. Flow separation control at cruise should also be researched to increase the performance of inviscid drag reduction approaches. This includes leading edge thrust, increased fuselage lift, increased lift from the upper surface, favorable shock interference, as well as inlet performance including the ramjet isolator. Laminar flow control for viscous drag reduction is another major performance improvement approach. There is also mixing enhancement for combustors and energy projection forward for drag and boom reduction along with liquid water injection for takeoff noise.

Fuels/Emissions/Climate/Propulsion – Solar hydrogen, solar methane, solar hydrocarbons and biofuels solve CO_2. Clever combustors reduce NO_x. Electrics also solve CO_2. Fuel cells can provide on board propulsion electricity using solar, green fuels. Electrics using batteries requires lithium/air class batteries and major improvements in drag and weight. Electric propulsors at SST speeds require serious conceptualization and subsequent R&D such as electric motors turning compressors, energy regeneration, and electric heating. For Mach 4, air-turbo-ram-jet research is needed.

Materials/Structures – External strut bracing can provide many benefits including weight and DDL reduction as can five times (hopefully heading toward ten times) nano-printed materials with superb microstructure and advanced composites. Materials that produce minimal secondary radiation are needed.

CONCLUDING REMARKS

Advanced aerodynamics, including extensive flow control and drag reduction, is an enabling technology for a commercially viable SST, including into the Mach 4 range. The drag on such a supersonic cruise aircraft is approximately equally split between friction drag, vortex DDL, and wave drag due to both volume and lift. Therefore, drag reduction approaches for all three sources of drag and their synergistic benefits should be considered. The classical drag reduction approaches yield an increase in L/D from the order of seven (Concorde) to the order of ten. Further increases on the order of 20% may be available from favorable interference (e.g., parasol wings, Busemann biplane class double fuselages), while extensive LFC and strut-braced wings suggest L/D values on the order of 16+ a truly revolutionary machine.

The present report includes the entire spectrum of possibilities from ideas which are, as yet, unevaluated and are included merely as possible suggestions for further research, to techniques which may, if pursued, yield the significant improvements in performance and capabilities required for a viable SST. In general, we tend to build what we can compute, and the Concorde class aircraft are excellent examples of linearized supersonic theory derived machines. Decades on greatly improved technologies and analyses may spawn quite different and hopefully better designs. A key to successful SST design is minimizing gross weight, which improves such key problems as sonic boom, sideline noise, ozone depletion, and economic viability. For SST class aircraft, with their large fuel weight fraction, drag reduction provides a highly leveraged approach for gross weight minimization.

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14. ABSTRACT

Commercially viable supersonic transports require solution spaces to a longish list of serious issues including high drag, heating, emissions, costs, weights, acoustics, etc. Report addresses potential approaches to these issues including drag reduction, flow control, propulsion/ fuels/energetics, and synergistic frontier aircraft configurations across the board proffering large increases in lift to drag ratio.

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