YC-14 System for Leading-Edge Boundary-Layer Control

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A high-lift leading-edge boundary-layer-control (BLC) system is an integral part of the design of the YC-14 prototype airplane. The system is based on the concept of "blowing" and uses bleed air from the eighth and fourteenth stages of the high-pressure compressor of the main engine. Air from the two sources is mixed in a fixed-geometry ejector to provide the necessary blowing. Automatic control permits the BLC system to select its own operating mode (takeoff or landing) and to accommodate all engine and engine-out maneuvers. This paper discusses the evolution of the YC-14 BLC system.

Introduction

THE Air Force/Boeing Advanced Medium STOL Transport Prototype, the YC-14,[1] is a twin-engine aircraft (Fig. 1) capable of operating from an airfield 2000 ft long while making allowance for a possible engine failure at the most critical time during takeoff or landing. It has a takeoff speed of approximately 96 knots and an approach speed of approximately 86 knots. The engines are General Electric CF6-50D's with a bypass ratio of 4.3 and a fan pressure ratio of 1.65 at takeoff thrust. They are located close to the body to minimize engine-out yawing and rolling moments, and forward and above the wing to provide upper-surface blowing. Blowing of the engine exhaust over the upper surface of the wing creates a powered lift system that provides efficient turning of engine exhaust, large induced circulation, and excellent boundary-layer control of external flow on the wing surface.[2] Across the entire span of the wing is a Krueger variable-camber leading-edge flap similar to that used on the Boeing 747. On the YC-14, the effectiveness of this flap is augmented by a leading-edge BLC system. The following discussion presents the evolution of this system.

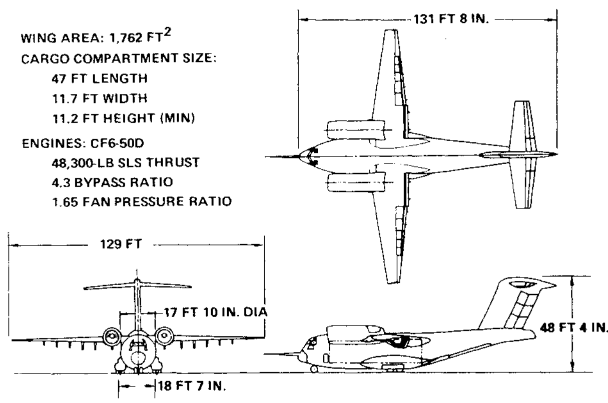

Fig. 1 Boeing advanced medium STOL transport prototype: YC-14.

System Overview

The YC-14 leading-edge BLC system (Fig. 2) is fully automatic. It is armed normally, and the simple on/off control valves (the only moving parts of the system) operate as a function of flap position. The valves normally are closed when the flaps are retracted; thus, the pilot needs only to lower the flaps to actuate the BLC system. Flap position activates one of two distinct system operating modes: short-field takeoff and short-field landing. During operation, the system self-accommodates all engine and engine-out performance.

The BLC system is powered by engine bleed and employs a common manifold ducting scheme between engines to prevent lateral asymmetry in case of engine or system component failure. In the takeoff mode, the system operates on eighth-stage bleed only, thereby conserving engine thrust for airplane acceleration and steep angle of climb. In the landing mode, operation is based on a combination of eighth and fourteenth stage bleeds mixed in a fixed-geometry ejector. Deployment of the engine thrust reverser shuts off the fourteenth stage bleed valves to provide increased thrust for airplane braking.

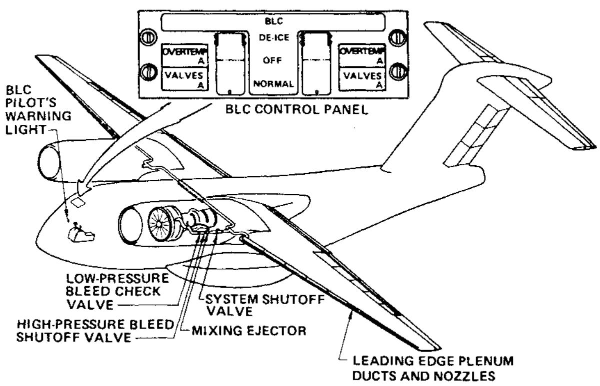

Fig. 2 YC-14 boundary-layer-control system.

Engine bleed is also the energy source for a deice mode that permits eighth-stage bleed air to flow through the ducting to prevent ice accretion on the BLC nozzles and the wing leading edge. The deice mode can be activated both in flight and on the ground, with flaps retracted or deployed.

Design Requirements and Objectives

The BLC system has been designed to provide two capabilities essential if an engine fails at the most critical time in short-field takeoff or landing: 1) adequate stall margin and lateral controllability; and 2) acceptable climb gradient for go-around or descent angle for landing. The BLC momentums required to provide these capabilities were determined from a series of wind-tunnel tests conducted on a 6% scale model of the YC-14 prototype in the Boeing Vertol 20- × 20-ft V/STOL wind tunnel. The BLC momentum (F_{BLC}) and

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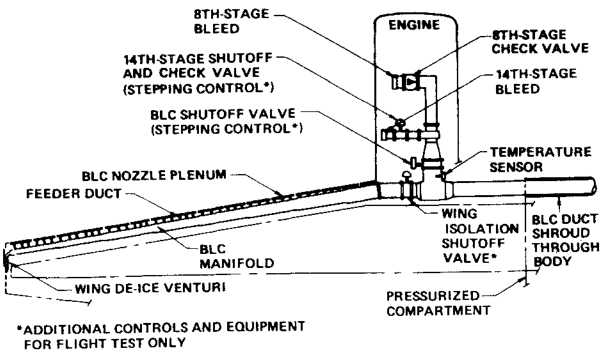

Fig. 3 YC-14 BLC system schematic.

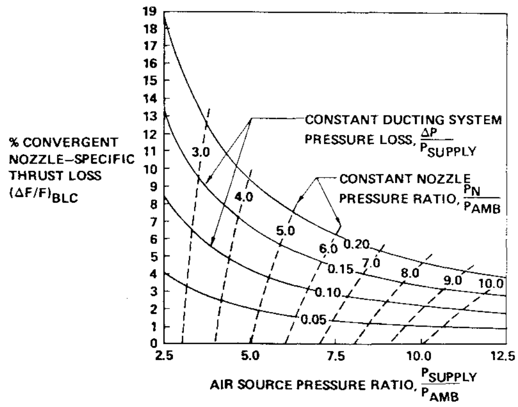

Fig. 4 Ducting system pressure loss/thrust loss characteristic.

momentum coefficient ($C\mu$) are defined as $F_{\rm BLC}=(W_a \cdot V_j)/g$, $C\mu = F_{\rm BLC}/(q_\infty S)$, where W_a = blowing aircraflow rate, V_j = blowing air isentropic velocity, q_∞ = freestream dynamic head, and S = wing area.

The design goal was that the BLC system be capable of providing the required blowing momentum levels listed in Table 1, distributed so that the sectional blowing momentum coefficient is essentially constant across the span and the system performance is symmetric under all operating conditions. Additional design objectives were 1) simple control, 2) automatic system operation to keep the crew workload to a minimum during the critical takeoff and landing operations, 3) maximum use of flight-proven hardware to optimize reliability and minimize cost, and 4) ease of system modification and high operational flexibility during the prototype flight test program. This last design objective was included because full-scale aircraft seldom exhibit stall characteristics identical to those of scaled wind-tunnel models. Included in this design objective was the capability to 1) modify the baseline symmetric BLC system to an asymmetric system (i.e., with BLC on only the wing with the failed engine during single-engine operation) for evaluation of lateral control requirements and airplane handling qualities; 2) vary BLC momentum, within system design capability, to determine the optimum propulsion/aerodynamic system design point; and 3) tailor spanwise BLC momentum distribution for effective BLC control over the whole wing span. These design requirements and objectives have been satisfied successfully on the YC-14 by superimposing additional flight test controls (Fig. 3) in a manner such that, at the conclusion of the flight test program, it will be possible through reconfigurement to return to a simple BLC system.

BLC System Development

In developing the BLC system just described, various trade studies and development tests were conducted. The following discussion considers studies that markedly influenced YC-14 system design.

Air Source Selection

Aerodynamic experimental investigations[3] indicate that the jet momentum coefficient ($C\mu$) is the main factor governing the effectiveness of blowing, provided that the system has been designed to operate at a greater-than-critical nozzle pressure ratio of 1.89. Other factors that affect the choice of air source include airplane performance effects such as aerodynamic, weight, and propulsion trades, the space available for system installation, the performance characteristics of candidate air sources, and the maximum blowing nozzle area that can be used without adversely affecting airplane low- and high-speed cruise performance.

BLC nozzle installation on the upper contour of the wing leading edge introduces a discontinuity in the aerofoil profile, creating a kind of "step" that can cause an increase in cruise drag due to step base drag, premature transition of the boundary layer from "laminar" to "turbulent," and induced wave drag due to sudden expansion. In general, this characteristic demands that the BLC nozzle area be kept to a minimum and, as a result, that an air source capable of providing air at the highest possible pressure be selected. High-pressure air source and minimum nozzle area installation allow, for a given installation space, design of a ducting system that operates at low flow Mach numbers, and hence at low pressure loss. Ducting system efficiency is also higher at high operating pressure (Fig. 4).

Although high operating pressure is clearly desirable, several considerations limit the maximum amount usable: fabrication and maintenance of BLC nozzles, requirements of adjoining structure protection in case of ducting component failure, high induced thermal stresses, and decay of system component mechanical properties at elevated temperatures. After careful study, the YC-14 main engines were selected as the air source to power the BLC system. An average nozzle pressure ratio of 5.5 was determined to be optimum for system design. Past BLC systems based on the concept of blowing[4] generally have operated with engine bleed air, and availability of large amounts of pressurized air from modern jet engines has, to a large extent, served as a strong impetus to the development of such systems.

The CF6-50D engine can be bled simultaneously from the eighth, tenth, and fourteenth compressor stages in the amounts of 5%, 2%, and 5% of the core flow, respectively.

Table 1 YC-14 leading-edge BLC system required and available blowing momentums (sea level, standard day)

Flight mode or flap position	Number of operating engines	Engine thrust	Required blowing momentum	Available blowing momentum
Takeoff	1	Max. takeoff	705	735
	2	Max. takeoff		1700
Landing	1	75% max. takeoff	...	1300
	2	65% max. takeoff		1300
Go-around landing flaps	1	Max. takeoff	1740	1760
	2			2650

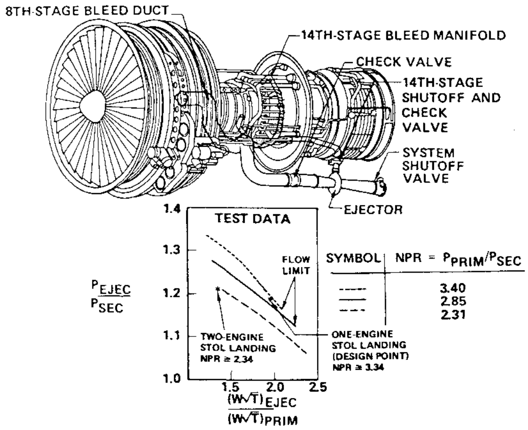

Fig. 5 YC-14 BLC ejector.

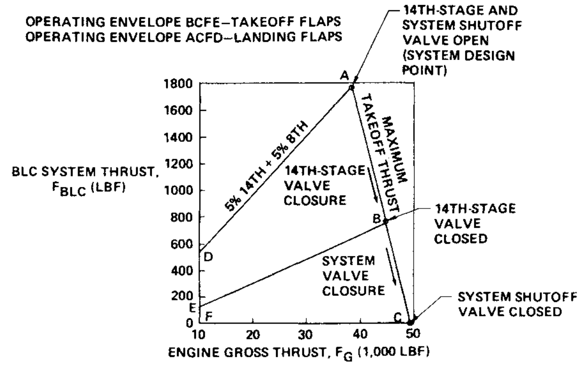

Fig. 6 YC-14 flight test operating envelopes (single engine, sea level, standard day).

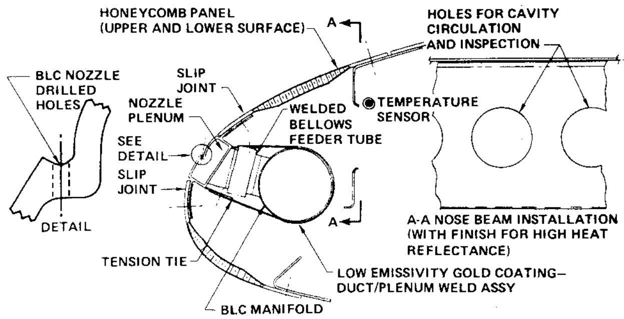

Fig. 7 Typical wing ducting between supports.

Analysis indicated that the system design bleed requirement could be satisfied with simultaneous bleed from the eighth and fourteenth stages mixed in a device capable of boosting the eighth-stage bleed pressure by approximately 18%.

Bleed-Air Ejector

An ejector was chosen to mix bleed air because of its generally simple construction, operation, and maintenance, and its low cost. Installation considerations (small frontal area required and noncriticality of environment) also played a role in selection. The device developed for the YC-14 (Fig. 5) is a fixed-geometry ejector with no moving parts; it consists of an integrated flow mixer and diffuser section, with peripheral high-pressure nozzles located at the throat. The YC-14 ejector is extremely simple in construction, weighs only 12 lb, and is roughly only half the length of a conventional ejector with discrete mixer and diffuser sections. Laboratory tests on a full-scale model at simulated engine bleed conditions have confirmed satisfactory performance with good stability. At its present design condition, the YC-14 ejector provides a pressure rise of approximately 19%, with a momentum recovery of 80%.

The bleed-air ejector is a highly versatile component of the YC-14 BLC system. It not only serves the conventional role of a mixing and pumping device but also controls engine bleed to allowable limits in case of a failure of the downstream ducting or BLC nozzles. This latter function is performed by the ejector nozzles, whose size limits each of the eighth and fourteenth-stage bleeds to a maximum of 5% of engine core flow. The ejector also serves as a device for accommodating single- and two-engine BLC requirements without any external control or moving parts. During two-engine STOL landing, the ejector mixes 2% of the flow from the eighth stage with 5% of the fourteenth-stage flow and delivers a total of 7% core flow per engine to the BLC system. In the event of an engine failure, with twice the BLC nozzle area exposed downstream of the operating ejector, response to the increased flow requirements is achieved automatically when the ejector self-adjusts its operating point to the flow limit required by design. This adjustment requires no sensing or control of system valves, and it occurs at the propagation speed of small pressure waves, commonly referred to as acoustic speed.

The bleed-air ejector has two distinct operating modes: takeoff and landing. These correspond to the system operating modes and are determined by flap position. When the flaps are in takeoff position, the system control causes the BLC shutoff valve to move to open position, thus permitting flow from the eighth stage. In this mode, the BLC system operates on 5% eighth-stage bleed per engine both in normal and engine-out conditions. The bleed is limited to this amount by the ejector throat, and the ejector behaves as an efficient flow-limiting venturi. With the flaps locked in the short-field landing position, the system control logic causes the system shutoff and fourteenth-stage bleed valves to move to full-open position, and in this operating mode the unique YC-14 ejector behaves as a conventional ejector, mixing 5% fourteenth-stage bleed with the required bleed from the eighth stage (up to a maximum of 5%) to match the system pressure-flow characteristics.

On the YC-14 prototype, additional "stepping" control regulates the maximum opening of the bleed-air valves in order to provide blowing momentum "dial-in" capability during the flight test program. The provision of such control allows flight testing of the system over the operating envelopes, as shown in Fig. 6, and thus permits determination of the optimum aeropropulsion operating point.

BLC Ducting

On the YC-14, the ducting design condition (maximum pressure, temperature, and flow) was determined to be two-engine go-around with STOL landing flaps, a brief operating condition necessary during aborted landing. A requirement effective during this operating condition is that air be transported at a pressure of approximately 120 psig and at a temperature of 915°F through each wing at a rate of 16.5 lb/sec. The YC-14 BLC air ducting scheme is a compression system in the wing and a tension system between the engines (refer again to Fig. 3), and the system is symmetric about the airplane centerline. The duct connecting the air sources is shrouded inside the airplane for personnel safety in case of duct failure.

For research purposes, wing isolation valves have been provided on the prototype to allow system operation in the asymmetric mode during the flight test program. This will allow evaluation of airplane lateral control requirements and handling qualities with both symmetric and asymmetric boundary-layer control during single-engine operation. The wing isolation valves are motor-operated, and their control is external to the baseline system control. Space has been reserved in the airplane to convert the baseline symmetric system to an asymmetric system, with no valves, by providing dual body cross-ducts in the event that the asymmetric system proves beneficial.

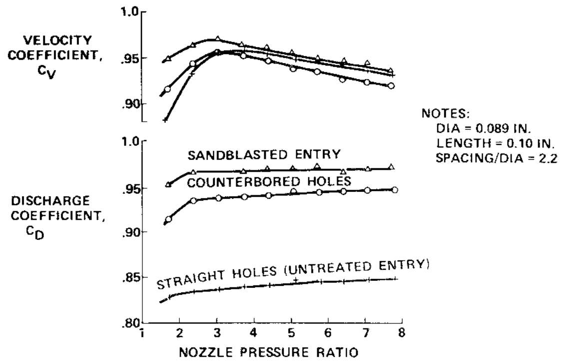

Fig. 8 Static nozzle performance studies: effect of nozzle entry shape.

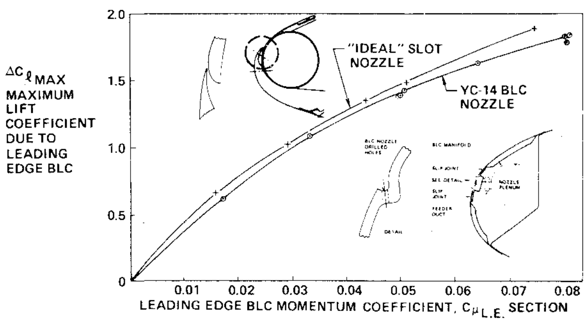

Fig. 9 YC-14 BLC nozzle aerodynamic characteristics.

The wing duct cross section, shown in Fig. 7, is located in the leading-edge cavity bounded by the wing nose and the nose beam forward of the front spar. Between the nose beam and the front spar is the cavity housing the Krueger leading edge flaps and the flap drives. The wing ducting consists essentially of a BLC manifold subdivided into eight sections that correspond to the eight flaps. Approximately 72 in. long, each manifold is attached rigidly to the main structure on one end and free to move axially on the other end; the eight manifolds are interconnected by metal bellows. The nozzle plenums, which form the leading edge of the wing, are connected to the manifolds via three short feeder ducts. (The two outer feeder ducts have metal bellows to absorb the differential growth due to thermal expansion.) There are two 36-in.-long nozzle plenums per manifold, and the distribution system provides boundary-layer control over 550 in. of the wing leading edge through an installed nozzle area of 10 in.^{2} per side. The nozzle plenums have been so integrated with the ducting system that they can be replaced easily by plenums of alternate-size nozzles during the flight test program. This permits tailoring of blowing momentum distribution for effective boundary-layer control over the whole wing.

Short, tubular nozzles, of the type commonly referred to as "drilled" holes, have been selected to inject high-energy air into the sluggish boundary layer. The nozzles are located at 0.5% chord aft of the leading edge and are 0.089 and 0.0625 in. in diameter, respectively, on the eight inboard and eight outboard nozzle plenums. The installed nozzle area has been distributed nonuniformly over the eight flap sections through varied nozzle pitches that range between approximately two and four times nozzle diameter, to maintain a constant sectional blowing momentum coefficient. There are approximately 2650 nozzles per side.

System efficiency demands nozzles with high discharge (C_D) and velocity (C_V) coefficients, and system effectiveness requires accurate nozzle location and orientation and close spacing. These characteristics could be satisfied by a slot nozzle, but slot nozzles have two inherent drawbacks: they are difficult to manufacture to close tolerance,[5] and they are difficult to maintain to design values in service.[6] Nozzle area control during manufacture and nozzle area maintenance in service are extremely important in the design of a BLC system. Loss of nozzle area control invariably leads to premature "stall" of some lifting surfaces, either by distortion of the blowing momentum distribution or by loss of BLC momentum.

Selection of nozzles and their distribution pattern for the YC-14 resulted from extensive static and wind-tunnel testing.[7,8] During the testing, methods of improving nozzle performance were evaluated (Fig. 8), velocity profiles were examined, and jet temperature characteristics were studied. The nozzles finally selected not only had extremely good nozzle area control, both in manufacture and in service, but also were less expensive to fabricate than other types. Installation of the plenums as an integral part of the leading edge of the wing made possible accurate drilling of the nozzles and thereby met the specified location, orientation, and spacing requirements. As illustrated in Fig. 9, the aerodynamic performance of the YC-14 BLC nozzle is comparable to that of the "ideal" slot nozzle.

Conclusions

YC-14 prototype leading-edge BLC system is a high-pressure blowing system with a high degree of operational flexibility. It can be operated in various modes and at various levels to optimize airplane low-speed performance and handling qualities. It is a product of close cooperation among system and structural designers, manufacturing and propulsion engineers, and aerodynamicists. During the system's development, various wind-tunnel and laboratory tests were conducted at simulated operating conditions to verify performance and structural integrity. The system uses existing technology and fabrication methods and flight-proven hardware. It is believed that the YC-14 BLC system will pave the way for successful exploitation of boundary-layer control and will extend the usefulness of air transport to areas and markets that require STOL capability.

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