ON THE STATUS OF V/STOL FLIGHT

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SUMMARY

Basic principles relating to the accomplishment of V/STOL flight are reviewed as they pertain to current prototype developments. Particular consideration is given to the jet flap, flow augmentation and circulation control separately and in combination. To be discussed will be such configurations as the augmentor wing, upper-surface blown flaps, externally blown flaps and the circulation-controlled rotor.

INTRODUCTION

The development of an airplane with vertical or short take off and landing capability, (V/STOL), and yet competitive with conventional airplanes in cruise, has been an elusive target over the last twenty years. Except for the Hawker-Siddeley Harrier and a few small STOL's none of the many experimental prototypes have gone into production. This includes such configurations as the compound helicopter, tilt-wing, deflected-slipstream, direct lift, tail sitter, tilting ducted propellers and the fan-in-wing.

At the present time there are six developments, three VTOL's and three STOL's, which appear to hold some promise. These are:

1. The tilt rotor; the Bell XV-15
2. Augmented VTOL; the Rockwell XFV-12A
3. Circulation control; the X-wing concept
4. Upper-surface blowing; the Boeing AMST YC-14
5. Externally blown flaps; the McDonnell-Douglas AMST YC-15
6. Augmentor wing; modified DeHaviland Buffalo

There are also other V/STOL configurations currently being proposed or investigated, such as the lift/cruise fan research and technology aircraft, undoubtedly worthy of discussion but this present paper will be limited primarily to a consideration of the above six configurations.

SYMBOLS

A throat area of thrust augmentor (Fig. 1), m^2

A_E exit area of thrust augmentor (Fig. 1), m^2

A_j primary nozzle area of thrust augmentor (Fig. 1), m^2

C_L wing lift coefficient

$C_{L_{max}}$ maximum value of the wing lift coefficient

C_μ jet momentum coefficient (ratio of jet momentum flux per unit surface area to free stream dynamic pressure)

m mass flow, kg/s

P power, W

T thrust, N

w induced velocity, m/s

α ratio of A_j to A

β ratio of A_E to A

ϕ thrust augmentation ratio; ratio of total thrust of augmentor to thrust of primary nozzle

C_l rolling moment coefficient

C_{l_α} $\frac{\partial C_l}{\partial \alpha}$

δ_f flap deflection

δ_a aileron deflection

VTOL

In the design of a VTOL aircraft the division between hovering and cruising flight in the mission profile plays a dominant role in determining the aircraft's configuration. This statement is easily understood from basic momentum principles. A static lift system having a mass flow rate of m and producing a thrust of T will, on the average, accelerate the flow to a final velocity of w where m, T and w, in consistent units, are related by,

$$T = mw \tag{1}$$

the power, P, delivered to the mass flow, by the lift system will equal the flux of kinetic energy in the ultimate wake; hence,

$$P = \frac{1}{2} mw^2 \tag{2}$$

Thus, combining (1) and (2), the power, thrust and average induced velocity in the ultimate wake are related by:

$$\frac{T}{P} = \frac{2}{w} \tag{3}$$

The above is actually an ideal upper limit on the thrust to power ratio. Because of other power losses in the system, T/P must always be less than the value predicted by Equation (3). Nevertheless, (3) provides a relative basis for comparing static thrust systems and suggests, for the same thrust, that the fuel flow rate will vary directly with the induced velocity. Typically w induced by a helicopter is approximately 12 m/s (40 fps); 70 m/s (230 fps) for propellers; 180 m/s (590 fps) for lift fans and 300 m/s (980 fps) for lift jets. Thus direct lift jet systems, on the one extreme, will burn fuel at a rate approximately 30 times that of the helicopter at the other end of the w spectrum. On the other hand the weight of a direct lift jet system will generally be less than that of a system with a low w (such as a helicopter with its large blades, hub, transmissions, etc.) so that weight can be traded for fuel.

One means of reducing the induced velocity in the ultimate wake is by the use of augmentation. As shown schematically in Figure 1, the primary jet is introduced into the throat of a surrounding nozzle, either along the centerline or along the walls of the nozzle. Viscous shear and turbulent mixing along the boundary of the primary jet entrains a secondary flow through the nozzle. This secondary flow mixes with the primary jet to produce an augmented mass and momentum flux issuing from the nozzle which can be appreciably greater than that of the primary nozzle.

The performance of an augmentor can be improved by diffusing the mixed flow as shown in Figure 1. The theoretical maximum performance of such an augmentor is shown in Figure 2 as taken from Reference 1. Here the ratio, ϕ, of the total thrust to the thrust of the primary jet is presented as a function of β for various values of α where; α is the ratio of primary nozzle area, A_j, to throat area, A and β is the ratio of nozzle exit area, A_E, to throat area. These curves neglect any losses and assume complete mixing of the primary and secondary flows resulting in a uniform flow at the diffusor exit.

The theoretical performance shown in Figure 2 is difficult to achieve in practice. First the primary flow suffers losses in total head as it is directed to the primary nozzle, and secondly, complete mixing of the two flows with a uniform discharge from the diffuser exit is never achieved.

For the last 5 or 6 years, experimental and analytical studies have been performed by personnel at the Aerospace Research Laboratories (Refs. 2-5) on means of achieving more complete mixing in augmentors. These efforts have led to the development of the so-called hypermixing nozzle. In this nozzle the exit plane is segmented so as to produce adjacent jets exiting in slightly different directions. Streamwise vortices then form between the jets which enhance the mixing between the primary flow and the secondary flow. Using these nozzles, augmentation ratios as high as approximately 2.0 have been achieved for β values of approximately 2.0 with ejectors half the length of earlier models. Some of these results are also shown in Figure 2 taken from Reference 5 .

An aircraft currently under development which utilizes thrust augmentation is the Rockwell XFV-12A. Scheduled for first flight in September 1976, this aircraft appears to be a typical high-performance jet aircraft but with a canard configuration. However both the canard and main wing are flapped to open as shown in Figure 3. Engine exhaust is diverted by means of a plug nozzle-sleeve valve combination and ducted to slots along the entrance walls of the diffuser formed by the flaps. The exhaust also exits in the middle of the diffuser entrance from a third smaller flap segment as shown. The outer jets are issued tangential to the diffuser walls in the direction of the diffuser centerline and are then turned to the vertical direction by the Coanda effect.

According to Reference 6, the installed engine thrust-to-weight ratio for the XFV-12A is estimated to be 0.72 with a net augmented thrust-to-weight ratio of 1.12 resulting in an augmentation ratio, ϕ, of 1.55. On the average, the exit velocity of the augmented flow is estimated at approximately 130 m/s, (427 fps), considerably higher than that for a helicopter but appreciably less than direct lift jet systems.

The above ϕ value may be somewhat optimistic. Recent results reported in Reference 7 show that a ϕ of 1.5 has been achieved to date out of ground effect for the main wing with a value of 1.3 reported for the canard surface. Since most of the weight is borne by the main wing, the combined ϕ is close to producing the net thrust-to-weight ratio of 1.05 called for in the Navy specification.

A definite plus for this configuration is its probable STOL performance. An appreciable portion of the main wing is ahead of the augmented flaps so that in forward flight the wing behaves as a jet-flapped wing with characteristics similar to the externally blown flap (EBF), the augmentor wing, and the upper-surface blown (USB) flap discussed in the next section. According to Reference 6, allowing the XFV-12A to operate as a STOL with only a 100 m takeoff roll increases the payload by 22241 N (5000 lbs).

Equipped with a better understanding of rotor-blade airframe dynamics and advanced material technology, the U.S. Army and NASA have revived the tilting rotor concept with the Bell XV-15 pictured in Figure 4. In hover this airplane enjoys the benefits of a disc loading not much higher than the helicopter. In forward flight it avoids the retreating blade stall or advancing blade compressibility limitations of the helicopter and is designed to cruise at a speed of approximately 185 m/s (360 kts).

This VTOL is powered by two uprated Lycoming T-53 engines, each with a contingency rating of 1342 kW (1800 SHP). The design maximum VTOL takeoff weight is 57826 N (13000 lbs). With two rotors each having a diameter of 7.62 m (25.0 ft), the disc loading is 634 N/m^2 (13.2 psf). Thus at standard sea level the downwash velocity w will be approximately 16.06 m/s (52.7 fps).

The X-wing at this point in time is only a proposed configuration. As shown in Figure 5 it is a stopped rotor configuration; however, the rotor is unique in its application of an elliptical airfoil section employing circulation control. As shown in Figure 6, by blowing tangentially from the upper surface of an ellipse near its trailing edge (Ref. 8), much higher lift coefficients are obtained than with a jet-flapped airfoil at the same momentum coefficient, C_μ. In addition to the high lift coefficients, circulation control achieves lift to drag ratios (including blowing power) for 20% or thicker sections comparable to those obtained by a 12% conventional airfoil. Thus, without sacrificing aerodynamic efficiency, one may be able to meet the structural requirements of the X-wing by using thicker sections.

At the present time a circulation controlled rotor (CCR) is being built for the U.S. Navy by the Kaman Corporation. This rotor will be flight tested on a modified H-2. Cyclic control will be achieved by means of a cyclic throttling of the blowing air to each blade. It should also be noted that a similar type of section has already been flown on a fixed-wing aircraft designed, built and tested by the Department of Aerospace Engineering at the West Virginia University (Ref. 9).

The WVU Technology Demonstrator STOL aircraft is a modified BD-4 incorporating drooped ailerons and a circulation-controlled, circular trailing edge flap over approximately 60% of the wing span. In cruise the circular trailing edge is designed so that it swings forward and retracts into the wing to form a conventional sharp trailing edge as pictured in Figure 7. Another unique feature of this system is also shown in the figure. Instead of blowing directly over the cylindrical trailing edge, the blowing is augmented as shown. This scheme not only provides increased blowing momentum for the circulation control but accomplishes suction boundary layer control as well at the flap hinge.

Finally, in the area of VTOL, it should be noted that several promising prototypes are being developed in the helicopter field. These include the Boeing-Vertol and Sikorsky entries in the Utility Tactical Transport (UTTAS) competition; the Bell and Hughes entries in the Advanced Attack Helicopter (AAH) competition; several commercial developments; and the Sikorsky Advancing Blade Concept (ABC). Innovations in the rotary wing field include fly-by-wire, extensive use of bonded honeycomb and advanced composite structures, elastomeric bearings, hingeless rotor and advanced airfoil technology. By careful attention to weight, aerodynamic cleanliness, and mechanical simplicity, the helicopter is rapidly improving its operating efficiency with operational cruising speeds in excess of 150 kts.

STOL

The concept of the jet flap has been known since the 1930's (Ref. 10). A theoretical solution to this device was first presented by Spence in 1956 (Ref. 11). The essence of Spence's solution together with some other aspects of the jet flap can be found in Reference 1. Essentially a thin sheet of high-momentum air issues from the trailing edge of an airfoil at some angle to the free stream and is turned in the direction of the free stream. In turning, its momentum is redirected so that a pressure difference is sustained across the jet sheet. The effect approximates the addition of a physical flap to the airfoil with both C_l and C_{l_α} being significantly increased. All three STOL prototypes mentioned earlier employ high-lift systems which approximate the jet flap. These systems, pictured in Figure 8, are referred to as the augmentor wing, upper-surface blowing (USB) and the externally blown flap (EBF).

The augmentor wing is a combination of flow augmentation with the jet flap. This scheme is currently being test flown on a modified DeHaviland Buffalo under a joint Army-NASA program at the Ames Research Center. Here high pressure air exits from a choked nozzle into a throat formed between two flap surfaces. The augmented flow is then diffused slightly and exits at some angle to the main stream to produce the effect of a jet flap.

In the USB configuration exhaust from the jet engine is spread laterally over the upper surface near the trailing edge of the airfoil and is turned by the flap system leaving the wing again in a manner similar to the jet flap. The USB high lift system is being incorporated into the Boeing YC-14 Advanced medium STOL transport (AMST) which is expected to be flown shortly.

EBF is employed on the McDonnell-Douglas entry for the AMST competition, the YC-15. Here the engines are mounted close to the underneath surface of the wing so that the jet exhaust passes through the flap system again spreading somewhat and producing an effect comparable to that of the jet flap.

Aerodynamically, it is difficult to make a choice between the augmentor wing, USB and EBF systems. Figure 9 (from Ref. 12) presents $C_{L_{max}}$ as a function of C_μ for the augmentor wing. Figure 10 (from Ref. 13) presents trim drag polars for both the USB and EBF configurations. Obviously all three systems are capable of producing C_L values much higher than those attainable without power. Also, for a given C_μ value it appears as if the performance of the three are about equal. The choice of one system over the other will probably depend upon such factors as mechanical complexity, weight, engine-out performance, noise, and cost.

The YC-14, which is yet to fly, is described in References 14 and 15. Figure 11 depicts this AMST which has a wing area of 163.7 m^2 (1762 sq. ft.), a gross weight of approximately 751,745 N (169,000 lbs.) and powered by two GE CF 6-50D engines with an installed thrust of 214,848 N (48,300 lbs.). This airplane is designed to operate routinely in and out of 600 m (2000 ft.) fields with a 120,100 N (27,000 lbs.) payload. Its approach speed is approximately 43.8 m/s (85 kts) while the takeoff speed is 50.0 m/s (97 kts). On landing the trim lift coefficient is approximately 3.60 for a C_μ of 0.78. The airplane has several unique features worthy of note. The USB flaps operate independently to provide thrust vector control. The lift system is further enhanced by leading edge blowing of the Krueger flaps through a series of closely-spaced holes. Being landing limited, the leading edge BLC allowed a reduction in wing area for the STOL mission. According to the specifications both AMST's, with one engine inoperative must have a 0.3 g maneuver margin at constant speed and a 20% speed margin from stall in one g flight. In order to obtain good performance from the engine nozzles which blow the flaps, a door is included on the outboard side of each nozzle. For takeoff the door is opened for maximum thrust but closed in the cruise mode. It is also interesting to note that turning is enhanced in the engine exhaust by the use of vortex generators which extend into the flow when the flaps are lowered but retract in the cruise configuration.

Both the YC-14 and YC-15 employ advanced technology airfoils and are thus able to cruise at M = 0.7 or higher with relatively thick, unswept wings. They are thus approximately 40% faster than current tactical transports.

The YC-15, pictured in Figure 12, is currently being flight tested and according to Reference 16 is performing up to expectations. In addition to this reference, a description of the aircraft can be found in Reference 17.

For the STOL mission this aircraft has a weight of 676,100 N (152,000 lbs.) comprised of an empty weight of 458,160 N (103,000 lbs.), a payload of 120,100 N (27,000 lbs.) with the remainder being the fuel required for the mission. The aircraft is powered by four Pratt and Whitney JT8D-17 engines rated at 71,170 N (16,000 lbs.) per engine. Its wing area is 162 m^2 (1740 sq. ft.) with an aspect ratio of 7.0. Direct lift control is provided through the use of spoilers. Control is accomplished through a fly-by-wire system which has stability and control augmentation.

CONCLUDING REMARKS

As the result of wind tunnel and laboratory investigations performed in recent years, improved thrust augmentors and blown flap systems have been developed. Because of these efforts, several new V/STOL prototype airplanes have been designed which hold promise of becoming operational.

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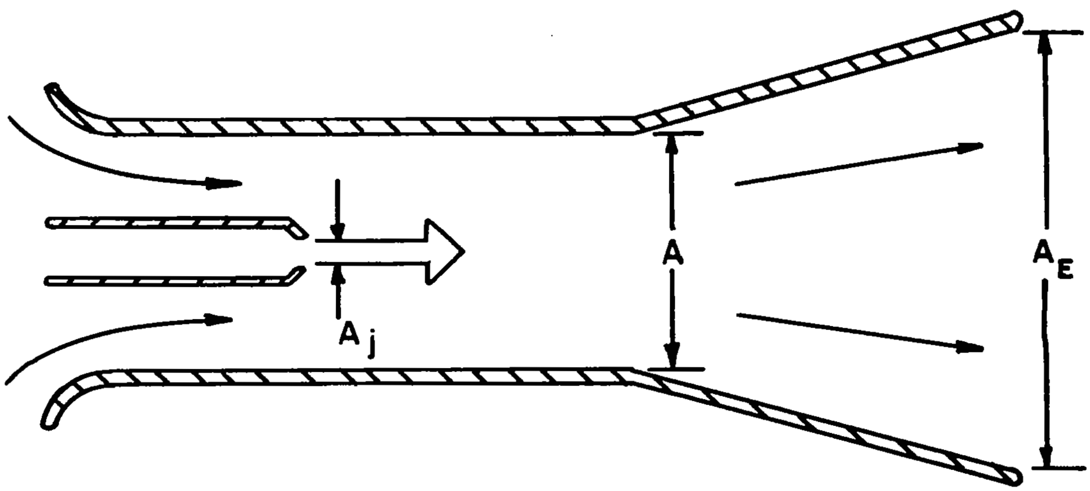

Figure 1.- Thrust-augmenting nozzle-diffuser combination.

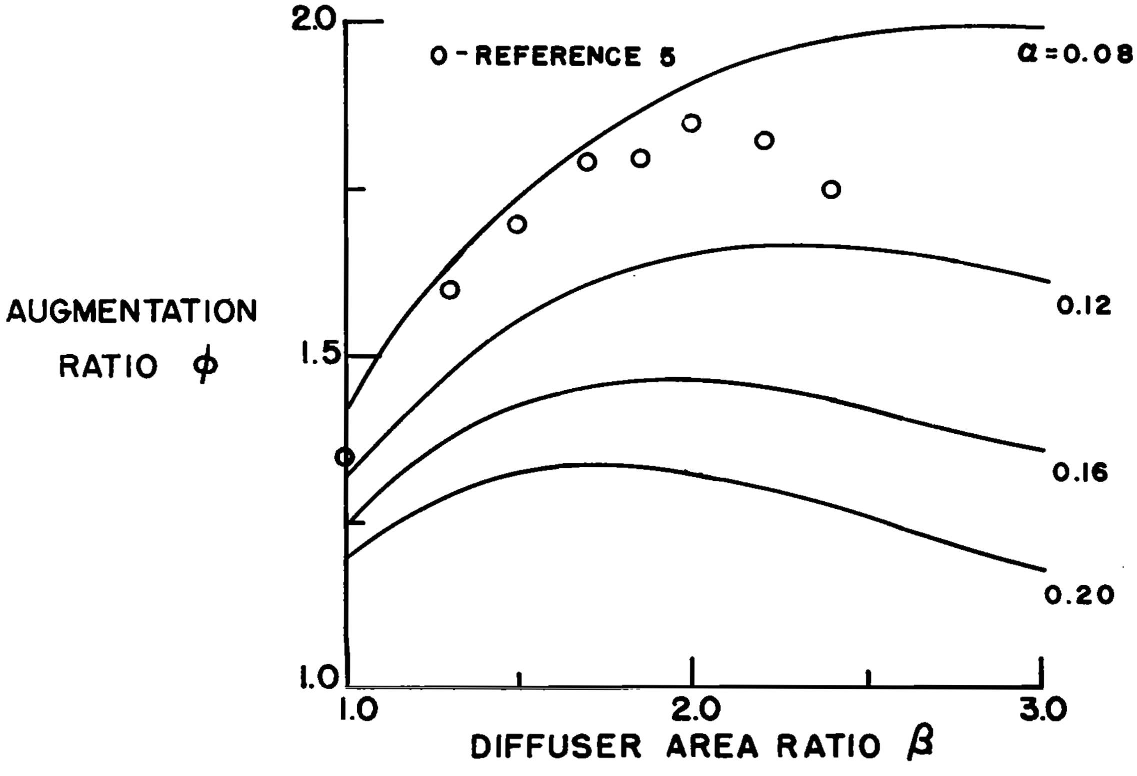

Figure 2.- Theoretical performance of a thrust augmentor including some experimental results.

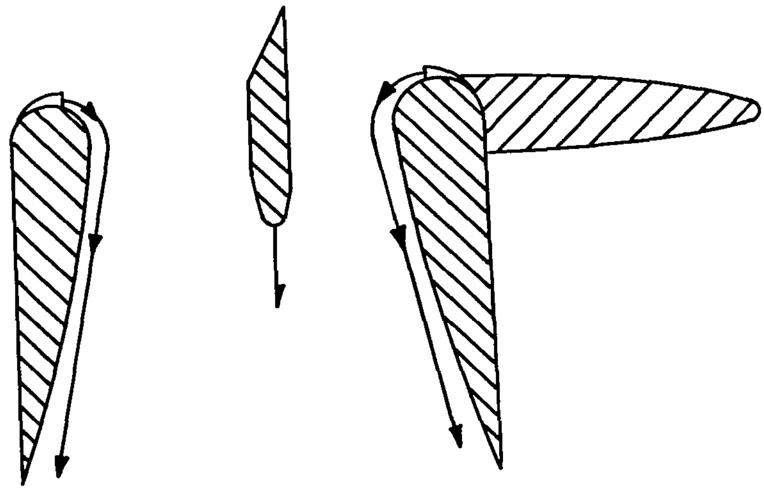

Figure 3.- XFV-12A augmentor wing-flap system.

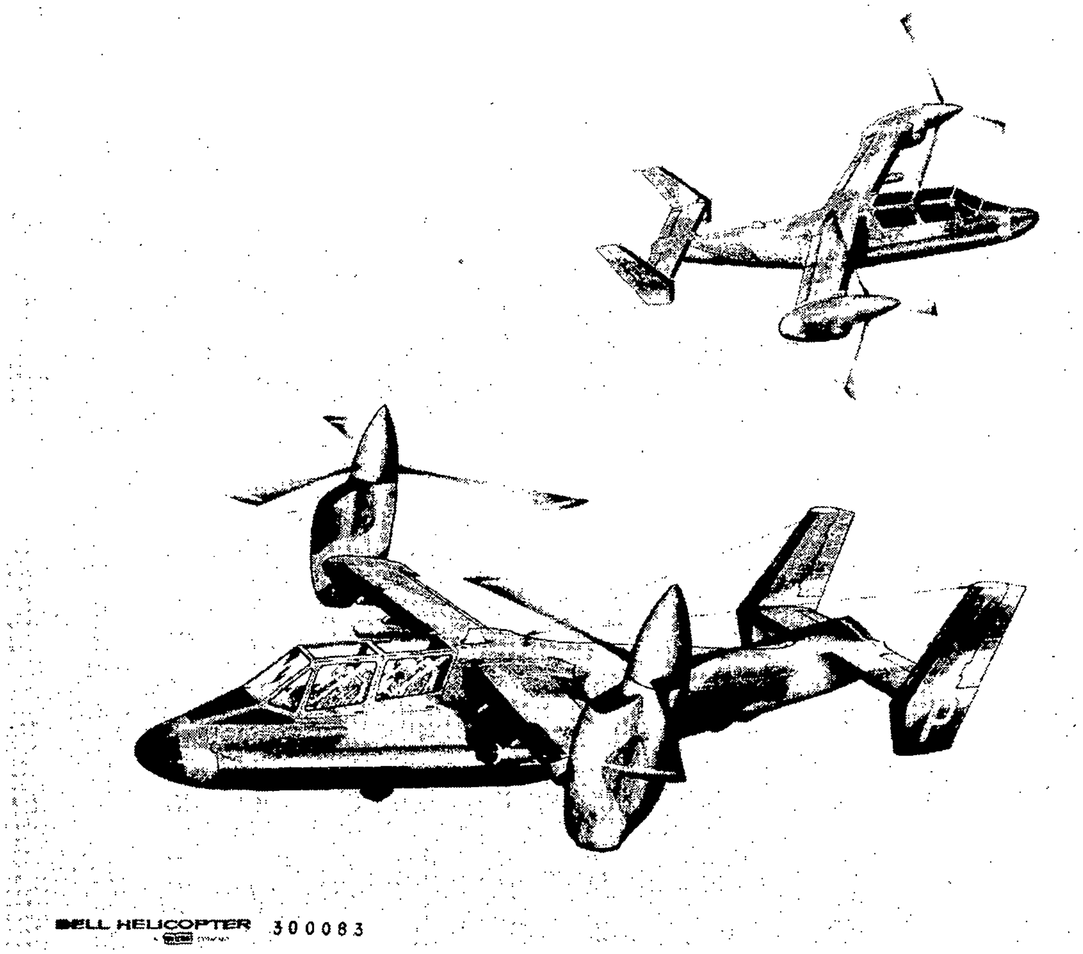

Figure 4.- Bell XV-15 tilt-rotor VTOL airplane.

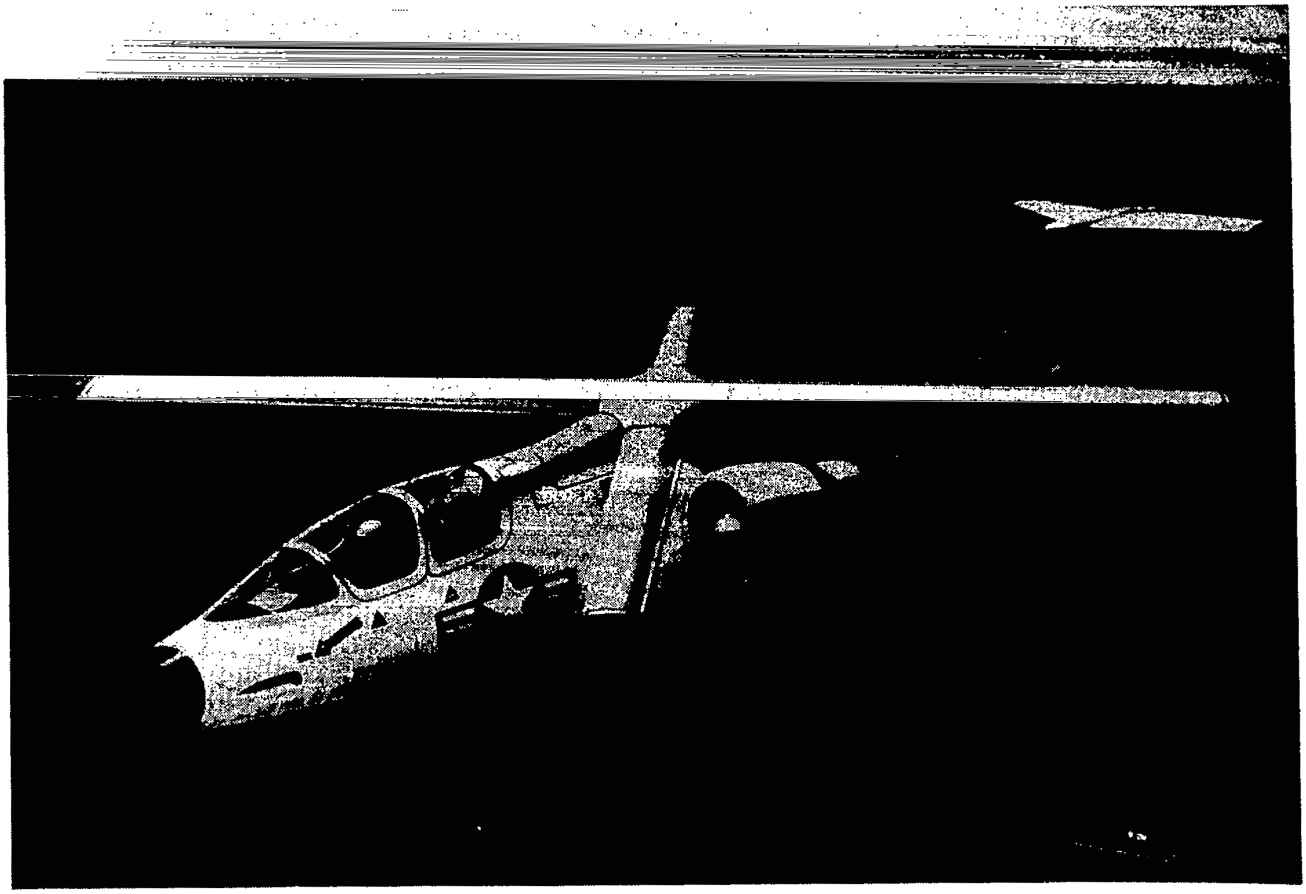

Figure 5.- Proposed X-wing VTOL configuration.

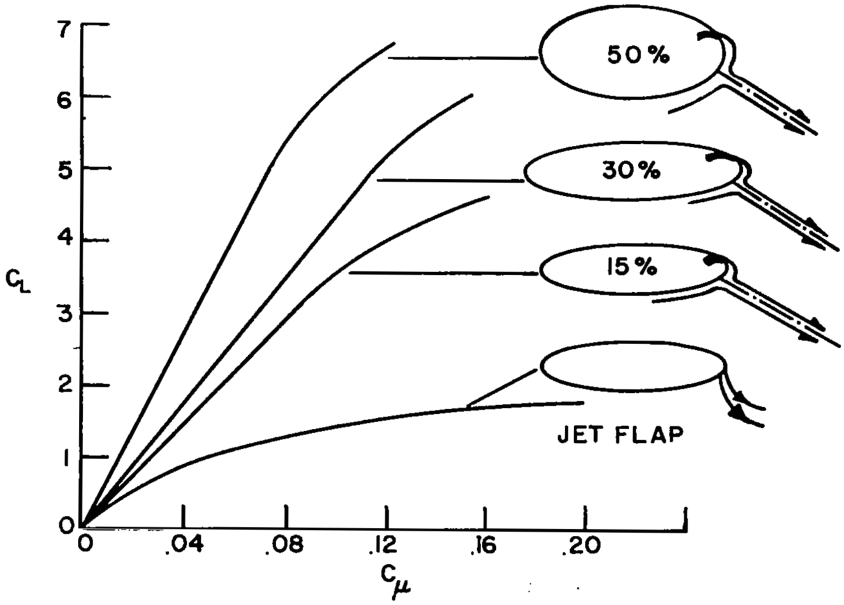

Figure 6.- Lift performance of elliptic airfoil sections with circulation control.

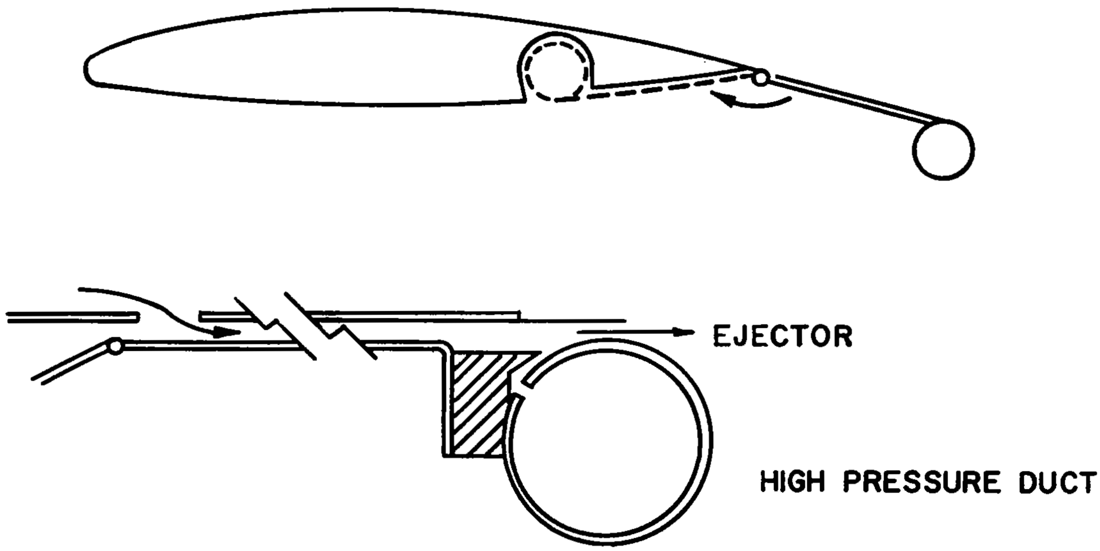

Figure 7.- Flap system for West Virginia University's technology demonstrator aircraft.

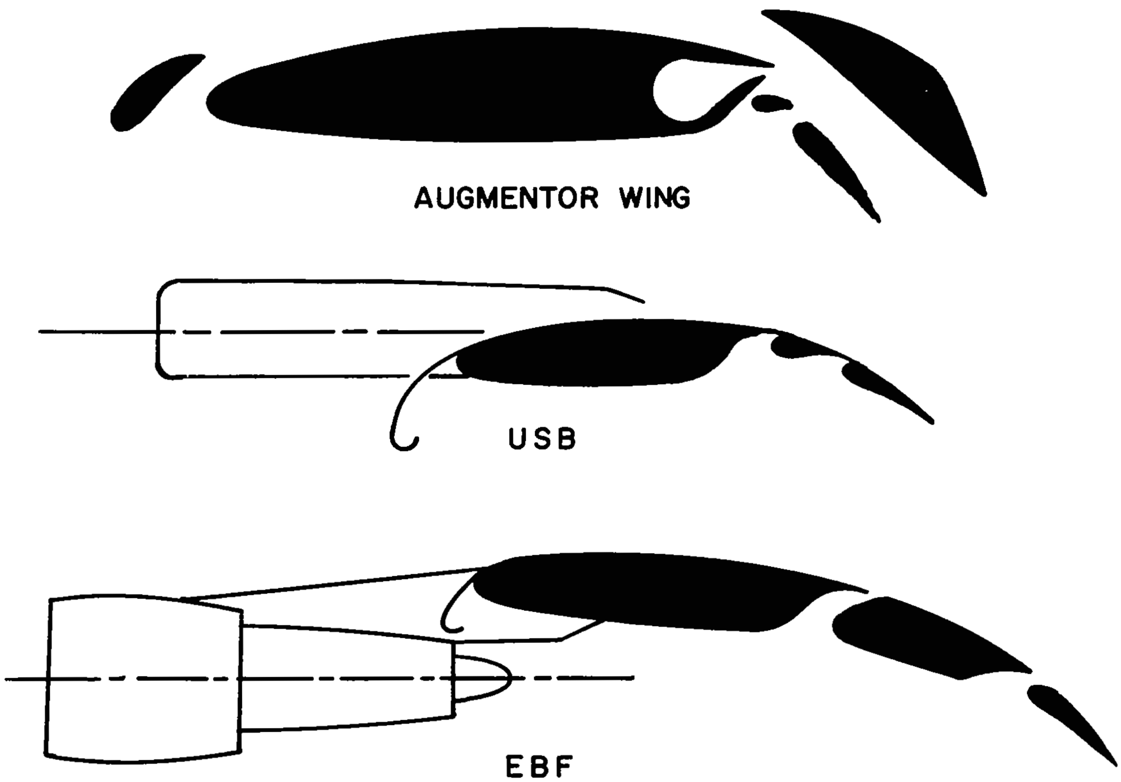

Figure 8.- High-lift systems for current STOL developments.

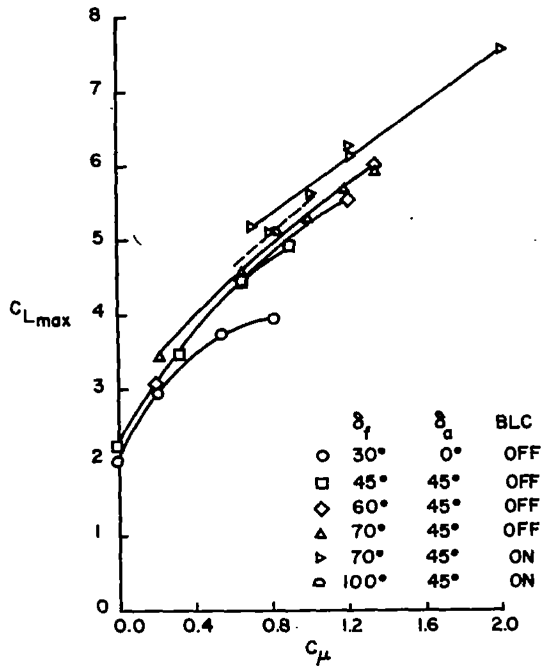

Figure 9.- Lift characteristics of an augmentor wing.

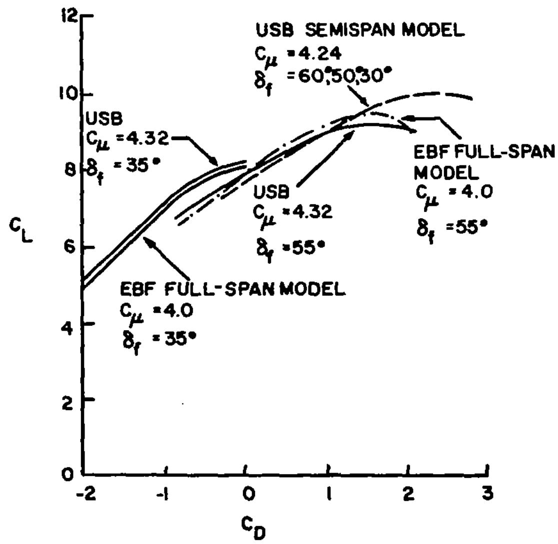

Figure 10.- Trim drag polars for the EBF and USB high-lift configurations.

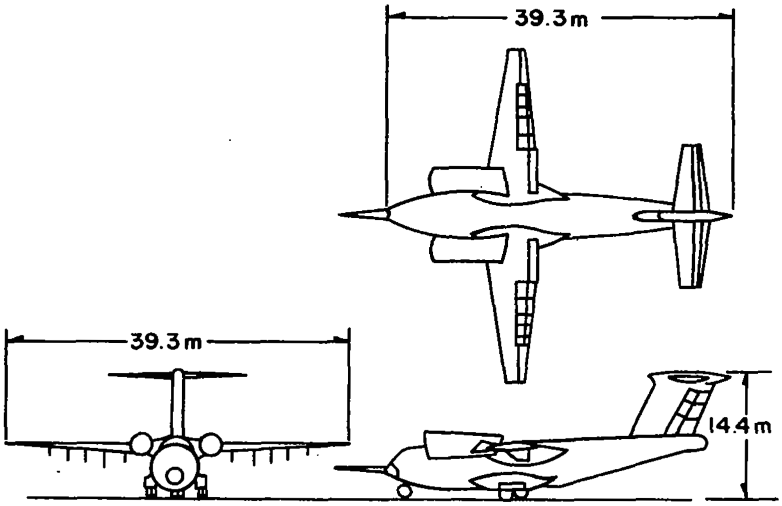

Figure 11.- Boeing AMST YC-14.

Figure 12.- McDonnell Douglas YC-15 advanced medium STOL transport.