SST Pilot Factors Program at Randolph Air Force Base indicate that such a device may well be required for any airplane attempting blind landing performance in order to ease the pilot workload. For these reasons alone, provisions will be made to incorporate the automatic throttles as future all-weather landing studies dictate.

Summary

In summary, the Lockheed studies to date show that the low-speed handling qualities of the double-delta SST are considerably better than those of the current subsonic jet transports. Considering the impressive safety record of the jet fleet and the increased margins that the SST will bring, we can anticipate that the transition to the SST will be accomplished with unprecedented ease and operational safety.

Reference

[1] Heppe, R. R. and Hong, J., "The double-delta supersonic transport," AIAA Paper 64-602 (August 1964).

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Development of a BLC High-Lift System for High-Speed Airplanes

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This paper presents the significant steps in the development of a boundary-layer control (BLC) high-lift system for the 367-80 (707 prototype) airplane. The design is based on an advanced boundary-layer control concept using an ejector for momentum augmentation of BLC air and primary air bleed from the propulsion system. A modulated thrust reverser for flight-path control has been integrated into the over-all design. Considerations leading to the selection of the design concept are discussed, and the importance of a well integrated program of aerodynamic and mechanical system development is shown. Pertinent results of research involving two-dimensional and complete configuration tests in the wind tunnel and full-scale ejector tests in the laboratory are given. A recently completed, joint flight research program by Boeing and NASA shows that large gains in low-speed performance can be made with blowing boundary-layer control. Landing speeds less than 85 knots at 140,000 lb airplane gross weight have been consistently achieved. Careful flight evaluation shows that conventional aerodynamic controls with stability augmentation can provide satisfactory handling characteristics for large jet airplanes throughout the extended low-speed flight envelope.

Introduction

THE problem of achieving high-lift coefficients for safe airplane operation at low speeds which is a crucial factor in modern airplane design has existed since the early days of aviation. As the art of airplane design progressed, the disparity between the requirements for efficient cruise flight and low landing and takeoff speeds became increasingly apparent. It was not long before compromises in wing and airfoil design were being made to favor the low-speed operation and soon thereafter high lift devices of varied types made their appearance. The identification of flow separation as the central problem in achieving high lift, focused attention on the mechanism of this phenomenon. The concept of the boundary layer and the influence of viscosity in leading to flow separation in adverse pressure gradients was advanced by Prandtl as early as 1904. He also showed how the application of suction to critical areas on the surface of a body could eliminate or delay the onset of flow separation. This idea, and that of rotating or moving part of the surface at the local fluid velocity, was explored by early workers in aerodynamics.

The first application of BLC using tangential blowing at the leading edge of an airfoil, was proposed by Baumann[1] in 1921. The application of this principle has long been recognized as providing, potentially, a powerful method of obtaining high lift coefficients. Various concepts, using both suction and blowing BLC have been studied intensively and a large amount of research both in the United States and in Europe has been carried on, particularly following World War II.[2] Impetus for this activity was provided by the availability of the jet engine as a potential source of air for BLC. However, practical difficulties have permitted only limited applications of the BLC technique to production airplanes up to this time and these have been exclusively on military airplanes where safety and economic considerations are somewhat less important than for commercial transport airplanes.

The subsonic jet transport, now well accepted in airline service, introduces several new factors, which interact unfavorably with those relating to good low-speed performance. The increase in airplane speeds, achieved largely by means of wing sweep, and the increase in wing loading have greatly complicated the problem of maintaining or improving low-speed performance to stay within acceptable takeoff and landing field-length limits. The prospect of the supersonic transport development which requires further design compromises in favor of efficient cruise performance extends existing design trends and further heightens the problems of achieving acceptable low-speed performance. The potential applications and extensions of high-lift technology to the military field have received a great deal of attention in the past. Current interest in a new configuration spectrum of

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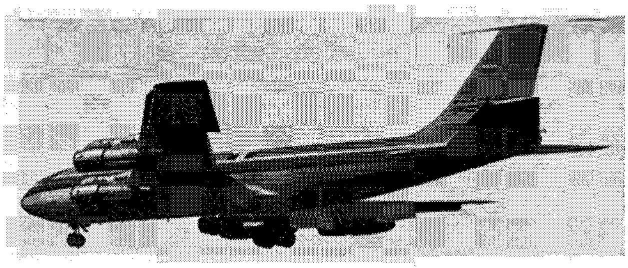

Fig. 1 367-80 airplane test flight.

air vehicles of all types from VTOL and VSTOL machines to heavy cargo airplanes serves to intensify the importance of exploring all avenues to achieve superior low-speed flight characteristics.

Mechanical high-lift devices have had a long period of development and application, and it is reasonable to assume that only relatively minor improvements in this area will prove possible. For this reason, the development of BLC techniques has occupied an important place in the high-lift research effort at Boeing. A comprehensive program involving development of theoretical design and analysis methods, wind-tunnel testing, and flight testing has been carried on to achieve continued progress in this area. This paper describes the significant steps in the development of a blowing BLC system for the 367–80 airplane (707 prototype) and the results of a flight-test program carried out jointly by Boeing and NASA to evaluate the airplane performance and handling characteristics. The 367–80 airplane is typical of present large jet transports and was modified from its original configuration to incorporate an integrated blowing BLC system and certain other modifications to provide a practical configuration for low-speed flight. Figure 1 shows an inflight picture in which the major configuration changes are visible. These include a large continuous span trailing edge flap with blowing at the hinge-line, a wing leading edge flap and slat combination, and a larger horizontal tail incorporating a leading edge slat.

High-Lift System Development

In order to achieve superior low-speed flight characteristics, which are operationally practical, a large jet transport airplane must satisfy certain fundamental requirements. It must have: 1) the ability to generate very high lift coefficients, 2) provisions for effective flight-path control, 3) satisfactory handling qualities so as to be easily flown under airline operating conditions, and 4) inherent fail-safe system design.

Figure 2 shows the lift coefficient C_L required to fly at various speeds for a wing loading typical of large swept-wing jet transports in the landing configuration. Also shown for reference are the values of $C_{L_{max}}$ for the 707 and 727 airplanes. The 727 point represents a very effective mechanical flap system, which incorporates a triple-slotted flap with considerable chord extension, as well as a large leading-edge slat. The 367-80 airplane with a blown flap has been flown regularly in the speed range represented by the shaded area. The lift coefficients are well beyond those currently used for large swept-wing transport airplanes.

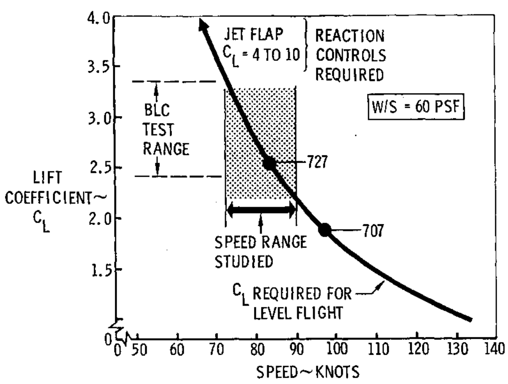

Fig. 2 Low-speed flight requirements.

One of the principal design features of the 367-80 high-lift system is the utilization of the basic propulsion system as the source of power for BLC. However, this choice introduces another problem because high engine power levels must be used during landing to provide maximum lift. At the same time reduced thrust is needed to allow a descending flight path. This problem is common to both propeller-driven deflected-slip-stream airplanes and jet airplanes using engine bleed air for BLC. Figure 3 shows the drag polar for the 367-80 airplane in a typical landing configuration and demonstrates the need for thrust modulation to obtain flight-path control with the engines operating at high-power levels.

The term "handling qualities" is used to denote the characteristics of the airplane which permit maintaining, with normal piloting skill, desired speed, altitude, and flight path during low-speed operation so as to achieve minimum safe landing distances. In this case the important considerations are the airplane speed stability, lateral-directional stability, and control response.

The regime of low-speed flight, including final approach and landing, is a critical phase of airplane operation. Transport design philosophy requires that adequate safety margins in performance and control exist, even if any single component should fail. The basic BLC system must be designed with this philosophy in mind. Later in this paper, a discussion of the 367-80 BLC system shows how an airplane can be protected against the results of failure of an engine, air ducts, or other system components. Adequate consideration and specification of operational margins is equally important in meeting the over-all objective of fail-safe design.

Flight Program Requirement

The successful development of a practical BLC high-lift system depends to a large extent on the degree to which the over-all concept meets the basic low-speed flight requirements. However, even an outstanding effort here will leave many questions, which cannot be finally resolved without a thorough flight-test program.

Unless flight data are available on an exactly similar configuration, the aerodynamic design and evaluation is carried out in the wind tunnel, and laboratory tests are run on other critical components. Scale effects are always somewhat unknown and difficult to predict, although available data shows that the effectiveness of BLC, for example, is substantially influenced by Reynolds number. Also, ground proximity effects are very important at high-lift coefficients since lift-curve slope, drag, and $C_{L_{max}}$ are generally reduced near the ground. Evaluation of these effects in the wind tunnel at

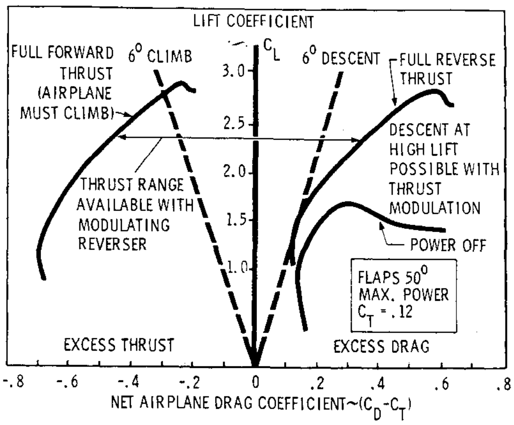

Fig. 3 Thrust modulation requirement.

high-lift coefficients is difficult because of large wind-tunnel wall effects and the presence of a boundary layer on the ground plane. Lack of information in these and related areas is a serious gap in current design information. A flight program can provide much of the information needed in addition to serving as a check on the validity of the over-all design concept.

The effects of thrust reverser operation and engine jet impingement on the flaps can be established fairly well by wind-tunnel and ground rig engine testing. However, flight testing is necessary to explore 1) dynamic interactions in actual operation, 2) possible buffeting problems, and 3) flight-path control techniques.

The problem of obtaining satisfactory handling characteristics in large airplanes becomes more difficult as the operating speed is reduced. Stability criteria have been defined for design and evaluation purposes for many years using variable stability airplanes and simulators. However, these criteria generally tend to show large, heavy airplanes to be unsatisfactory, whereas they are considered to be quite good in actual operation. Such inconsistencies make it necessary to evaluate these criteria with a large airplane duplicating the actual characteristics of typical jet transports.

The determination and specification of adequate operational margins has been carried out in the past by such agencies as the Federal Aviation Agency (FAA), the U. S. Air Force, and the U. S. Navy for guidance in airplane design. However, many of the requirements depend on power-off stall speed. Thus, a power-augmented lift system cannot be effectively utilized if such a philosophy is maintained, because the stall speed is below the power-off stall speed. Furthermore, these criteria are likely to be different for commercial and military use, because military safety margins may be reduced in order to achieve higher performance in critical situations. New operational criteria are required, and they can be determined only by operational experience with power-augmented high-lift systems.

BLC Systems Development

The development of the design concept must be carried out to satisfy the basic requirements for an effective high-lift system. Concentrated effort in the following areas, all equally important, is necessary to achieve the over-all design and performance objectives: 1) airplane system philosophy, 2) mechanical system development, and 3) aerodynamic development. These points will be discussed in relation to the specific development program for the 367-80 airplane.

One of the principal difficulties associated with blowing BLC systems in the past has been the large amounts of air required for BLC, particularly where the main engines are used as a BLC power source. To alleviate this problem a system utilizing an ejector to augment the momentum from the basic source was incorporated in the over-all design. The application of the ejector-nozzle to a BLC flap is one of the key elements in the achievement of a practical high-lift system by means of blowing BLC. This new concept enables the propulsion system to supply the required high-pressure air through direct engine bleed with no increase in size of the propulsion system or without resorting to auxiliary pumping equipment.

The general arrangement of the 367-80 airplane will be evident from examination of Fig. 1 as well as Fig. 4 which shows the wing layout. The following configuration details are pertinent to the BLC high-lift system. The trailing edge flaps are continuous from the body to the outboard aileron at the 68% wing span location. The flaps are simply hinged and operate from 0° to 85° deflection. Boundary-layer control is provided by ducting high-pressure engine bleed air through primary nozzles exhausting into ejector channels placed along the full span of the flap at the hinge line. The wing leading edge is fitted with Krueger-type

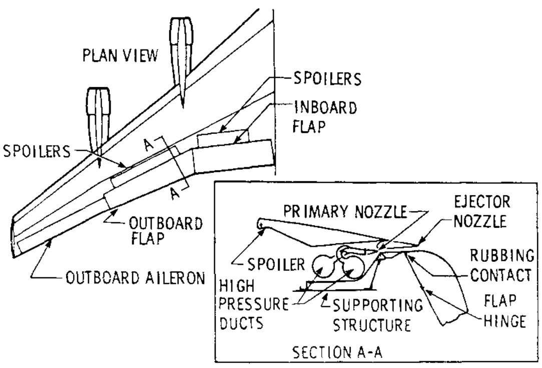

Fig. 4 Wing and BLC system detail.

flaps between the inboard engine strut and a point halfway to the body. A slat is provided along the remainder of the span to the wing tip.

Lateral control is provided by an outboard tab-operated aileron and five spoiler panels on each wing ahead of the flap hinge line. The horizontal stabilizer has been changed to that used on the larger 707-320 airplane with a leading-edge slat incorporated to provide the trim capability required at high-lift coefficients and better control at low speeds. The elevator is operated manually through a tab control system. Yaw control is provided by a hydraulically-boosted rudder having 25° maximum deflection.

Four Pratt & Whitney JT3D-1 turbofan engines are installed in separate wing pods, and inlets are provided with slats to aid inlet recovery at low flight speeds. Thrust reversers are provided for both the primary and fan sections of the engine for maximum braking at landing. The primary reversers can be modulated for flight-path control as shown in Fig. 5 indicating a partial thrust condition at full throttle.

Figure 6 shows the large variations in flight path possible with engines at maximum rpm. At full forward thrust and maximum BLC, the upper curve indicates substantial climb capability over a wide speed range to less than 80 knots. With varying amounts of reverse thrust, this curve is shifted downward to provide a large range of flight paths including descent at more than 8°. The shaded portion indicates the area for normal maneuvering during an approach. Sufficient thrust is available with normal bleed to provide adequate margin for go-around capability even with an engine failure.

Figure 4 shows the general arrangement of flaps and lateral control devices, and a typical cross section through the flap region. The primary nozzles are supplied with high-pressure air from a continuous dual duct system. The primary flow mixes with the secondary flow in the ejector shroud to give an increase in momentum at the ejector exit. Secondary airflow is supplied through ample openings in the lower wing surface.

The achievement of high lift coefficients by means of blowing BLC depends principally on the availability of large

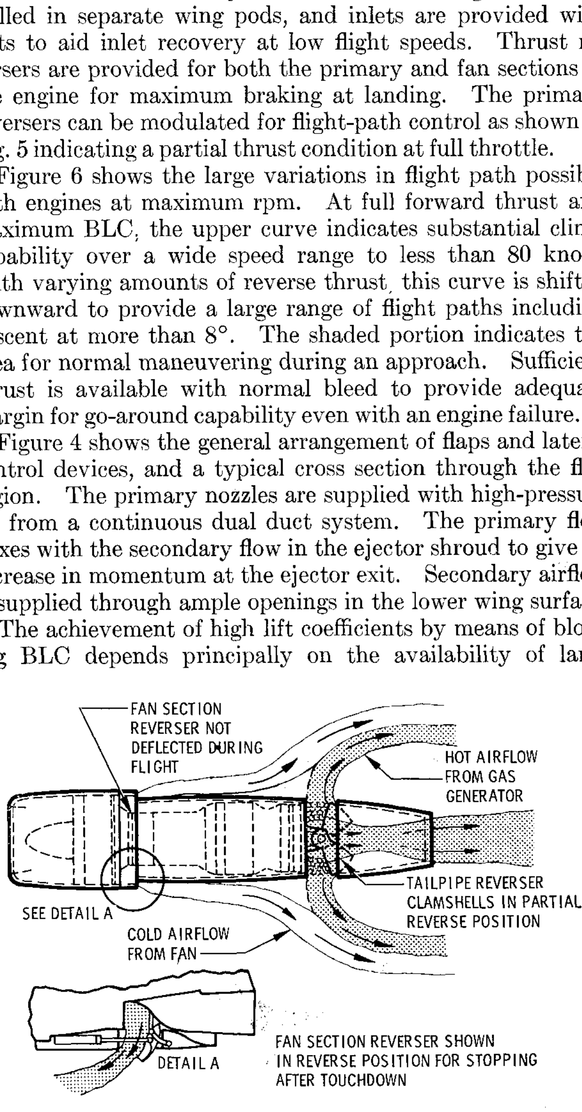

Fig. 5 Thrust reverser system.

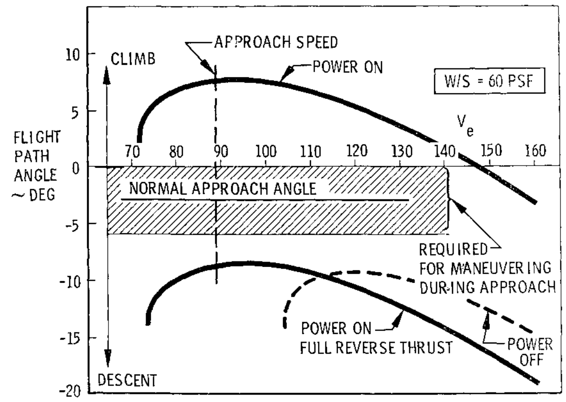

Fig. 6 Flight-path control.

amounts of momentum from the power source. For this reason, considerable effort was expended in analytical studies and an engine test program to determine the maximum amounts of bleed air available from the engine under various power conditions. With this established, the primary nozzle area was selected to limit the bleed extraction to a level consistent with engine operating limits and airplane power requirements, while providing sufficient momentum for blowing BLC. The arrangement finally selected permits full-power bleed flows up to 18 lb/sec/engine for normal operation, and up to 23 lb/sec in situations corresponding to an engine failure or duct rupture.

The selection of the ducting system to supply the BLC air was made after analysis of a number of possible arrangements. Primary consideration was given to 1) safety and reliability, 2) simplicity, and 3) best system capability in the event of any engine or duct failure. Figure 7 shows the general arrangement of the system selected and a detail of the primary nozzle configuration. The system features two manifolds, or distribution ducts, each of which crosses the body and is continuous along the flap span. The crossover is necessary to maintain lateral symmetry in the event of engine failure or duct rupture.

The dual distribution duct arrangement supplied jointly by each engine ensures that the loss of lift because of engine failure or duct rupture, at a critical point, will be minimized. The dual ducts supply alternate primary nozzles to maintain a continuous spanwise supply of BLC air in the event of the rupture of a distribution duct. The estimated effects of failures of the type discussed previously are as follows: 1) failure of a single engine reduces maximum lift 4%, 2) failure of a distribution duct reduces maximum lift 6%, and 3) lateral symmetry of the system is very nearly maintained at all times. To date, flight tests in which failures were simulated have shown the losses in lift to be somewhat smaller than estimated.

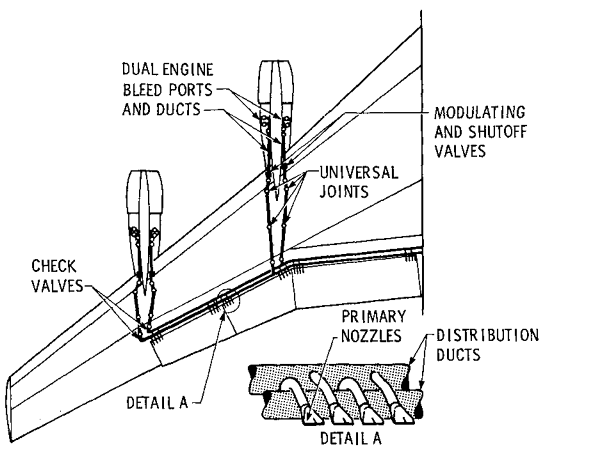

Fig. 7 Duct system and nozzle arrangement.

Aerodynamic Development

In the development of the system described previously, the achievement of the performance goals depends to a great extent on optimization of the configuration details to obtain favorable aerodynamic characteristics. The literature on blowing BLC applications (e.g., Ref. 3) shows that a useful correlating factor in determining BLC effectiveness is the momentum coefficient $C\mu$ which is defined as follows:

$$C\mu = \frac{\text{blowing momentum}}{\text{dynamic pressure} \times \text{wing area}} = \frac{\dot{m}V_j}{q_\infty S}$$

In general, large values of $C\mu$ are desirable to give high C_L. However, a survey of the literature showed that the effects of numerous other variables on BLC effectiveness had not been systematically evaluated over the working range. Also, much data, particularly in two-dimensional testing, have been accumulated under testing conditions of doubtful validity.

A method of two-dimensional testing, particularly suitable for the evaluation of high-lift configurations at a reasonable scale, has been developed at Boeing as part of the over-all program of high-lift development. Figure 8 shows the general arrangement of the two-dimensional test section in the Boeing transonic wind tunnel, which incorporates boundary-layer suction on the walls to avoid wall-flow separation near the test airfoil. This was necessary to obtain accurate two-dimensional data. During the development of the 367-80 BLC system, extensive tests were run in the two-dimensional section to evaluate the effects of various BLC configuration details including the following: 1) nozzle width (jet velocity), 2) nozzle location and orientation relative to flap, 3) simulated failure conditions, and 4) spoiler effectiveness with BLC flaps. Nozzle width effects are particularly important because of their influence on the selection of the ejector configuration. Configuration details based on the results of the preceding studies were incorporated in the design of the 367-80 BLC system.

In the present BLC system concept, the function of the ejector is to increase the momentum of the primary air so as to obtain maximum lift from a given amount of engine bleed air. An ejector can be characterized as a jet pump, which discharges a high-speed jet into a surrounding shroud as shown in Figs. 4 and 9. The jet from the primary nozzle induces a secondary flow through the shroud by mixing. The resulting mass flow at the ejector exit is much larger than the primary flow, and substantial increases in the exit momentum can be achieved with favorable ejector geometry. A comprehensive program of ejector development, involving both theory and experiment, has been carried on at Boeing which has contributed substantially to the system optimization in the present application. Selection of the ejector configuration for the 367-80 was made on the basis of tests run with full-scale models of appropriate geometry under conditions simulating the actual operating environment of the ejector on the airplane. Of some importance is the fact that the ejector performance is influenced by the flap deflection, which causes a reduction in exit pressure in flight and a corresponding in-

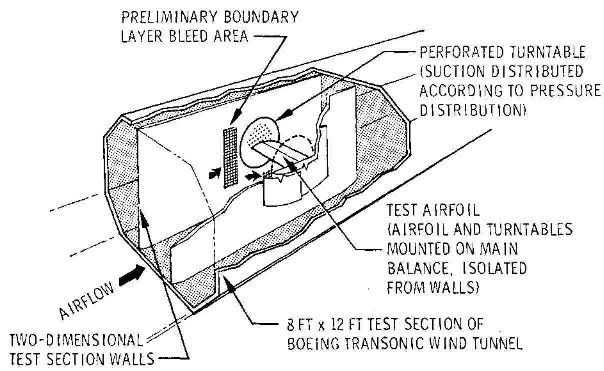

Fig. 8 Two-dimensional test section.

crease in ejector augmentation particularly at large flap angles. For the present application, the constant-area shroud shape is nearly optimum and ejector augmentation increases gradually as the area ratio is increased. The results of tests in which the proper exit pressure was simulated are shown in Fig. 9 for two primary pressure ratios corresponding to 50% and maximum engine bleed.

To obtain the optimum performance of a BLC system which incorporates an ejector, it is necessary to make a proper selection of the ejector geometry and operating conditions. Since the geometry and arrangement of the system is rather complex, many parameters play a significant role in determining the over-all performance of the system. The most important of these are 1) ejector area ratio, ejector area/primary nozzle area; 2) primary nozzle pressure ratio P_T/P_∞; 3) primary nozzle area/wing area; and 4) flap angle. The method of selecting the system geometry can be illustrated by reference to Fig. 10 in which the solid lines for h/c = const show the effect of nozzle height to wing chord ratio on the variation of C_L with $C\mu$. The data shown are taken from Boeing two-dimensional test results for a 27% chord flap at 50°, with 0° angle of attack. This corresponds to a typical operating condition for a midspan section on the 367-80 airplane during landing approach. The trends shown for a given nozzle height are typical of this type of configuration,[4–6] although the level of C_L is generally higher than that obtained elsewhere for comparable values of $C\mu$. For a given $C\mu$, increasing nozzle height substantially reduces the C_L available; a characteristic that is essentially independent of flap angle and angle of attack. On the other hand, if the system includes an ejector, Fig. 9 shows that an increase in the ejector area per unit span h will result in an increase in $C\mu$ for a fixed value of the primary momentum coefficient $C\mu_{pr}$. This leads one to expect an optimum $C\mu$ at a point where the increase in ejector augmentation is balanced by the decrease in BLC slot effectiveness as h/c increases. To show that this is indeed the case, we construct the dashed lines of Fig. 10 corresponding to constant values of momentum coefficient for the primary nozzle $C\mu_{pr}$. With primary nozzle area fixed (in this case $(w/c)_{pr} = 0.0002$), these lines correspond to constant values of primary nozzle pressure ratio. The construction of the dashed lines is carried out by selecting a given $C\mu_{pr}$ and cross-plotting $C\mu$ as a function of h/c with the aid of Fig. 9. Note that h/c is related directly to the ejector area ratio since h/c = (ejector area ratio) $\times$ $(w/c)_{pr}$.

Finally, the "best-performance" curve, shown in Fig. 10 as the heavy line to the left, is obtained by plotting the peak C_L of each dashed curve at a $C\mu$ equal to its corresponding value of $C\mu_{pr}$. A comparison of the "best-performance" curve with the best that can be achieved with ordinary blowing ($h/c \doteq 0.001$) shows that the use of the latter would require a 35 to 40% increase in $C\mu$ over the ejector system at high C_L. Since ordinary blowing nozzles tend to lose effectiveness for $h/c < 0.001$, the increase in mass flow required from the power source for ordinary blowing may be as high as 50%. The optimum geometry is seen to correspond quite closely to constant nozzle height for all of the primary nozzle pressure ratios. In any event, the precise selection of h/c near the optimum is not critical. In this case, the optimum h/c is approximately 0.0042, corresponding to an ejector area ratio of 21 to 1 which is used for the 367-80 system.

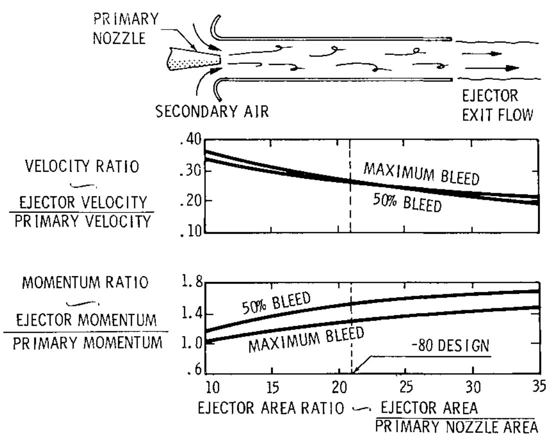

Fig. 9 Ejector augmentation characteristics.

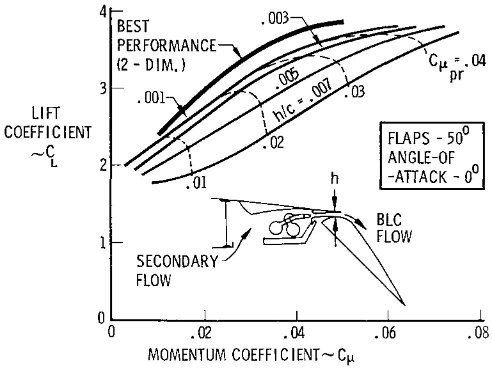

Fig. 10 Ejector BLC characteristics.

A comprehensive series of wind-tunnel tests was conducted with a 0.068 scale model of the 367-80 airplane in the Boeing transonic wind tunnel. Figure 11 shows the model in the tunnel, mounted on a hollow strut through which BLC air is supplied. The primary purpose of the tests was to establish the characteristics of the airplane throughout the low-speed flight envelope. New and unusual conditions, reflecting the effects of engine exhaust impingement on the flaps and thrust reverser operation were explored. For these tests, the engines were simulated by means of externally mounted nozzles so that only airplane reactions were measured. Also, critical factors in the high-lift system design, including the distribution spanwise of blowing momentum and the leading-edge flap configuration were resolved. Evaluation of stability and control characteristics showed adverse yaw due to lateral control to be a large effect for wings at very high-lift coefficients. Longitudinal trim requirements were large, as expected, necessitating the incorporation of a leading-edge slat on the horizontal stabilizer. The results of the wind-tunnel test program have been compared with the flight data from the subsequent flight program for which data are given in the following section. The results compare well when proper account is taken of ejector performance, engine jet impingement, and other factors that are peculiar to the flight vehicle. A detailed analysis is highly complex and is not attempted here because of lack of space. However, for general comparison, Ref. 7 is cited showing results of large scale wind-tunnel tests on a representative transport airplane configuration. The comparison is quite good in the applicable $C\mu$ range, although the level of lift coefficients achieved on the 367-80 airplane is higher, principally because of higher available $C\mu$ and flap angle.

Flight-Test Program

During the high-lift development of the 367-80 airplane, it was recognized that the effect of low flight speeds on control

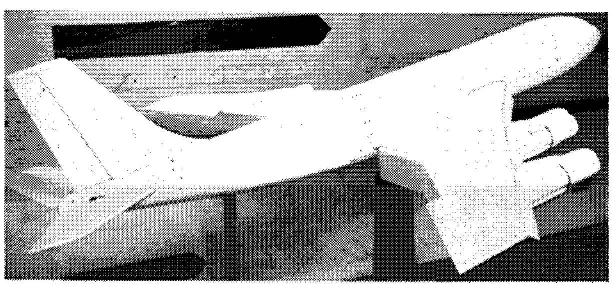

Fig. 11 367-80 model in wind tunnel.

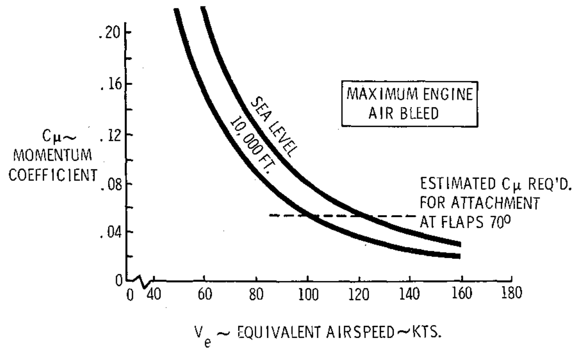

Fig. 12 Maximum BLC capability.

requirements for large swept wing transports was relatively unexplored. With the capability for very low flight speeds in its revised configuration, the 367-80 airplane provided an ideal vehicle for exploring low-speed effects on airplane handling characteristics and control requirements in addition to evaluation of the performance and practicality of the basic high-lift system. Because the results of an investigation of control requirements are of interest to most of the industry as well as to The Boeing Company, a proposal was made to NASA to use the 367-80 to investigate this region of flight. Discussions between NASA and The Boeing Company resulted in a two-phase NASA-Boeing flight-test program. Phase I was conducted to evaluate and report the low-speed characteristics of the 367-80, whereas the purpose of phase II was to investigate the effects of slow approach speeds on airplane handling qualities. In addition, prior to NASA testing, a short Boeing evaluation flight-test program was conducted to establish the airplane's flight worthiness throughout its operational envelope. This section deals with the following pertinent results of the three flight-test phases: 1) performance including a) maximum lift capability, b) lift and drag, and c) flight-path control; 2) longitudinal stability and control; and 3) lateral-directional stability and control.

Maximum Lift Capability

Initial flight testing demonstrated that the airplane as a complete system functioned quite well. However, one aerodynamic problem became apparent when BLC flow attachment could not be maintained above flap settings of 55°. Flight evaluations at speeds below 90 knots at altitudes as low as 3000 ft were flown in an attempt to achieve attachment at higher flap deflections. These flight conditions, when referred to maximum BLC system capability, as shown in Fig. 12, indicate that high values of momentum coefficient were being obtained. The predicted value of $C\mu$ necessary for flow attachment at flaps 70° was 0.051, considerably below the value being obtained. Based on the preceding considerations, the problem was determined to be in the method of discharging the BLC flow rather than in the amount of momentum supplied.

The flow attachment problem was solved by the addition of a short trailing edge extension to the ejector upper surface. Vortex generators also were applied in a single row just upstream of the spoiler panels to provide better mixing of the boundary layer with the BLC flow over the flap. Subsequent testing showed some gain in flap effectiveness with no blowing, although the effectiveness of the vortex generators at high blowing rates was not specifically investigated. The ejector modification moved the discharge point 10° around the flap and provided a convergent nozzle for the ejector exit. The modifications to the wing and ejector resulted in flow attachment through the full range of flap deflection to 85°.

With the preceding modifications, the airplane was flown throughout its low-speed flight envelope and landed using up to 70° of flap and maximum blowing. The lowest approach speed utilized was 78 knots equivalent airspeed (EAS) and the corresponding landing speed was 75 knots EAS at an airplane weight of 135,000lb.

The maximum lift capability of the airplane at two flap settings is shown in Fig. 13. Stalls were performed with all four engines supplying BLC and, in addition, with only three-engine supply to check the effect of asymmetry in BLC supply on $C_{L_{max}}$. A simulated engine failure condition is indicated on the plot which shows an initial operating condition with four engines supplying BLC air. With an outboard engine shut down, $C\mu$ decreases noticeably, although only a small change in $C_{L_{max}}$ occurs. If power is increased on the remaining three engines so that $C\mu$ is brought back to the initial conditions, the original value of $C_{L_{max}}$ is attained. This verifies the safety concepts of the ducting and system design. Another rather important factor that can be seen on the maximum lift plot is the double value of $C_{L_{max}}$ obtainable at zero BLC momentum coefficient. The difference between the low- and high-lift available is due to a jet flap effect caused by the inboard engine exhaust impinging on the inboard flap and being deflected. This effect had been measured previously in the wind tunnel with the characteristic of contributing a large effect at zero $C\mu$ and a proportionately smaller effect as momentum coefficient increased.

The data shown are for a pressure altitude of 10,000 ft. At sea level, the $C\mu$ available increases because of high ambient pressure ratio as shown in Fig. 12. The highest maximum lift coefficient at flaps 70° based on the available $C\mu$ at sea evel would be somewhat greater than 3.2.

Lift and Drag

The effects of BLC on lift and drag are shown in Fig. 14 for zero and maximum blowing with flaps 50° and 70°. It will be noticed that the lift curves are nearly parallel. One would expect that some increase in slope with increased blowing would occur, since the flight data are all taken at constant values of blowing momentum which makes $C\mu$ proportional

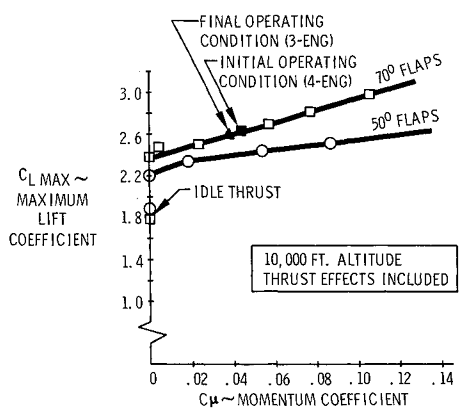

Fig. 13 Maximum lift capability.

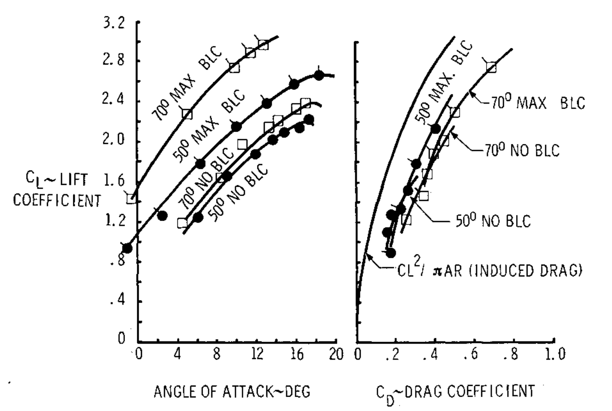

Fig. 14 Effect of BLC on lift and drag.

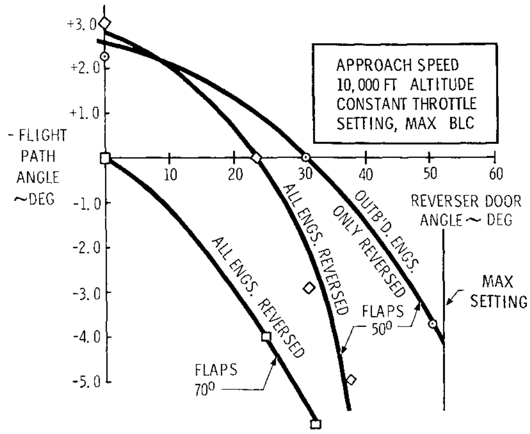

Fig. 15 Reverser effectiveness in flight.

to C_L. However, in this case, engine jet impingement on the flap interacts strongly with the external flow to mask the characteristics normally associated with a BLC flap.

The drag polars indicate that, with engine thrust effects included, the aerodynamic drag level change between zero and maximum blowing is small. However, climb performance suffers at maximum BLC because of the thrust loss incurred by bleeding the engines (approximately 3 lb of engine thrust/lb of primary nozzle BLC thrust). Comparing the shape of the drag polars to a pure induced drag relationship, $C_L^2/\pi AR$ indicates that at approach lift coefficients (approximately $C_{L_{max}}/1.44$) the lift distribution with engine jet impingement alone is considerably more nonelliptic than that with jet impingement plus blowing. This is readily apparent from geometric considerations, since the inboard engines have considerably more impingement than the outboard engines and, consequently, the lift would tend to be concentrated on the inboard portion of the wing. Furthermore, there is ample evidence from two-dimensional wind-tunnel data that large reductions in the profile drag of a flapped wing section occur as $C\mu$ is increased and flow separation on the flap is reduced. These effects are clearly evident in the higher values of L/D at approach C_L for the maximum blowing cases.

Figure 15 shows the flight-path control available with modulated thrust reversers at constant approach speed. These are actual flight data points in which the airplane was trimmed, and the thrust reversers used to change climb angle. The ability to control the flight path at high engine power is important when supplying BLC from the main engines, since the $C_{L_{max}}$ available is dependent on the engine compressor rpm. By using modulated thrust reversers, the engine rpm can remain high to supply BLC air, while the forward thrust can be varied to control flight path, thus keeping the airplane stall margin independent of thrust at approach speed. The reversers, in actual operation, were superior for flight-path control to the normal engine throttles even with BLC off since their thrust response was much better. Referring again to Fig. 15, it can be seen that using only the outboard engines for flight-path control furnishes a sufficient range of flight paths to be usable for normal instrument landing system (ILS) operation. Therefore, for operation in the C_L range where the lift caused by jet impingement is important, the outboard reversers can be used for flight-path control while using the lift increment from inboard jet impingement.

Longitudinal Stability and Control

The longitudinal handling qualities of the 367-80 with BLC on and off are quite reasonable. Trim changes caused by thrust and BLC are quite small, requiring a maximum of 2° of elevator or $\frac{3}{4}$° of stabilizer. Since no ballast system was installed in the 367-80 and because the range of c.g. travel available with fuel loading was small, all of the testing was conducted with the center of gravity between 29 and 31% mean aerodynamic chord (MAC). Figure 16 shows curves of stabilizer required to trim vs airplane lift coefficient for zero and maximum blowing at 50° and 70° of flaps. Compared to production 707's, the 367-80 exhibits much more longitudinal speed stability, requiring 1.8 times as much stabilizer to trim a given increment in lift-coefficient. This is caused by the increase in $C\mu$ and the corresponding increase in pitching moment, as speed is decreased while the BLC momentum is held constant. The effect of jet impingement changes the slope of the curves for zero BLC, so that the stability is increased in this case also.

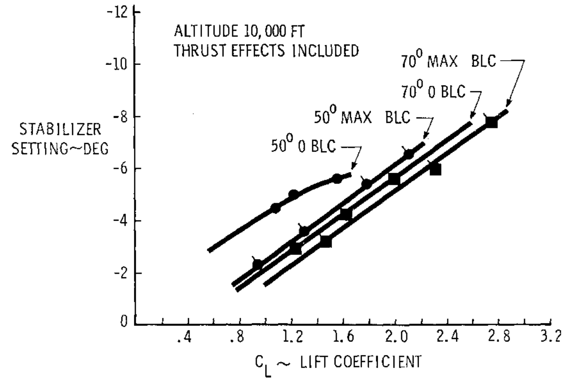

Fig. 16 Effect of BLC on trim.

The stall characteristics of the airplane are quite good up to a flap deflection of 60°, with a well-defined pitch break at stall. Above 60° of flap and at high blowing, the airplane begins to exhibit a slight pitchup tendency at stall that becomes more pronounced as the flap deflection and amount of blowing are increased. In all cases, elevator control is positive and is more than sufficient to produce nose-down rotation at any time during the maneuver. The flow reattachment following a stall is quite rapid and only small airspeed increases are required to reestablish the wing flow. The resultant altitude loss is nominal and generally in the range of 100 to 200 ft.

The dynamic stability of the airplane in the longitudinal mode was evaluated at flaps 50° and 70° with maximum blowing. The phugoid mode has a period for both flap settings of 31 to 32 sec and a damping ratio of 2.9%. The short period mode has a period of 4 to 5 sec and is heavily damped.

The most significant result of the flight-test program relating to longitudinal control is the large trim change introduced by ground effect. This reflects the large nose-down pitching moment changes resulting primarily from the reduction of downwash angle at the tail. Figure 17 shows the elevator required to flare for two flap settings and three airspeeds. For an order-of-magnitude comparison, a 707, during a normal landing, requires a maximum of 6° of elevator to flare. The effect of operation near the ground was explored at great length, both analytically and in the wind tunnel. The primary variables affecting pitching moment in ground effect are height and the lift coefficient at which the airplane is operating; nose-down pitching moment tends to become more severe at high lift coefficient and low heights. The flight values, although somewhat smaller in magnitude, compare favorably with those predicted.

In general, the longitudinal stability could be summarized as very good for both the static and maneuver cases. The longitudinal control is good at airspeeds above 90 knots. Below 90 knots, the control deflections to obtain a given response are larger than normal; thus, the column forces are somewhat higher than desirable. Available evidence indicates that this can easily be remedied by the addition of hydraulic boosts to existing aerodynamic surface controls.

Lateral-Directional Stability and Control

The directional control presented no difficulty, since control power available is very high and airplane response quite

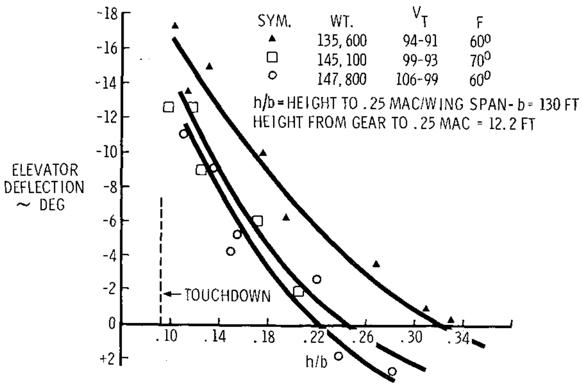

Fig. 17 Elevator deflection in flare.

rapid throughout the flight envelope. The lateral-directional characteristics evaluated on the initial flights posed several problems. As anticipated, airplane flight characteristics at very low speed exhibited divergent Dutch roll, nonlinearities in lateral control effectiveness, and adverse yaw due to lateral control. The lateral-directional problems were solved in the following manner: 1) stability augmentation was added using appropriate input signals to the rudder, and 2) the lateral control system was modified to improve its sensitivity at small deflections and to reduce nonlinearities.

The stability augmentation system installed in the airplane served the purpose of damping Dutch roll and aiding the pilot in making coordinated turns. Dutch roll damping was furnished by a rudder input proportional to sideslip rate $\dot{\beta}$. The Dutch roll mode has a period of about 8 sec and a time to double amplitude of nearly 20 sec without the damper operating. With the damper fully effective, the motion was made highly convergent with a time to half-amplitude of less than 10 sec. Airplane turns were aided with rudder inputs proportional to aileron angle δ_a and roll rate $\dot{\phi}$. The aileron input to the rudder provided proverse static yaw to aid turn entry and rollout, whereas the roll rate input eliminated the dynamic adverse yaw. The stability augmentation system has a maximum authority of ±9° rudder angle.

The adverse yaw due to lateral control was demonstrated to be a basic effect of lateral control devices operating on a wing at very high lift coefficient, as predicted from both theory and wind-tunnel tests. The control nonlinearity was established as an inherent characteristic of a spoiler operating near a BLC flap. This appeared as a zone of low spoiler effectiveness for the first 6° of travel. Thus, for small control wheel deflections, the primary rolling moment contribution was that due to aileron. Beyond 10° of travel, a rapid progression of flow separation over the flap caused a large change in lift with correspondingly large rolling moments.

Development of modifications to the lateral control system was conducted with the objectives of increased control effectiveness for small wheel deflections and reduction of the adverse yaw and control nonlinearities in the system to acceptable levels. The wheel to aileron gearing was changed to command full aileron (18°) at 30° of control wheel. A 90° flange was installed on the lower surface trailing edge of the spoiler panels that overlapped a similar flange on the upper surface of the ejector. The flanges on the spoiler and ejector served to block flow from the undersurface of the wing through the spoiler gap, thus increasing spoiler effectiveness for low deflection angles. The outboard spoiler panel was disconnected and locked down. A comparison of the original system and the final system characteristics is shown in Fig. 18. The revised lateral control system reduced adverse yaw in addition to improving roll response for small control wheel inputs. As can be seen from the plot, the lateral control nonlinearities were reduced considerably, representing a significant improvement over the original situation. The combination of stability augmentation and revised lateral control system gave the airplane sufficient roll rate and roll acceleration throughout its flight envelope and made its turn characteristics quite acceptable. As in the longitudinal case, accumulated data indicate that the addition of hydraulic boosts to existing controls on the lateral axis can change control wheel forces to provide completely satisfactory handling characteristics in the lateral-directional mode.

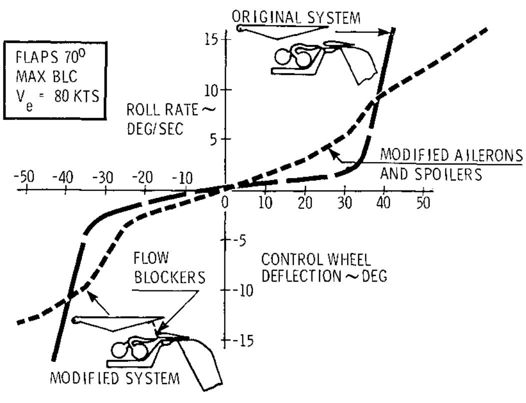

Fig. 18 Lateral control characteristics.

Conclusion

This presentation has shown the important steps in a program of engineering research and development to provide a large jet transport with a BLC high-lift system enabling safe approach and landing at very low airspeeds. A joint flight research program conducted by Boeing and NASA has proved the practicability of a new high-lift design concept and has shown that large gains in low-speed performance can be achieved with blowing boundary-layer control. Valuable information to allow further gains in low-speed performance has been accumulated. An extensive evaluation of handling characteristics shows that basic aerodynamic controls with stability augmentation can provide satisfactory control at very low airspeeds. The incorporation of hydraulically boosted aerodynamic surfaces for all control axes, together with stability augmentation, is viewed as the ultimate means of providing completely satisfactory handling characteristics in the very low-speed flight regime. It is intended that the 367-80 airplane will continue to be used as a valuable tool in the development of all phases of high-lift technology.

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