Influence of Aerodynamic Research on the Performance of Supersonic Airplanes

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This paper illustrates the type of aerodynamic research being done toward the development of supersonic vehicles and demonstrates how the results of this research can influence the conclusions of parametric studies of supersonic vehicle performance. Research areas that are covered include high lift, transonic drag, and supersonic drag. Testing techniques are discussed briefly, as well as results showing the improvements that research effort is producing in each of these fields. The parametric studies use wing loading and thrust loading as basic parameters. The effect on range for a given payload and gross weight is shown along with the limitations imposed by takeoff and landing field lengths, climb requirements, etc. Finally, the changes in performance are described which result from improvements in the various aerodynamic areas discussed earlier.

Introduction

THE private companies that are interested in building airplanes in the subsonic and supersonic areas are conducting research to extend their aerodynamics knowledge and apply it to their designs. This work includes the development and extension of aerodynamic theory, as well as the adaption of classical theory to modern computing equipment. It also includes systematic testing of new concepts in aerodynamics and the application of the results to complete configurations.

This research can influence the airplane's performance in several ways. The direct influence is the most obvious: an improvement in an aerodynamic characteristic generally improves the over-all airplane performance. There is also an indirect effect: a change in an aerodynamic characteristic influences the choice of other basic parameters of the design, such as wing loading or thrust loading. This latter influence can be strong, and it is important that the research be done early enough in the design cycle so that the effects can be seen before basic design decisions are made.

The objectives of this paper are twofold: to illustrate the type of aerodynamic research being done within The Boeing Company toward the development of supersonic airplanes, and to demonstrate how the results of this research can influence the conclusions of parametric studies of supersonic airplane performance. This current aerodynamic research covers a wide spectrum of activity. Rather than present a broad review, three specific examples will illustrate the research techniques and the progress being made. These same examples will be used to demonstrate their influence on the parametric design of a variable sweep, supersonic airplane.

Aerodynamic Research

The three areas of aerodynamic research to be discussed are high-lift systems, transonic airfoils, and supersonic arrow wings.

High Lift

Creating high lift to be used during takeoff and landing involves two major objectives: 1) developing an airfoil having a high maximum section lift coefficient; and 2) developing the three-dimensional wing so that it generates high lift while retaining good stability and drag characteristics. Both objectives must be pursued within the restraints of geometry, weight, and complexity which are dictated in order to retract the high-lift system into a good, high-speed airfoil for cruising flight.

High lift generally is associated with low-speed flight, and the flow about the airfoil is everywhere subsonic. Theoretical methods of analyzing this flow have been known for many years, but the application has been so tedious that only the flow about simple shapes has been treated analytically. The capacity of modern electronic computing machines to solve many simultaneous equations rapidly has led to new applications of the existing flow theories to much more complicated situations.

Two examples are shown in Fig. 1. On the left is a complex high-lift section that is represented analytically by distributed vorticity to represent the circulation and thickness to give a smooth distribution of pressure around the airfoil. The method has been checked against transformation methods on particular airfoils, as well as against test values of pressure distributions, and it has given very accurate results. Using a total of 100 singularities, the method can be used for multisegment airfoils (slats, flaps, etc.) or other shapes with no restrictions on thickness or camber. It has been used to evaluate such things as ground effect and wind-tunnel wall corrections, as well as for straightforward lift determination. By using compressible flow corrections, the method has been used also to compute the high-speed, subsonic flow about sections being considered for cruising flight.

The right diagram of Fig. 1 represents an analytical model of a wing having a partial span flap deflected to a large angle. The wing is represented by a series of horseshoe vortices that lie in and follow the distorted plane of the wing surface. The vortices then leave the trailing edge at the effective downwash angle. These nonplanar effects are an improvement over the usual air-load computations that assume all vortices to lie in a horizontal plane. This improved analytical method is necessary if the lift is high and the flap deflections are large. The computations produce lift, induced drag, and pitching moment of the wing being considered, and the method has been used to study flap span and chord effects, ground effect, and wind-tunnel wall corrections. The method has been particularly useful in checking the validity envelope of simpler theories that can then be used for many of the design calculations.

Two-dimensional wind-tunnel testing of high-lift sections permits refining the details of the section with a model of

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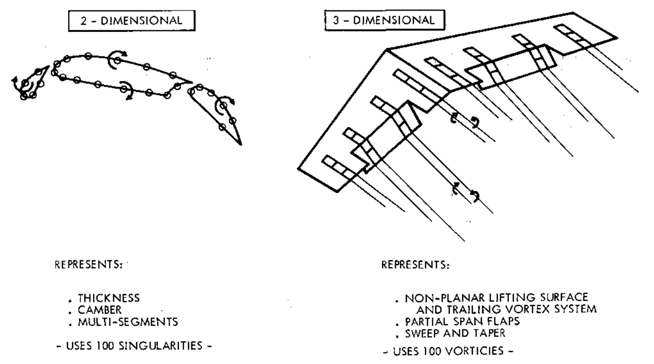

Fig. 1 Application of theory.

reasonable size and without the complication of span effects. In the past, these tests have used models spanning the tunnel test-sections, but the data have suffered because the boundary layer on the walls separates as a result of the pressure gradients created by the highly lifting airfoil.[1] Both lift-curve slope and $C_{L\,max}$ are reduced because of this separation, and considerable induced drag is created by the resulting trailing vortex system. Figure 2 shows a method of curing the wall separation to achieve truly two-dimensional data. The boundary layer is removed completely just ahead of the airfoil section, and then boundary-layer control (BLC) is applied locally as required to prevent separation in the areas close to the airfoil.

Both suction and blowing BLC have been used successfully. Suction BLC has the advantage of requiring less airflow, but the momentum forces carried by the sidewall turntables are difficult to determine. These forces can be determined when blowing BLC is used, and the added flow is not large enough to affect the main airstream.

Example data resulting from such tests are shown in Fig. 3. With BLC on, the lift-curve slopes show reasonable agreement with potential flow theory of the type discussed in connection with Fig. 1. Both flap effectiveness and $C_{L\max}$ are increased. The induced drag is essentially eliminated up to the point where the section itself starts to separate, as indicated by the drag polars being nearly vertical over a wide range of C_L's.

This testing technique, using an airfoil of 2-ft chord and 3-ft span, has been used to develop both mechanical slotted and BLC flaps. The effects of many design parameters, such as slot shape, size, and BLC nozzle position, have been determined rapidly and accurately. BLC flaps have achieved appreciably greater C_L's for a given blowing coefficient than those shown by other investigators using the usual two-dimensional testing procedures.

The BLC flaps developed by this procedure were used on a conventional three-dimensional model to evolve the configuration presently being prepared for flight test on the 367-80 airplane (the 707 prototype). Over the past nine years, this airplane has been used to test a series of high-lift systems.

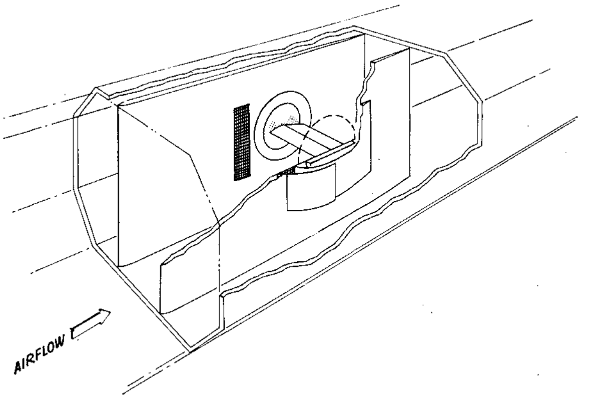

Fig. 2 High-lift test rig.

Scale and ground proximity effects on lift, drag, and trim requirements have been evaluated, as well as general flying characteristics associated with very slow flight, stalls, and landings. Figure 4 shows the -80 airplane equipped with a duplicate of the 727 flap and slat system, which was tested thoroughly before committing it to production. The progress made in reducing stall speeds of the 367-80, by increasing the performance of both the leading edge and trailing edge systems, is shown in Fig. 5. The data points shown are as follows:

1) The original 707 type double-slotted flap. A small split flap was used under the wing-body fillet, but no leading edge devices were used.

2) The 720 type, with Krueger flaps on the leading edge inboard of each nacelle and at the wing tip. This system is still in production.

3) The split fillet flap replaced by a larger plain flap using blowing BLC at the hinge line.

4) The 727-type triple-slotted flap with leading-edge slats, as tested on the 367-80 airplane.

5) The 727 production system, if used on this airplane, would give this lower value due to refinement of many details.

6) The 727-type slat replaced by a plain Krueger flap with blowing BLC at the flap-wing juncture. This device gave excellent control of the pitching moments in the stall.

7) This point is the anticipated stall speed for the blowing BLC system presently being installed on the -80. A 727-type slat will be used and possibly the blown leading edge flap at a later date.

The results of this series of developments has been a 30% reduction in the airplane's stall speed, which permits a more accurate approach path and shorter stopping distance after touchdown.

Transonic Airfoils

In the United States, the development of airfoil sections for high subsonic speed operation has received little attention for

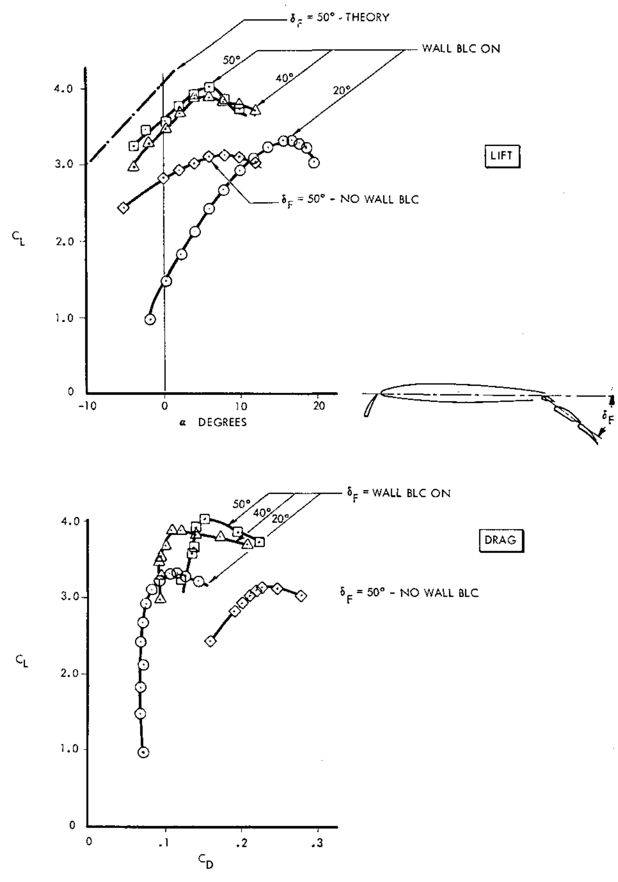

Fig. 3 Two-dimensional high-lift data.

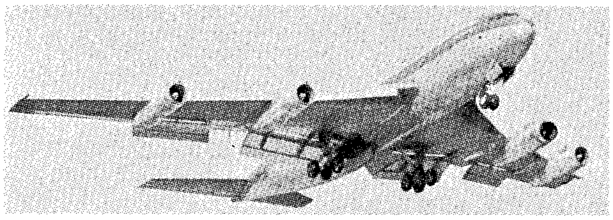

Fig. 4 High-lift flight test.

several years. During the 1930's and 1940's NACA developed a large family of airfoils having various subsonic applications.[2] Some of the later airfoils had pressure distributions designed to produce long runs of laminar flow, and these distributions also gave a high Mach number for drag divergence. These airfoils, particularly the "6" series, became the basis for most high subsonic speed wings used today. Soon after these airfoils came into widespread use, interest shifted to the supersonic speed range, and subsonic airfoil development was de-emphasized. Although a limited amount of work was carried on in the United States[3–5] and Russia,[6] a substantial effort[7–9] has continued in Europe. Results of this latter work have appeared on the latest family of British jet transports which has taken advantage of improved airfoil designs.

A typical subsonic airfoil moving at high speeds develops a region of local supersonic flow on its upper surface, as shown at the top of Fig. 6. This supersonic region terminates in a shock wave as the air recompresses toward the airfoil's trailing edge. The severe pressure gradient through the shock wave causes the boundary layer to separate, causing drag in addition to the rise in entropy through the shock wave itself. The lower sketch indicates an airfoil that is contoured to make a supersonic area that is completely compatible with the surrounding subsonic stream without a terminal shock wave. The recovery to subsonic speed is essentially isentropic, and the final pressure recovery occurs with minimum separation.

The mathematical possibility of such a flow has been known for some time, but actual existence depends on the flow pattern's being stable. This stability has not been demonstrated analytically.

The upper curve in Fig. 7 shows the results of two-dimensional tests of an airfoil designed for isentropic pressure recovery compared to data from a 707 airfoil. Both airfoils are at a C_L of 0.65 which corresponds to the cruise C_L of the 707 measured perpendicular to the wing quarter-chord line. Formation of a severe shock wave was delayed by more than 0.03 in Mach number by the new design. The lower curve translates this same comparison to complete airplane performance. The parameter ML/D (Mach number times lift-to-drag ratio) is proportional to airplane range if engine specific fuel consumption is constant. Because of the wing sweep, the improvement in cruise Mach number (approximately 0.04) is greater than that shown by the sections themselves, and range increases by 6%. The speed can be increased 0.06M at the

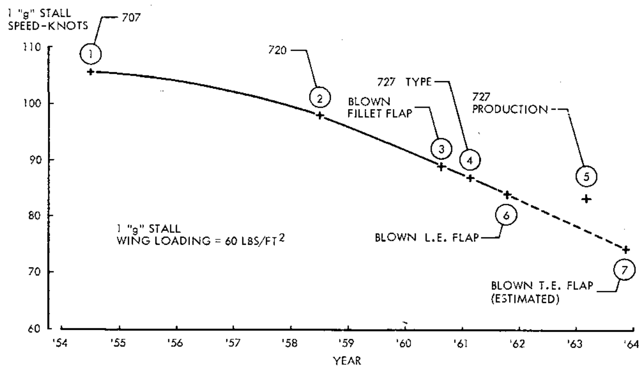

Fig. 5 Flight-test data, 707 prototype.

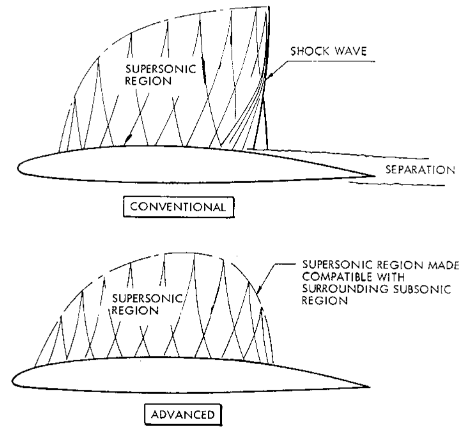

Fig. 6 Transonic airfoils.

same range. This plot assumes that the airfoil of the three-dimensional wing performs as well as the two-dimensional sections. Actual tests of complete wings have not shown this large an improvement. A better understanding is needed of the three-dimensional boundary layer and of wing-body effects before the potential section performance can be realized.

These developments have obvious applications to subsonic, long-range airplanes. They also have applications to the large supersonic airplane because, for many configurations, smaller engines can be used if the drag is reduced at transonic speeds.

Supersonic Arrow Wings

Widespread interest in a long-range supersonic airplane has pushed the development of wings having a high L/D at supersonic speeds. Many types of wings have been considered, and the final choice becomes a compromise between aerodynamic performance, weight, complexity, flutter, and many other

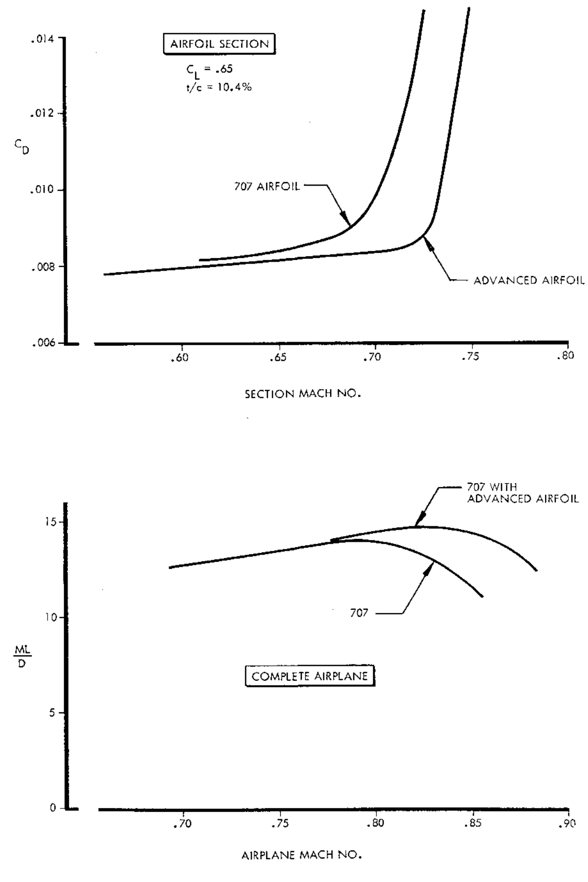

Fig. 7 Airfoil performance.

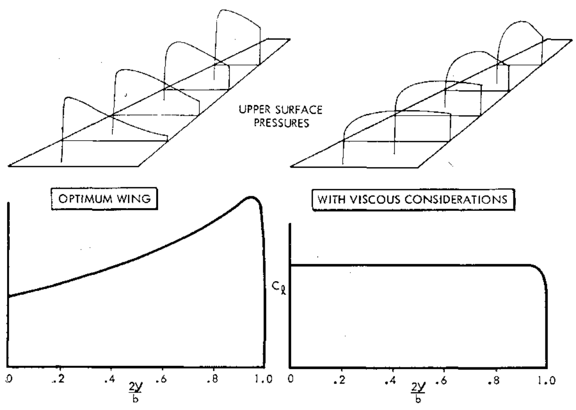

Fig. 8 Supersonic wings, design approach.

factors that influence airplane design. The arrow wing planform, with its subsonic leading edge, theoretically promises particularly high L/D's.[10-12] NASA and others have put considerable effort into translating this theoretical potential into practical reality.[13]

Figure 8 illustrates a promising approach to the problem. On the left is the pressure distribution on the upper surface when the wing is twisted and cambered to produce minimum drag-due-to-lift from this particular planform. The pressure gradients ahead of the trailing edge are high, particularly near the wing tip where the optimum spanwise lift distribution calls for very high section lift coefficients. These gradients are aggravated by the pressures due to wing thickness that are felt most severely near the tip. Experiments show that these severe gradients cause the boundary layer to separate, and the wings have not performed as expected. On the right in Fig. 8 a revised wing is shown, where the pressures due to both thickness and lift combine to give a distribution that is nearly constant over the entire upper surface. The final recovery to freestream values occurs through a shock wave at the wing trailing edge. The theoretical performance of this lift distribution is poorer than for the optimum wing, but the boundary layer remains attached and the experimental values are improved.

The curves at the top of Fig. 9 show the experimental results in terms of the drag-due-to-lift factor $C_D/\beta C_L^2$, where $\beta = (M^2 - 1)^{1/2}$. The lower curve represents the theoretical values for an arrow wing having optimum camber and twist, whereas the upper curve gives the values for a flat delta wing as reference. In-between lies the line that represents the

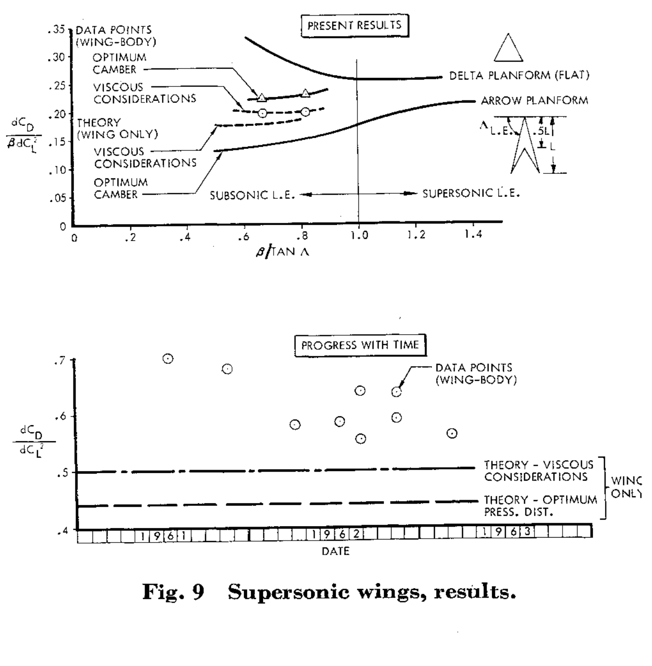

Fig. 9 Supersonic wings, results.

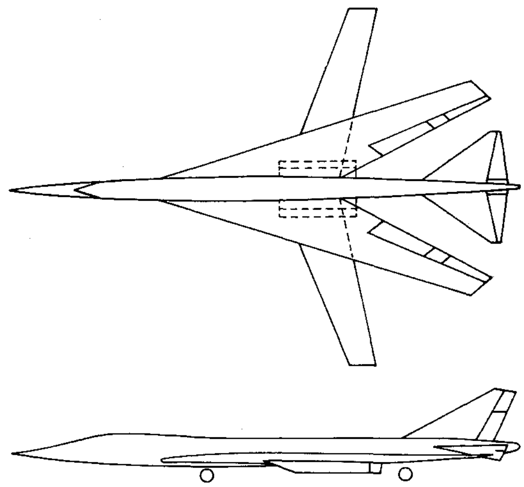

Fig. 10 Variable sweep configuration.

theoretical values for the wing having the flatter pressure distribution. The data points are for wing-body combinations and show the poor performance of the wings having optimum camber. The revised wings show superior performance approaching very closely the expected theoretical values.

At the bottom of Fig. 9 the improvements made in reducing the drag-due-to-lift are shown as a function of calendar time. Progress has been relatively slow and has come through careful consideration of the pressure distributions and the wing-body interference. The bodies used have become more representative of useful transports as time progressed, and so the improvement in wing-alone performance is better than the data points indicate. This curve implies that considerable progress can yet be made, particularly as the three-dimensional boundary layer becomes better understood.

Three areas of aerodynamic research have been discussed which are of importance to the performance of a large supersonic airplane. The analytical and experimental tools have been described and the recent developments in each area indicated. The next section of the paper will discuss the influence on airplane performance of progress made and anticipated in these and other areas of aerodynamics.

Parametric Design Study

The aerodynamic research work performed at Boeing in high-lift devices, transonic airfoil development, and twisted and cambered wings for supersonic flight, will now be used in a typical parametric design study. It is assumed throughout that the results of the research can be translated into practice

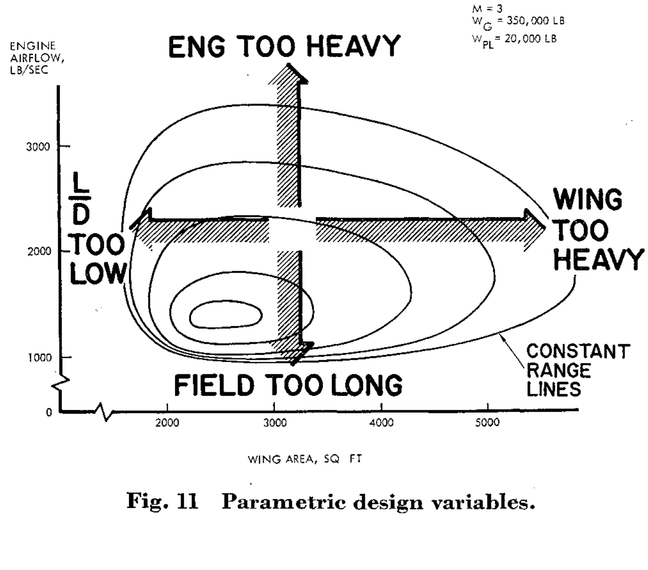

Fig. 11 Parametric design variables.

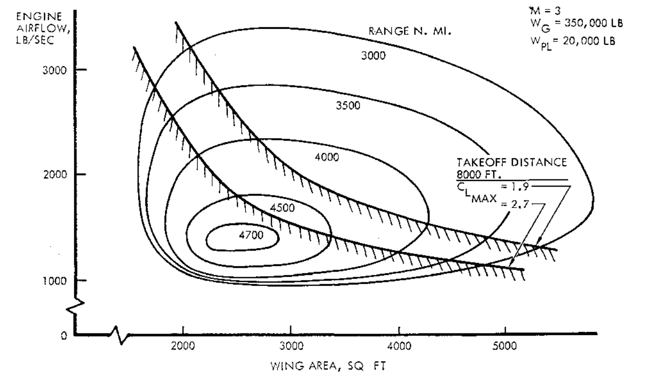

Fig. 12 Parametric design variables, takeoff restrictions.

on the chosen configurations. This problem is one requiring careful development and refinement of the airplane details, but deviations from the chosen numbers will not change the study approach, only the numerical values of the results. All of the data used for this study are applicable to a variable sweep airplane such as shown in Fig. 10. The selection of the type of airplane configuration establishes a basis for a rough drag polar. The configuration also establishes a basis for modifying the structural weight and powerplant weight as a function of wing area. The selected mission and the configuration provides a set of ground rules for the equipment which, for a parametric study of this type, also varies with wing area. The powerplants used for this study are of the turbofan type representative of a supersonic design with pressure ratio of about 11, bypass ratio of 1.5 to 1.0, and turbine inlet temperatures of 2600°R. A gross takeoff weight of 350,000 lb and a payload of 20,000 lb was selected. These two factors will give meaning to the parametric study.

A typical all-supersonic high-altitude mission is selected for analysis. The climb performance of the airplane is restricted to a placard such that no sonic boom overpressures are created greater than 2.5 psf (roughly equivalent to the placard for the *B*-58).

Figure 11 shows the engine total airflow at sea level in pounds per second as a function of the wing area in square feet for the variable sweep airplane for a series of constant ranges. It is easy to see that for a fixed gross weight and payload an increase in engine airflow or thrust at constant wing area will result in a shorter range because fuel weight is being substituted for engine weight. In the solution of the total airplane design problem, this is often necessary to obtain adequate takeoff performance, transonic altitude performance, or maneuver margin at altitude. If the engine airflow is decreased, there is an area where increased range results, but the takeoff field length will become too long. It should also be noted that cruise below the optimum altitude will result if the engines are too small, and the range will decrease. It is quite often an academic point, but there are two combinations of airflow at fixed wing area which will give maximum range and, conversely, two combinations of wing area at fixed airflow that will produce maximum range. If airflow is held constant at 2000 lb/sec, e.g., which could be four engines, each of 500 lb/sec, and the wing area is increased, the wing soon becomes too heavy, and range is lost because fuel weight is sacrificed. There is a small area where L/D increases faster than wing weight increases, and longer ranges result. If the wing area is decreased, the L/D generally decreases faster than wing weight is saved, and range is lost. There are, of course, many subtleties to these curves which are not shown. The important role that the high-lift research described previously can play in the airplane design process will be described in detail.

Figure 12 shows the same parameters as before, but the restriction of an 8000-ft takeoff distance over the 50-ft obstacle has been added. If a good double-slotted trailing edge flap system is assumed on the 30° extended variable sweep wing, a maximum lift coefficient of about 1.9 is a reasonable value. An 8000-ft takeoff distance C_{LM} = 1.9 will be obtained along the line shown. This line represents a type of boundary then on range, for no combinations of airflow and wing area are available to this machine which lie to the left of this line. Hence, if no further restriction was placed on the machine, a a wing area of about 3300 ft² would be chosen to give maximum range. If the intensive research in high-lift devices were used, however, a C_{LM} of at least 2.7 could be realized; it is quite apparent that the smaller combination of wing area and airflow results in an increase in range. Prior knowledge of this important research will lead the designer to concentrate his preliminary searches at higher wing loadings. For military airplanes this generally means longer ranges.

A landing field distance restriction is now added to these plots (Fig. 13). For the purpose of this discussion, a calculated landing distance of 5000 ft over the 50-ft obstacle is assumed. This will insure that the skilled pilot can safely land (in poor weather and at night) in his 8000-ft takeoff field. Two nearly vertical lines are shown for $C_{L\text{Max}}$ = 1.9

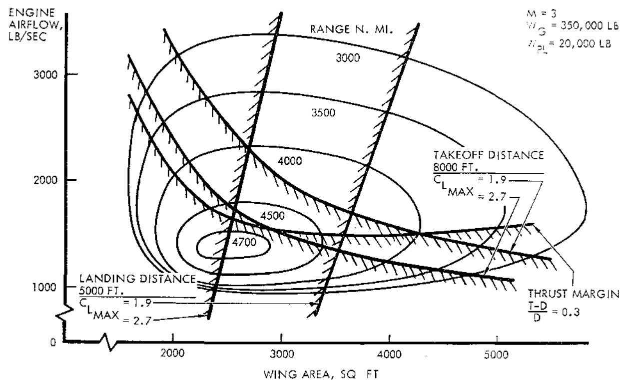

Fig. 14 Parametric study, thrust margin restrictions.

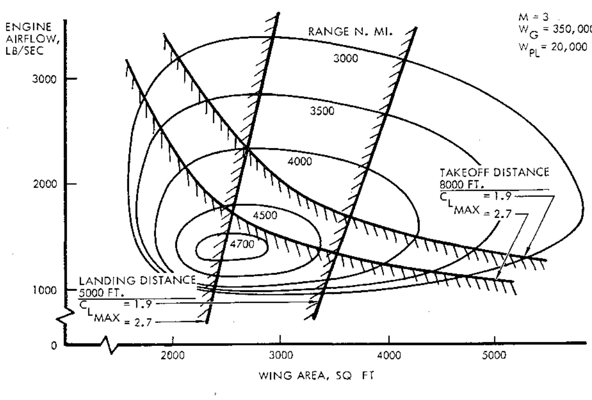

Fig. 13 Parametric design values, landing restrictions.

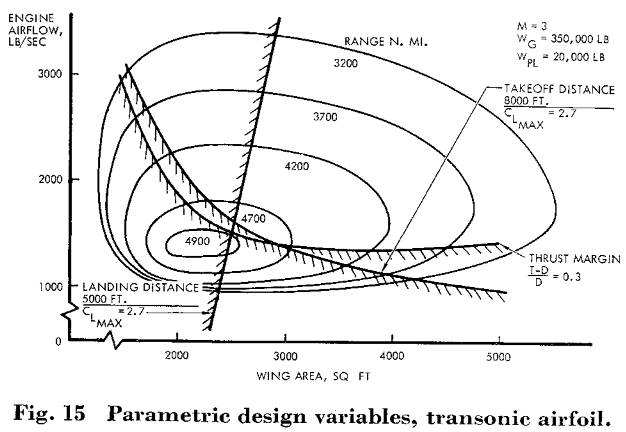

Fig. 15 Parametric design variables, transonic airfoil.

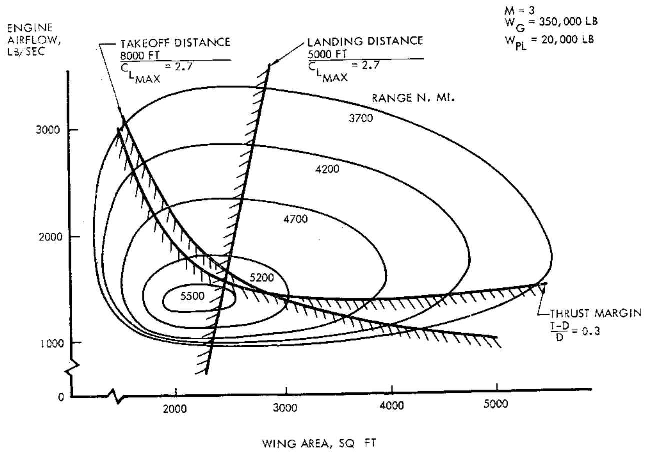

Fig. 16 Parametric design variables, supersonic twist and camber.

and 2.7 as before. The airplane with the lower lift coefficient is now restricted to operate in the area above the 8000-ft takeoff field line and to the right of the 5000-ft landing field line. The range available to this machine has now decreased about 300 naut miles compared to the same airplane with an improved high-lift system. Further limits can and would be applied to such an airplane; second-segment climbout, for example. The restriction of an adequate transonic thrust margin is added in order to minimize sonic boom, and a value of 0.3 was selected as typical for this machine (Fig. 14). The thrust margin restriction poses no further problem for either machine but comes very close to determining the wing area for the airplane with $C_{LM} = 2.7$. In the real case the designer would undoubtedly be faced with a choice of powerplants. As soon as a selection is made, an upper limit is placed on the airflow available, and the airplane would now be immediately restricted to a small area. In general, the choice would then be a machine that met all the ground rules, gave the maximum available range, and, with an eye to future growth, gave the largest possible wing area. For instance, on the advanced airplane one would select a wing area of 3000 ft^2. For the state-of-the-art machine one would select a wing area of 3800 ft^2, since it gives maximum range.

These data have all been for a purely supersonic mission, and in order to show the benefit of the transonic airfoil research this mission will be retained. New values of aerodynamics are now calculated for the transonic region based on the wind-tunnel research and the whole parametric relationship adjusted. Shown in Fig. 15 is a new thumbprint‡ calculated for the variable sweep airplane using transonic airfoils. Considering only range performance, the optimum wing loadings are higher and the thrust loadings lower. However, takeoff, landing, and acceleration restrictions require the engine and wing size to remain the same as before. Improved range is achieved; if desired, a smaller airplane may be used to give the same range.

‡ This type of plot is so named because of the thumbprint shape of the lines of constant range.

The last figure, Fig. 16, shows a completed thumbprint for the same variable sweep airplane with a twisted and cambered wing. Here the primary change is in supersonic lift-to-drag ratio. The eye of the thumbprint tends to move to lower airflows and wing areas, but the important point is that the range has increased considerably. For a constant range, one would use a smaller over-all airplane; for a constant gross weight, as shown here, one would tend to choose the highest wing area possible at maximum range.

There are many factors that affect the over-all airplane design procedure; only a few of the larger items have been discussed. Airflow and wing area were chosen as the primary variables to establish the large items of the configuration. The last two items discussed tend to three-dimensionalize the thumbprint and make one want to work in and out of the page.

This presentation has shown how intensive research in high-lift devices, transonic airfoil sections, and supersonic twist and camber can enlarge the possible choice of parametric design values. This enlarged choice of values enables the designer to create his airplane with fewer compromises and can yield greater ranges, smaller gross weights, and larger payloads.

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