Arrow Wings for Supersonic Cruise Aircraft

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The arrow wing planform has a far greater range potential than the delta wing planform for utilization on a commercial supersonic cruise vehicle. A supersonic cruise vehicle concept must be configured to favor cruise efficiency. The arrow wing planform cruise lift-drag ratio is approximately one unit higher than the delta wing. The small weight advantage of the delta wing cannot offset the large cruise efficiency advantage of the arrow wing. The low-speed aerodynamic characteristics of the arrow wing are acceptable and can be further improved by continued research and development. For this, additional analytical tools need to be developed and wind tunnel tests conducted to provide verifications and empirical adjustments to the analytical tools. The major emphasis for arrow wing development should be in the low-speed regime. The design challenge is to seek out design features and refinements that remove any deficiencies of the arrow wing, while not sacrificing the superior cruise efficiency.

Introduction

WING planform selection is a classic problem for commercial supersonic cruise vehicles (SCV's). This fact is highlighted by the various proposed and actual supersonic aircraft that were studied during the USA FAA/SST program, the British/French Concorde program, and the Russian TU 144 program of the 1960's. The NASA SCAT series included arrow, delta, and variable-sweep concepts. Lockheed, Boeing, Douglas, and North American addressed many of the same concepts and modifications thereof, as well as their own concepts. The final Lockheed and Boeing configurations were fixed-wing delta concepts. Both the Concorde and the TU 144 configurations are fixed-wing delta (ogive) concepts. The basic conclusion to be drawn from these SST planform selections is that, based on the available technology, design philosophy, and design requirements of the 1960's, a fixed delta-type wing planform was the unanimous choice.

Numerous considerations enter into the selection of planform parameters that lead to the final choice of wing planform. These include such items as cruise lift-drag ratio (L/D), weight, low-speed aerodynamic characteristics, and simplicity. Based on the mission requirements of a given supersonic aircraft, trade studies of the various considerations just mentioned establish the optimum wing planform. These trade studies must be reiterated every time technology is advanced, design philosophy reevaluated, and/or design requirements updated.

The first-generation SST developed by Lockheed during the FAA/SST program of the 1960's featured a double-delta planform, tailless concept. The delta wing planform was Lockheed's first choice due to its lighter weight, superior low-speed aerodynamic characteristics, and simplicity. The arrow wing planform was Lockheed's second choice. This planform displayed superior cruise efficiency (cruise lift-to-drag ratio), but was heavier than the delta planform. Also, there was concern with regard to the low-speed aerodynamic characteristics of this planform. The variable-sweep wing concept was abandoned because of weight bogies and extreme design complexity.

The first-generation SST concept developed by Lockheed featured a double-delta planform with a low wing loading, no high-lift devices, no horizontal tail. The philosophy of this design was to aerodynamically reduce aerodynamic center movement due to Mach number change (double-delta planform), eliminate cruise trim drag with proper wing shape and center-of-gravity location to enhance cruise L/D (tailless configuration) and utilize a large wing area to permit higher cruise altitude operations to lower sonic boom overpressures, and, at the same time, allow operations in the terminal area without need for high-lift devices. Fundamentally, the concept stressed simplicity.

What's New in SST Concepts?

Since the inception of the NASA-sponsored Supersonic Cruise Aircraft Research (SCAR) program in 1972, efforts have been directed toward conducting technology assessment studies to determine the impact of new technology advances on the design and performance of supersonic cruise vehicles. Several important technology developments and improved methodology have emerged from the SCAR program efforts.

Flight controls/electronics technologies take advantage of the dynamic progress being made in the electronics industry, and parlays this into improvements for aircraft systems. The most promising advanced technology that will see early implementation on future subsonic transport aircraft will involve use of advanced controls. These advances will pave the way for extensive application on SST's in the 1990's.

Advanced controls have several potential benefits. Throttle management, programmed flaps, and relaxed stability will produce better climb profiles, less trim drag, and resulting noise relief. Maneuver load control (MLC), gust load alleviation (GA), elastic mode suppression, and relaxed stability are means for weight savings that will be employed in the 1980's on subsonic aircraft. Flight station ride quality and envelope limiting are safety items needed for long-body aircraft. Relaxed stability, fuel management, and digital-integrated propulsion controls will improve performance by reducing trim drag and improving engine performance.

Flight management systems are in operation today on wide-body subsonic transports. These systems achieve fuel savings through automatic aircraft control (climb, descent, and holding using autothrottle and autopilot), reduce approach noise, assist in abnormal operations such as one engine inoperative, and reduce crew workload. The incorporation of

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digital electronics will bring about fully automated aircraft systems.

Propulsion technology, which encompasses long lead time, high-risk items, offers improvements in fuel economics along with reductions in noise and emissions. Variable cycle engines are desirable for supersonic cruise vehicles because of their ability to operate like turbofans during takeoff and subsonic cruise and to operate like turbojets at supersonic cruise for low specific fuel consumption (SFC). The variable cycle engine has a variable geometry fan and high-pressure compressor and individually variable fan and primary nozzles. The pumping capability of the fan is sufficiently variable to provide the inverted velocity profile required for coannular noise relief at takeoff and the pressure ratio required for efficient supersonic performance.

Lockheed-California Company has identified an engine arrangement concept that uses mutual exhaust plume-shielding as a potential means for reducing jet noise. The concept has engines mounted in an arrangement that places two of the engines on top of the wing, positioned above two below-wing mounted engines in an over/under arrangement. Jet noise shielding such as provided by an above-wing engine installation has been demonstrated in experimental results from twin jet noise studies. Reference 1 includes a more detailed discussion of this configuration.

Advances in aircraft structures offer significant potential when applied to supersonic cruise vehicles, with the prospect that the "1960 all-titanium structure" vehicle weight can be decreased by 10%. This will be achievable because of new developments in materials, controls technology, manufacturing processes, and analytic methods.

A new structural advancement receiving great attention at present is the prospect of using advanced composite materials to replace metal alloys. These composites are formed from filaments of metal or carbon imbedded in a formable matrix. The orientation of the fibers can be arranged to produce any desired structural property with regard to load intensity and direction. Strength/weight properties exceed conventional metal alloys. Therefore, these new materials have the potential of offering lighter, more efficient structures for advanced aircraft.

Advances in aluminum technology to provide improved strength, fracture resistance, and corrosion resistance with increased temperature capability are encouraging. Candidate systems include aluminum-lithium and powder metallurgy products.

A very significant technology emerging from the SCAR program is recognition of the impact of new titanium manufacturing techniques such as high-temperature forming (superplastic forming) and no draft forgings. These techniques make a significant impact on fabrication cost by eliminating machining operations and by providing large structural assemblies with fewer detailed parts.

Many new analytic methods have emerged since the first-generation SST programs. The benefits from these new analytic methods include accelerated design processes, more efficient structure, greater accuracy, improved correlation of theory and experimental tests, all at reduced cost. The ability to use computer programs which are properly interfaced and combined with computer graphics, measurably helps to improve response time and accuracy of results.

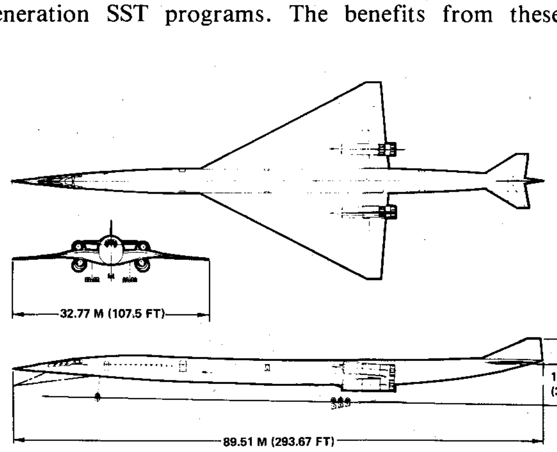

Fig. 1 General arrangement drawing for the delta wing concept.

New analytical computer methods like the vortex lattice method,[2] the advanced panel method,[3] and finite difference solutions are making possible detailed aerodynamic analyses as well as aerodynamic loads analysis to an extent never before possible. At the same time, detailed computer structural models are able to define the exact required strength for the airframe, thus reducing the excess weight formerly included to compensate for unknowns in the structural analysis.

What's New in Configuration Requirements?

Technology advancements made since the 1960's suggest that alternatives to that earlier design philosophy may offer attractive potential. In addition, different, and in most cases, more demanding design requirements are imposed by today's scenario. Noise, emissions, cost, and risk have become more critical considerations. Propulsion technology leading to more advanced engine concepts offer reductions in noise and emissions along with improvements in fuel economy and economics. To insure economic viability, the design should emphasize the smallest aircraft size possible, cruise speeds commensurate with best possible utilization, and payload fractions at least twice that of Concorde. Aircraft size can be held to a minimum by designing for nonstop North Atlantic operations with one-stop Pacific operations. Nonstop Pacific operation with the same capacity would increase takeoff gross weight by approximately 150,000 lb. A smaller aircraft size reduces development, facility, first, and support costs. The small-size aircraft further reduces noise and emissions. The stringent noise rules and emission requirements that are being put into effect, as well as the formidable pressures of keeping costs in line and reducing risks, are demanding the smallest possible aircraft powered by advanced engine concepts. To address risk, the aircraft must continue to reflect simplicity in design wherever possible; a simple aircraft design reduces unknowns.

The more critical noise considerations force the aerodynamicist to develop better subsonic lift drag ratio levels for aircraft operation. Vortex lift cannot be relied upon because of attendant vortex drag and resultant low levels of L/D. High lift-drag ratios for second-segment climb and low approach speeds coupled with low approach attitudes require a wing with high-lift devices which, in turn, requires a horizontal tail to trim out the large pitching moments. The added complexity of high-lift devices is measurably offset by the benefits in wing weight savings achieved because the high-lift devices permit adoption of a higher design wing loading (smaller wing). The wing weight savings has a significant, favorable impact on design range or gross weight for a given range. The best wing loading for achieving maximum payload range characteristics is always higher than the wing loading desired for airport performance needs. All subsonic transports in operation today adopt wing loadings that favor cruise performance, and adopt high-lift devices to tailor the wing aerodynamic characteristics to provide good airport performance characteristics. A similar philosophy appears attractive for an SST.

Supersonic flight for the second-generation SST is planned only for over-water routes; therefore, sonic boom restraints no longer actively shape the eventual design. This allows lower cruise altitudes and high-wing loading designs. A lower cruise altitude is in keeping with the emission requirements in that the aircraft is flown at the mixing altitudes which minimizes loss of the products of combustion to the upper atmosphere regions. The use of advanced structural materials and active controls on second-generation SST's present different tradeoffs between structure and aerodynamics. The use of active controls no longer demand that the aircraft be statically stable, and with it flutter penalties will be considerably reduced or eliminated.

Study Task

From an examination of the types of new technologies being considered for SST design, as well as from new requirements and restraints placed on future aircraft, it can be readily appreciated that the forces of today and the future may formulate an SST design that is somewhat different from that of the 1960's. Thus, the question that needs to answered is: How would the SST design of the 1960's compare to today's SST design under today's requirements? Also, is the emphasis that is being put on the arrow wing technology justified?

The answer to these questions is the subject of this paper. Two SST concepts, a delta and an arrow wing, were compared on an equal basis for figures of merits that bring into focus the important advantages of each concept. The study examined cruise efficiency, structural weight, and low-speed aerodynamic characteristics by means of an analytical investigation supported by available wind-tunnel data. The guidelines for the study include Mach 2.55 cruise speed with takeoff gross weight, wing area, and span held constant. Mission range was the figure of merit in the comparison.

Concept Definition

The delta wing configuration investigated is presented in Fig. 1. This configuration differs somewhat from the concept Lockheed pursued in the 1960's. The outstanding differences are: small wing with the chine or double-delta concept eliminated, horizontal tail added, empennage surfaces noticeably smaller due to active controls, trailing edge controls which serve as a combination of high-lift devices and roll control panels, and no wing leading edge devices. The over/under engine installation was adopted for potential noise shielding benefits. The wing area and aspect ratio are 6720 ft^2 and 1.72, respectively. Leading edge sweep is 63 deg.

The arrow wing shown in Fig. 2 has the leading edge swept behind the Mach line in cruise so that rounded wing leading edges (0.005 $\bar{c}$ radius) can be employed without subsonic cruise drag penalty. This provides airfoil shapes that are similar to conventional subsonic transports, but with reduced thickness-to-chord ratio. The leading edge sweep angles range from 73 deg at the root to 58 deg in the tip region. The notch ratio is 0.14. Both inboard and outboard trailing edge flaps are installed and leading edge lift augmentation devices are utilized in the wing tip region. The wing is highly warped to provide improved cruise lift-drag ratio by improving the load distribution to minimize drag due to lift and trim drag. The wing thickness ratio was kept consistent between the two planforms.

Cruise Drag Comparison

The cruise drag comparison is shown in Table 1 for the delta and arrow wing configurations. The delta has a higher zero-lift drag coefficient which is attributed to higher wave drag for the supersonic leading edge wing and a lower fineness ratio for the equivalent body. The induced drag coefficient of the delta wing is also higher than that for the arrow wing. In comparing the lift-drag ratio at a representative lift coefficient of 0.10, the arrow wing holds an advantage of close to 1 – a benefit that also holds true for the maximum lift-drag ratio. The mission range impact based on the L/D advantage for the arrow wing manifests itself in a 552 n. mi. range difference. This range increment is entirely due to L/D advantages and must be adjusted for weight fraction differences between the delta and arrow wing.

One of the prominent advantages of the arrow wing is in the area of induced drag. This is illustrated in Fig. 3 where the planform with a trailing edge cutout or notch ratio is shown to have lower induced drag.

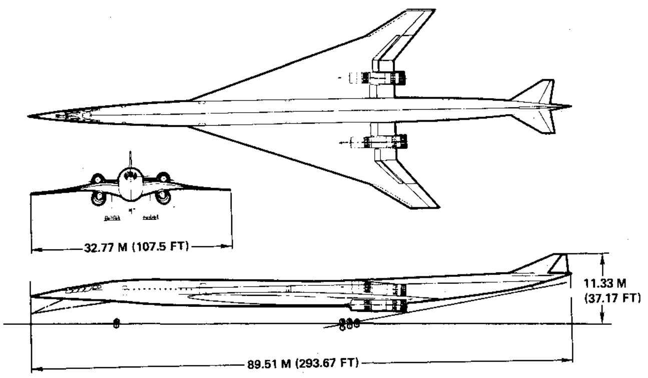

Fig. 2 General arrangement drawing for the arrow wing concept.

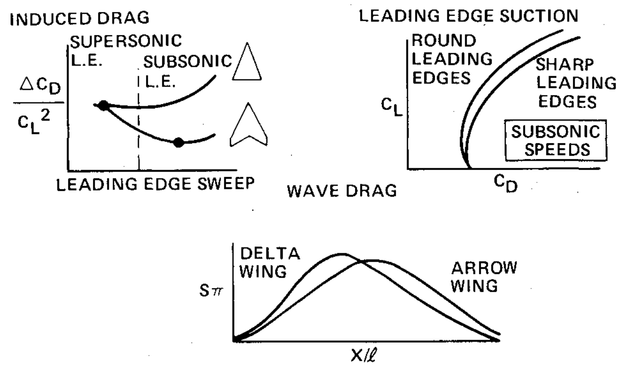

Fig. 3 Aerodynamic benefits of the arrow wing.

The second advantage of the arrow wing is its ability to retain a subsonic round leading edge at an aspect ratio that is of the same level as that of the lesser swept supersonic leading edge delta. The advantages of the subsonic leading edge are a lower wave drag at cruise and a high L/D for subsonic flight operations due to increased leading edge suction. In addition to a lower wave drag due to a subsonic leading edge, the highly swept arrow wing also realizes wave drag reductions as a result of higher fineness ratio.

In general, the delta has more linear pitching moment characteristics, but today we can rely on active controls and horizontal tail so that the importance of inherent linear aerodynamic characteristics are less significant. Also in today's design philosophy the trend is toward operation at lower angles of attack where the nonlinearities are much less. First-generation SST concepts were slated to operate at high angles of attack to take advantage of the vortex lift, but the associated vortex drag results in lower L/D and increased approach noise. The present-day SST design concept stresses a higher L/D, lower approach attitudes, and lower approach noise levels. Figure 4 shows that in order to meet approach conditions using reasonable approach attitudes, either planform concept must adopt high-lift devices and a horizontal tail surface for trim.

Table 1 Cruise drag comparison for the delta and arrow wing configurations

Mach 2.55 Altitude = 60,000 ft	Delta wing configuration	Arrow wing configuration
Zero lift drag	0.00763	0.00713
Induced drag at $C_L = 0.10$	0.00627	0.00532
L/D at $C_L = 0.10$	7.19	8.03
C_L for $(L/D)_{max}$	0.110	0.116
Induced drag at $(L/D)_{max}$	0.00763	0.00713
L/D max	7.23	8.12
Δ Range impact	...	+ 552 n. mi.*

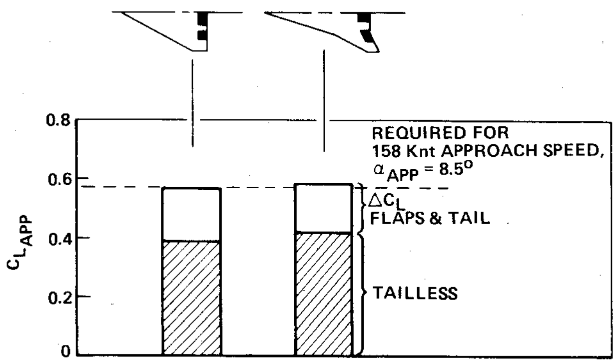

Fig. 4 Required vs available lift coefficient at landing approach.

Wing Structural Study

The parameters that determine the mission range of an aircraft are: specific fuel consumption, Mach number, lift-drag ratio, and weight fraction. In this comparative study, specific fuel consumption and cruise Mach number are common to both concepts. Therefore, the only two parameters that impact the mission range of each concept are L/D and weight fraction. The mission range advantage previously cited for the arrow wing is due to its superior cruise L/D and must, therefore, be adjusted for differences in the weight fraction. This weight difference was evaluated and verified through a structural study. The basis for this study is an arrow wing configuration with a large wing area (10,923 ft^2) and an aspect ratio of 1.6. This configuration was chosen because of the existence of a comprehensive structural data base from Ref. 4. In order to obtain the best possible weight estimate and structural definition for that configuration, a systematic, multidisciplinary analysis was conducted to asses the effects of the complete environment on the structural integrity of the aircraft. This analysis involved the complex interactions between static aeroelasticity, thermodynamic, flutter, static and dynamic loads, and strength.

A major problem in the previous SST program was the time required for the completion of a structural design cycle. Frequently, the impact of configuration changes on the structural design could not be assessed until it was too late to influence the change. As a result of the efforts under the SCAR program, the time for completion of a structural design cycle has been greatly reduced. By use of a parallel iterative method, as illustrated in Fig. 5, rather than the former sequential iterative method, the time for a structural resize cycle has been reduced from months to weeks. This new development permits a more rapid, more accurate, and less expensive assessment of configuration changes on the structural design.

The design loading conditions for the final design cycle are shown in Table 2. These load cases include jig shape effects considering the final design structural weight and flexibilities.

The aeroelastic analysis includes the calculations of airframe deflections during 1-g trimmed flight throughout a typical flight profile. A sample graphic representation of static deformation of the wing is shown in Fig. 6. The vectors represent elastic offsets relative to the jig shape and are normalized to the maximum value.

The details of this structural analysis are found in Ref. 4; the final wing structure skeleton layout and the wing weight breakdown are shown in Fig. 7 and Table 3, respectively. A weight penalty of 4300 lb is included for increased stiffness in order to clear the flutter speed of 1.2 V_D.

Use was made of this structural model in order to assess the wing weight changes as trailing edge sweep is varied. This trailing edge sweep study involved the forward shearing of the outer panel of the arrow wing, resulting in a wing with a straight trailing edge. This wing geometry change may be visualized through the skeleton drawing of the final analysis results shown in Fig. 8. The weight breakdown of the straight trailing edge wing is shown in Table 4. Certain wing structure components have been determined to remain invariant with wing trailing edge sweep. Those components are indicated by an asterisk (*) in Table 4.

The major wing weight changes occur in the tip and transition region where the increased stiffness for flutter penalty is affected, in the rear-spar region because of a reduced structural length, and in the buttline 470 region because of reduced kick loads. The total wing weight decrease as a result of reducing the trailing edge sweep from 47 deg to 0 deg is 3383 lb; this represents a 4% reduction. This small weight difference is influenced by the desensitizing effect of composite reinforcement applied to the titanium alloy spar caps. An all-metal wing would show a larger weight difference.

While the wing structural study was performed for an arrow wing of 10,923 ft^2 wing area because of the existence of a comprehensive structural data base, the wing area for the planform study was 6720 ft^2. Thus a means of translating the results of the structural study to the smaller wings was required. This was achieved through the use of Lockheed-developed parametric weight equations. By applying the parametric weight equations to the configurations of the

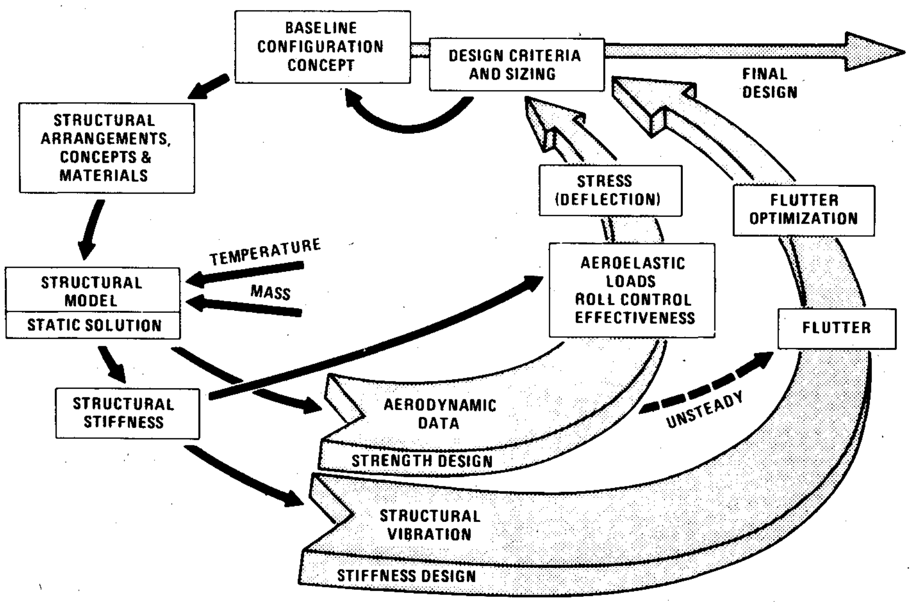

Fig. 5 Structural analytical design cycle.

Table 2 Structural Design Conditions

NASTRAN Cond. No.	Weight, 1000 lb	Mach No.	Altitude, 1000 ft	Load factor	Airspeed, knots	Remarks
4,5	745	0.40	0	2.5	264.6	strength design
6,7	700	0.90	36	2.5	282.4	strength design
8,9	700	0.90	30	2.5	325	strength design
10,11	700	0.90	22	2.5	390	strength design
12,13	690	1.25	48	2.5	294.3	strength design
14	690	1.25	48	−1.0	294.3	negative flight
15,16	690	1.25	38.2	2.5	372	strength design
17,18	445	1.25	34	2.5	420	descent – thermal
19,20	660	2.70	61.5	2.5	460	start of cruise
21,21	550	2.70	64	1.0,2.5	433.6	midcruise
23,24	700	0.90	30	...	325	pseudogust (positive and negative)
25-28	430	...	0	...	100	dynamic landing conditions

Table 3 Wing weight breakdown for arrow wing

Primary wing box structure	
Forward box	20,580
Aft box	17,384
Tip and transition	12,468
Other structures	
Rear spar	3,400
B.L. 470 rib	700
L.E./T.E. control surfaces	21,353
Support structure (doors, etc)	14,699
Wing weight, lb	90,584
Unit wing weight, lb/ft^2	8.29

Table 4 Wing weight breakdown for straight trailing edge wing

Primary wing box structure	
Forward box	20,580*
Aft box	16,884
Tip and transition	10,425
Other structures	
Rear spar	2,790
B.L. 470 rib	470
L.E./T.E. control surfaces	21,353*
Support structure (doors, etc)	14,699*
Wing weight, lb	87,201
Unit wing weight, lb/ft^2	7.98

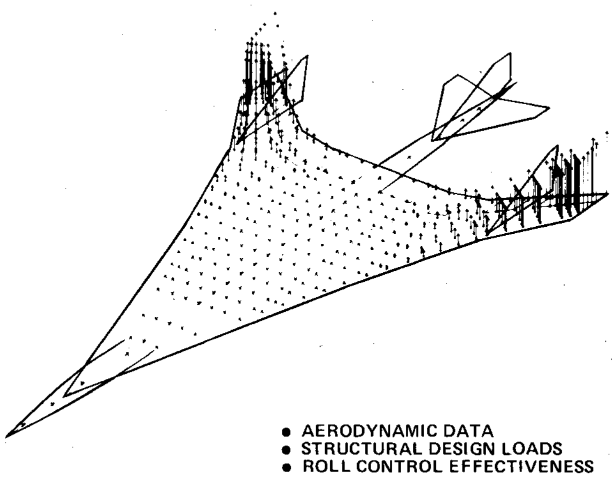

Fig. 6 Sample computer output for static aeroelasticity analysis.

Table 5 Impact of operating weight empty on mission range

	Delta wing configuration	Arrow wing configuration
Unit wing weight, lb/ft^2	7.42	7.80
Wing weight, lb	49,863	52,428
OEW, lb	233,308	234,529
Δ Range impact	...	− 12 n. mi.

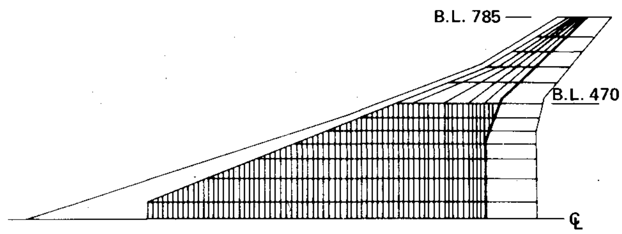

Fig. 7 Wing structure skeleton for the arrow wing.

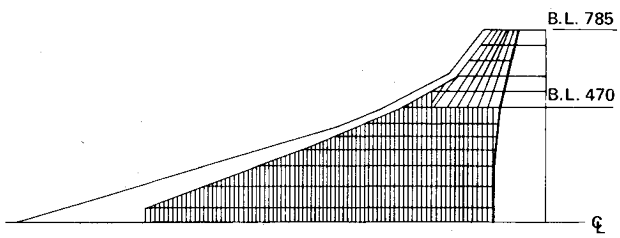

Fig. 8 Wing structure skeleton for the straight trailing edge wing.

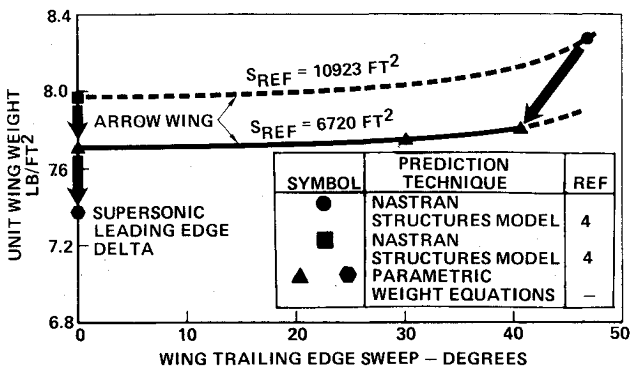

Fig. 9 Wing weight vs trailing edge sweep.

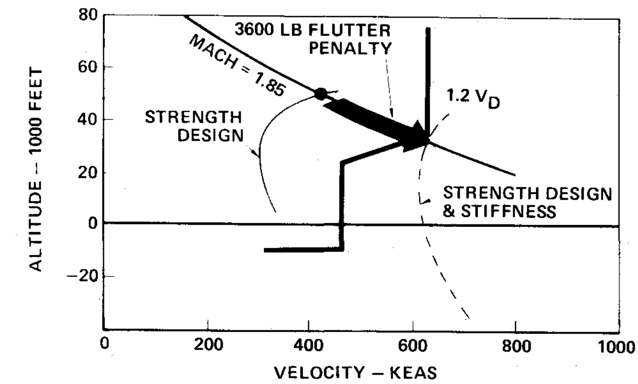

Fig. 10 Arrow wing flutter speed for symmetric bending and torsion mode.

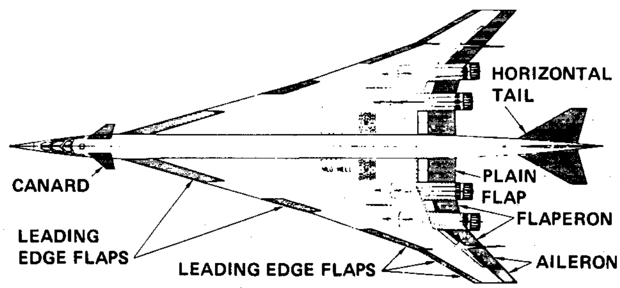

Fig. 11 Candidate flutter mode control surfaces.

structural study, and accounting for wing area effects and a small trailing edge sweep adjustment, the unit wing weight variation with trailing edge sweep for the smaller wing area was derived. The results of both the structural study and the parametric weight equations are shown in Fig. 9. By applying the parametric weight equation to the straight trailing edge wing, the unit wing weight of the delta was also derived and is shown on the same figure.

A weight comparison for the delta and arrow wing configurations is shown in Table 5. The wing weight of the delta is lighter than that of the arrow wing by 2565 lb, whereas the operational weight empty (OEW) difference is only 1221 lb. This weight reduction arises from empennage size differences and the fuselage/wing carry-through structure effects. The small weight difference between the delta and arrow wings results in a negligible mission range difference.

Active Controls Feasibility Study

A 4300 lb flutter weight increment was identified for the arrow wing used in the wing structural study. This weight increment results from increases in the outer wing stiffness (3600 lb) and from increases in the engine beam stiffness (700 lb) over and above the strength design wing to extend the flutter speed to 1.2 V_D (Fig. 10). A feasibility study was initiated to use active controls for flutter suppression with a goal of eliminating the 4300 lb weight increment associated with satisfying the flutter margin requirements of the arrow wing design.

The scope of the feasibility study was limited to improving the flutter characteristics of a strength design arrow wing configuration for which a mathematical model and the associated baseline analyses already existed.[4]

Methodology for flutter mode control synthesis is based on a concept in which the active control system is designed to specified active constraints. These constraints normally include flutter, gust, and handling qualities. The problem presented herein considers only the flutter margin requirements. The method, which is an outgrowth of work on structural resizing for flutter,[5] makes extensive use of solving two equations for two unknowns in the flutter determinant and in the response equations.

Control Surface Location Selection

The initial task was the selection of control surfaces for flutter mode control. Figure 11 shows the control surfaces chosen for the study. In the selection of these control surfaces it was necessary to keep in mind that two flutter modes had to be suppressed: the wing bending-torsion mode and the stability mode. Of the chosen control surfaces, only four represent existing control surfaces, these being the plain flap, the two flaperons, and the horizontal tail. The existing outboard aileron was split to form two outboard ailerons. This was in anticipation of the wing bending-torsion mode being sensitive to wing tip control surfaces and, thus, requiring less control surface area for flutter suppression. It was also anticipated that the stability mode could be effectively suppressed using the outboard wing control surfaces due to the large wing tip motions noted. The inboard wing, canard, and horizontal stabilizer control surfaces were included, primarily for the evaluation of the stability mode, since it was unlikely that the wing bending-torsion mode would be sensitive to these surfaces. Leading-edge control surfaces were included to evaluate the possibility of these surfaces, separately or in combination with trailing edge surfaces, being more effective than trailing edge surfaces alone.

Figure 12 shows the sensor locations used in the study. Wing tip vertical acceleration sensors were used in the wing bending-torsion mode analysis and the inboard engine aft mount vertical acceleration sensors were used for the stability mode analysis. Control surface effectiveness was computed for two quantities in the sensitivity studies: control surface hinge moment per g, and control surface angular displacement per g at the sensor station.

The sensitivity studies provided a basis for selecting an optimum combination of control surfaces and sensors. The closed-loop gain and phase calculations for each flutter deficiency defined envelopes of gain and phase constraints that a control function must satisfy in order to achieve the objectives for flutter mode control. Transfer functions were derived that best satisfied the active constraint points (gain and phase), while conforming to constraints imposed by mechanization considerations. The study included two active flutter modes at Mach 0.6 and one active flutter mode at Mach 0.9 and 2.7. A high degree of coupling between aircraft dynamic modes at Mach 2.7 demonstrated a need for a methodology that accounts for the model damping effects on noncritical dynamic modes during the synthesis process of a flutter mode control.

Table 6 Estimated mission range comparison

	Delta configuration	Arrow configuration
Zero fuel weight, lb	291,308	292,529
Block fuel, lb		
Climb to cruise altitude	76,270	64,091
Cruise	150,559	165,163
Total	257,004	255,886
Mach 2.55 cruise		
L/D	7.06*	7.96*
SFC, lb/hr/lb	1.533	1.526
Mach 0.92 cruise		
L/D	10.54*	11.33
SFC, lb/hr/lb	0.966	0.958
Hold at FL 15		
L/D	9.85*	10.91
SFC, lb/hr/lb	0.91	0.916
Total range, n. mi.	3,257	3,798

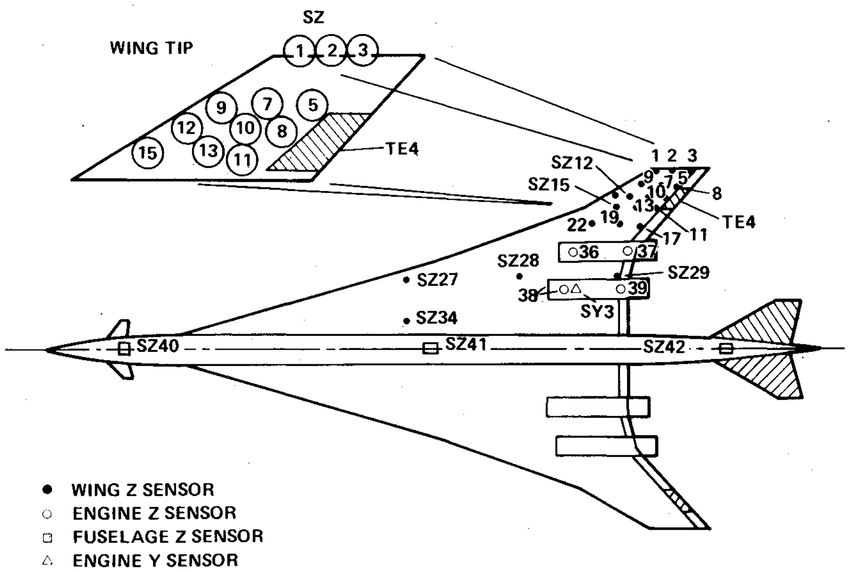

Fig. 12 Flutter mode control study – sensor location.

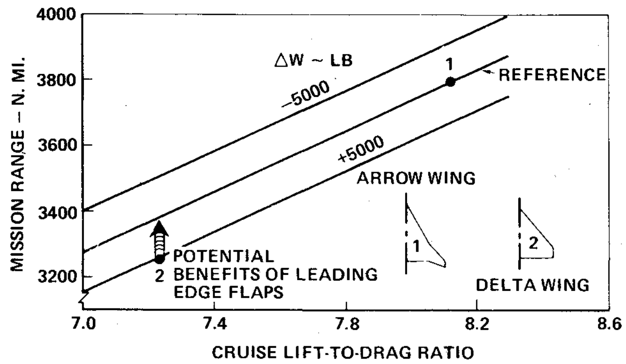

Fig. 13 Impact of cruise L/D and weight on mission range.

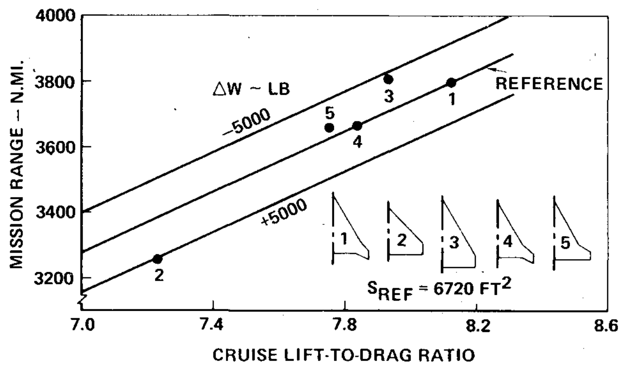

Fig. 14 Range comparison for alternative planforms.

The results of this study indicate that satisfying 1.2 V_D flutter margin requirements for the strength design configuration with active controls requires no structural items. Significant weight savings amounting to 4-5% of unit wing weight are feasible. Existing wing trailing edge control surfaces and horizontal stabilizer appear to be satisfactory for flutter mode control, and present actuator specifications appear to be adequate for active controls application. Several of the candidate control surfaces could be effectively used for flutter mode suppressions making possible backup systems to satisfy fail-safe requirements.

This feasibility study in flutter mode control has shown that the weight increment, due to increased stiffness for flutter margin requirements, can be eliminated through the use of active controls. The study conclusion generalized to include other planforms, such as the delta wing configuration and other size scalings, *having similar levels of flutter deficiencies is valid*. This means that for sizing and planform studies the flutter weight increment can be replaced by requirements for an active control system for flutter.

Arrow vs Delta Mission Range Comparison

Table 6 shows the mission range breakdown for the delta and the arrow wing configurations. The combined effect of lift-drag ratio and weight differences produce a 541 n. mi. range advantage for the arrow wing concept.

The range tradeoffs between cruise L/D and ΔW are shown in Fig. 13. The indicated range variation due to weight changes (ΔW) reflect operating weight empty (OEW) differences as well as reserve fuel requirement adjustments, as effected by subsonic L/D variations, are also included where applicable. This indicates that mission range is far more sensitive to L/D than to weight. The mission range of the delta can be improved with the use of leading edge flaps or devices that increase the leading edge suction of the sharp leading edge. Such measures, however, would not bring the delta wing into a competitive position in terms of mission range.

Further Planform Refinement

In addition to the two basic planform concepts examined in this study, derivative planforms of the delta and the arrow wings were also investigated. These derivatives included a subsonic leading edge delta, and two arrow wings having trailing edge sweeps of 30 deg and 0 deg, respectively. The estimated range of the various planforms investigated is plotted against their respective cruise L/D's in Fig. 14. Configuration 3, the subsonic leading edge delta, has the highest mission range. This, however, is misleading because the geometry definition of this planform produces an aspect ratio which is considerably less than that of the other planforms. When the effects of the lower aspect ratio are compensated for in terms of airport performance, the mission range for this planform is reduced to 3550 n. mi. The other two arrow wing planforms investigated differ from the basic arrow wing in their trailing edge sweep. These two configurations (4 and 5 in Fig. 14) have a range which is 130 n. mi. less than that of the reference arrow wing.

The two derivative arrow wings were investigated because wind-tunnel tests have shown that the reference arrow wing, with a 41 deg trailing edge sweep, has marginal roll control during a 30-knot crosswind landing. Wind-tunnel tests also show that a reduction in wing trailing edge sweep improves aileron effectiveness at low speed (Fig. 15). By reducing the

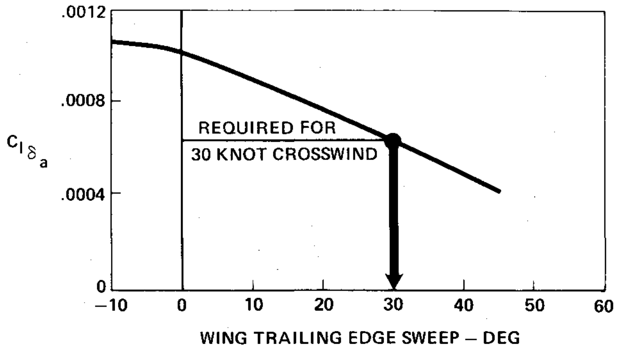

Fig. 15 Effect of wing tip sweep on aileron effectiveness.

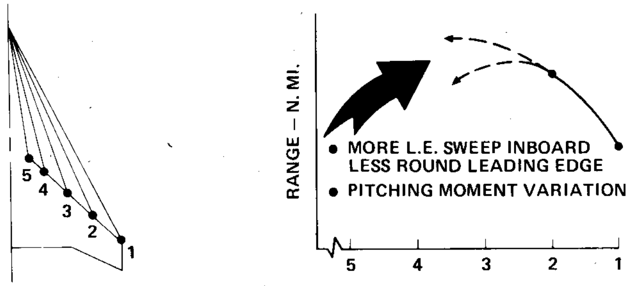

Fig. 16 Suggestions for planform refinement study.

trailing edge sweep to 30 deg, sufficient aileron control is obtained to correct for the effects of a 30-knot crosswind. The aforementioned range decrement of 130 n. mi. represents the penalty that must be paid to obtain sufficient roll control for crosswind landing requirements. Reducing the trailing edge sweep to zero improves aileron effectiveness still further for a negligible decrease in range.

Until other means are found for obtaining adequate roll control for crosswind landings, the trailing edge sweep of the arrow wing planform has been reduced to 30 deg. The resulting configuration retains all the features of the basic configuration except for the trailing edge sweep.

Study Results and Recommendations

This study has shown that the arrow wing concept offers the greatest range potential for commercial supersonic cruise vehicle. The effects of aircraft operating constraints, as well as the benefits of advanced technologies, make the arrow wing the preferred planform. This planform has a subsonic leading edge inboard, and a swept tip panel with a trailing edge sweep of 30 deg. The large potential range advantage of the arrow wing planform justifies the emphasis that is being placed on arrow wing technology by both NASA and industry.

It is recommended that the investigations into the arrow wing concept be greatly expanded, possibly in the manner indicated in Fig. 16. Further range gains may be possible by varying the leading edge intersection point (crankpoint) of the inboard wing panel with that of the more highly swept outer panel, as shown in the figure. Investigations should also be expanded to derive improved analytical tools for preliminary design purposes.

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