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SOME EXPERIMENTAL RESEARCH ON A NEW AIRCRAFT CONFIGURATION INCORPORATING EJECTOR TYPE THRUST AUGMENTORS FOR VTOL

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SOME EXPERIMENTAL RESEARCH ON A NEW AIRCRAFT CONFIGURATION INCORPORATING EJECTOR-TYPE THRUST AUGMENTORS FOR VTOL

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SUMMARY

There are certain well documented advantages associated with ejector-powered VTOL aircraft which arise because the high intensity primary jet is mixed with secondary air so as to markedly reduce temperature, velocity and noise. However, previous experience with experimental VTOL aircraft has shown that the ejector system occupies most of the useful volume in the fuselage thus tending to preclude meaningful application of the concept. The present paper describes research work on some new aircraft configurations in which the ejector system is contained within the root section of a wing having double-delta planform so that the fuselage centre section remains mostly free for storage of fuel and payload.

The configurations which are described suggest the use of light-weight lift jets or lift fans to power the ejector system with separate engines for cruise propulsion. The primary jets are directed inward toward the centre line and adhere to the fuselage contour to form a single keel-like lifting jet.

Experimental results are presented showing ground proximity effects in hover and aerodynamic/jet interference effects during the transition flight regime. The configuration is shown to exhibit certain favourable interference effects.

INTRODUCTION

The research work described in this paper concerns a VTOL configuration which can be applied to a variety of aircraft types. The configuration represents the synthesis of a number of ideas and considerations which are described and illustrated in the text. Foremost among these considerations is that the main lifting jet should be in the central plane of the vehicle so as to minimize asymmetry in the event of engine failure and yet the turbomachinery should not occupy premium space in the fuselage at the centre of gravity. It was also appreciated that a central jet configuration is known to suffer a substantial loss of lift in close proximity to the ground due to the well known "suck-on" tendency and therefore some means would be needed to offset this adverse effect.

It was conceived that a long chordwise ejector slot could be formed at the wing root, that the primary jet would entrain secondary air from above and that the resulting mixed flow would adhere to the underside of the fuselage to form a central jet. In broader terms, the lifting jet might be generated by a row of lift fans and therefore aerodynamic research work on an ejector configuration might have a more general applicability.

These ideas formed the basis of a research program which began in 1965 and has been supported jointly by de Havilland and the Defence Research Board of Canada.

THE EXTERNAL AUGMENTOR CONFIGURATION

The fundamental ideas associated with the concept are illustrated in Figure 1. The primary lifting jets issue from long narrow chordwise nozzles which are located on either side of the fuselage and which direct the jets inward toward the centre. Each jet is deflected downward by a Coanda flap into an ejector passage formed between the flap and the side of the fuselage. The entrainment action of the jet induces air through the slot in the upper surface of the wing and the flow from each side coalesces beneath the fuselage to form a single keel-like lifting jet. The bottom shape of the fuselage is designed so that, as the vehicle closes with the ground, the jets (one from each side) separate and form an air cushion beneath the fuselage; thus possible "suck-on" tendencies (which are normally associated with a central jet configuration) can be wholly or partly offset by the increase in lift from the cushion.

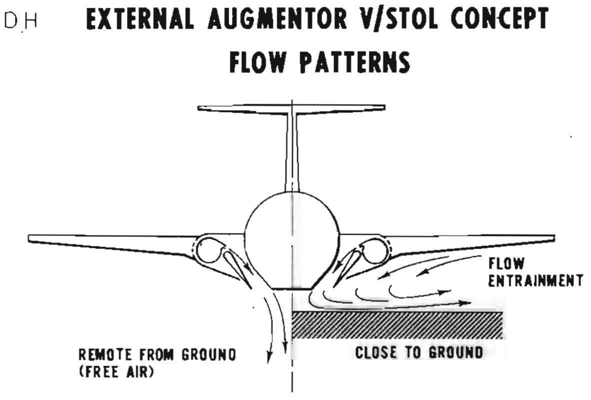


FIGURE 1

It is part of the concept that retracting flaps or doors are designed to increase the length of the mixing passage so that provision of space for the ejector does not occupy an unduly large interior volume. The space required is located external to the fuselage and partly external to the normal frontal contour of the aircraft and it is this feature which suggested a title for the concept, namely, "The External Augmentor for V/STOL Aircraft".

The structure which houses the ejector system forms part of the wing root and this places certain constraints on wing planform. It is a necessary design requirement to maintain approximate coincidence of the centre of jet lift, the centre of gravity and the centre of aerodynamic lift; if the ejector slot is to occupy a substantial length of the fuselage, then "Draken" or "Concorde" type planforms represent shapes which fulfil this necessary condition.

SCOPE OF RESEARCH PROGRAM

Some early experiments were carried out to investigate the strength of the ground cushion effect before embarking on a more general research program. These early experiments were completed in 1965. The scope of the subsequent research program was established as follows:

- Project studies.
- Static tests to simulate hovering flight.
- Wind tunnel tests.

Some selected results of the work in each category are presented. Project work is discussed first so as to provide a background for appreciation of the experimental results.

PROJECT STUDIES

Consideration was given to the use of lightweight lift engines to power the ejector system with separate engines for propulsion. Design layouts were prepared which illustrated the application of the concept to a medium-size transport, a small executive airliner and a lightweight tactical fighter, (see Figures 2, 3 and 4).

MEDIUM-SIZE TRANSPORT AIRCRAFT

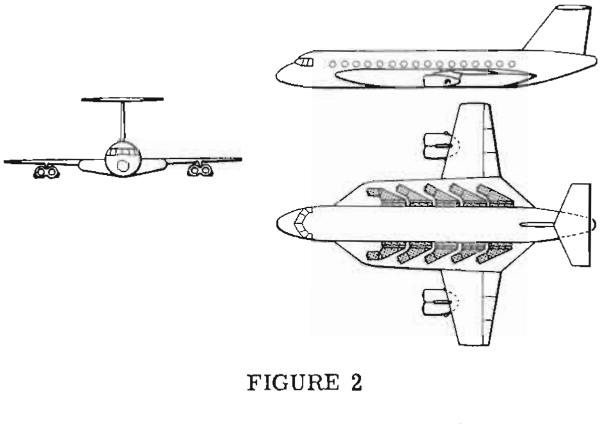


FIGURE 2

In the case of the transport aircraft, engine failure is accommodated by the use of a relatively large number of lift engines as proposed previously for many other VTOL projects employing "lift pods". The use of lift/cruise engines for propulsion provides a powerful speed control to accomplish transition from hover to cruising flight and eliminates the need to vector the main lifting jet. It was assumed that the four lift/cruise engines would operate at half thrust for hover so that adequate roll control would be available in the event of failure (since the thrust level of the companion engine could be increased to provide full compensation).

SMALL EXECUTIVE JET AIRCRAFT

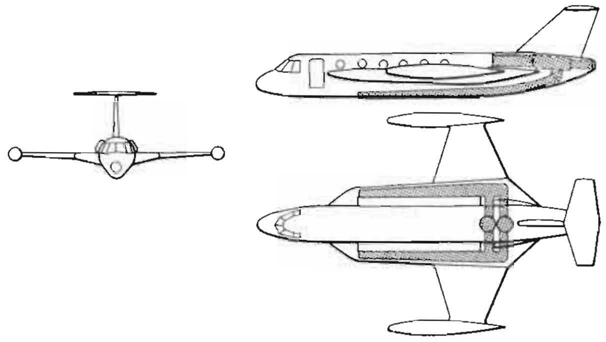


FIGURE 3

In the case of the executive jet, two lightweight lift engines provide the vertical thrust and power the ejector through a divided duct with twin nozzles. The single propulsion engine is fitted with a two-way valve to divert the thrust from cruise mode to hover mode in the event of failure of a lift engine. In the hover mode the cruise engine thrust issues from a duct/nozzle assembly located on the centre-line of the fuselage.

LIGHTWEIGHT TACTICAL FIGHTER

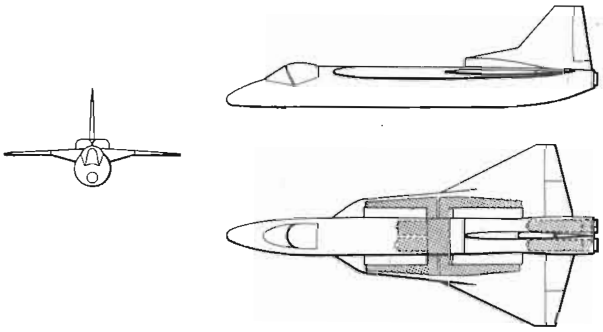


FIGURE 4

In the case of the tactical fighter, there are two lift engines and two propulsion engines. The design layout does not provide for full restoration of hover lift in the event of failure, in fact, lift would fall to about 60% of the weight but nevertheless symmetry would be maintained. The two propulsion engines are fitted with reheat to permit flight at supersonic speeds.

Clearly, an integration of powerplant and wing of the kind proposed is open to a variety of interpretations so that the designs shown here should be considered only as indicative of the likely configurations. In general, the design layout objectives can be stated as follows:

- Use of small lightweight lift engines for compact design.
- Minimum asymmetry of jet lift in the event of engine failure.
- Lift engines remote from the centre leaving fuselage space at the centre of gravity available for disposable load (fuel and payload).
- Ejector mixing slot, external and adjacent to fuselage contour, creating a central keel-like lifting jet.
- Double-delta or similar planform to achieve coincidence of centre of jet lift, centre of aerodynamic lift and centre of gravity.

The characteristics and advantages of such a configuration are as follows:

1. Reduction in noise.

An ejector represents a powerful means of noise suppression and ejectors have been developed specifically for suppression of noise of lightweight lift engines. In a similar way, the specific ejector configuration proposed here will provide attenuation for a number of reasons, namely:

- A reduction in shear velocity due to secondary flow through the augmentor.
- A relatively low velocity of the resultant mixed jet from the ejector.
- A shielding effect of the jet by the walls of the ejector; these walls being lined with sound absorbent material to further attenuate noise.

Noise emitted from a long thin jet nozzle has a higher frequency spectrum than noise of equal strength from a round nozzle. This implies that the sound will be more easily attenuated by surrounding structure and by the atmosphere.

The introduction of corrugations in the primary slot nozzle would further attenuate noise at the source.

2. Reduction in ground erosion and jet recirculation.

Mixing of the primary jet with a large amount of secondary air in the ejector reduces both velocity and temperature of the exhaust flow. This results in beneficial effects with regard to ground erosion, recirculation and jet re-ingestion.

3. Favourable ground cushion effects.

As already mentioned, the ejector configuration and the underside shape of the fuselage is optimized to form an air cushion when the vehicle is in close proximity to the ground. The increase in pressure on the underside of the fuselage provides additional lift to offset "suck-on" tendency normally associated with central jet configurations.

4. Reduction in adverse interference between jet and wing during transition.

Experiments have shown that the double-delta wing planform tends to exhibit unsatisfactory stalling characteristics because a strong vortex pair is shed from the highly swept, forward leading edge. These vortices flow over the upper surface and interfere with normal flow over the outer wing panels; they also interfere with flow over the empennage. Such phenomena would result in poor aerodynamic characteristics during the transition flight regime. However, in the case of the "external augmentor" configuration, the long ejector inlet adjacent to the fuselage ingests the vortex and this tends to eliminate the undesirable characteristics described above.

5. Augmentation of jet thrust.

The ejector configuration and shroud location is optimized to give maximum augmentation of thrust. The shape of the underside of the fuselage must be a compromise between one which gives good efficiency when hovering in "free air" and one which generates a substantial cushion effect close to the ground.

STATIC TESTS TO SIMULATE HOVERING FLIGHT

Based on the project design work described above, it was possible to define a generalized jet/body configuration for an experimental program to investigate hovering flight. The purposes of the tests were as follows:

- To optimize shroud geometry to give maximum augmentation of thrust.
- To investigate ground cushion effect and "free-air" efficiency for various body shapes.
- To measure the "suck-on" effect with various wing shapes.
- To investigate static stability of the jet/body configuration when close to the ground.

The experimental work was carried out in the Aerodynamics Research Laboratory at de Havilland (Canada). The program inherited much in the way of augmentor technology and testing techniques from the companion STOL Augmentor-Wing research program. The first two objectives listed above were investigated using a reflection plane model whereas the remaining two objectives were investigated using a complete model fuselage.

Reflection Plane Model Tests

The desire to test at reasonably large scale and the existence of a suitable rig, led to the choice of a reflection plane model mounted between end plates. This model was used to develop a satisfactory jet/body configuration and the data then used to design a complete fuselage model of smaller scale. The reflection plane technique has some disadvantages (such as friction on the reflection wall) but nevertheless it has proved useful as a development tool. A typical configuration is shown in Figure 5. The model is supported on a long semi-rigid air-supply pipe from the ceiling and is restrained by strain gauge dynamometers in the plane of the model.

At first, ground cushion effects were measured by integration of 40 pressure tappings in the ground board. More recently an ingenious and simple force balance has been fitted. Correlation between force and pressure measurements has been good except in certain cases where highly non-uniform flow existed spanwise across the model, (Figure 6).

There are two basic geometric parameters

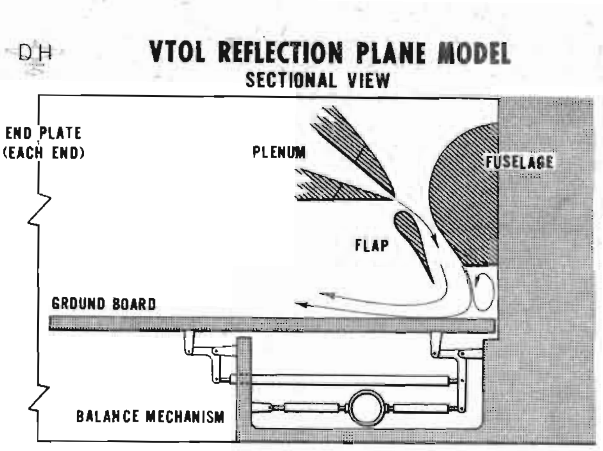


FIGURE 5

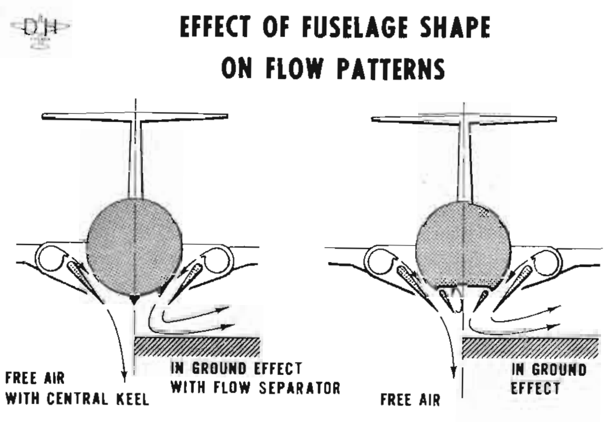


FIGURE 7

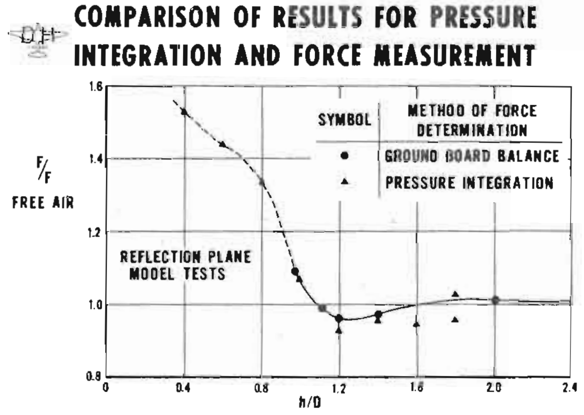


FIGURE 6

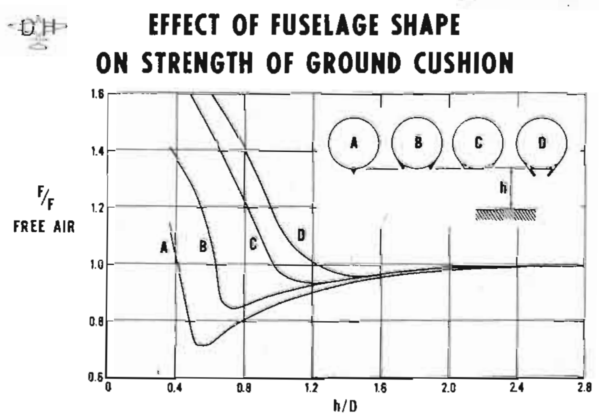


FIGURE 8

which govern the thrust augmentation of the ejector, namely, the ratio of throat width to jet thickness (which should be greater than about 10) and the ratio of ejector length to throat width (which should be at least 5). In the case of the augmentor flap (1) and (2), it is possible to achieve this and values of net augmentation between 1.4 and 1.5 have been achieved at model scale. However, in the VTOL ejector configurations described here, it may not be possible to meet these geometric specifications and our experience suggests that the augmentation may lie between 1.2 and 1.3. The main reason for failure to provide a better ejector geometry is that the nozzle width (or jet thickness) for the VTOL design is greater than in the case of the augmentor flap because thrust-to-weight ratio has increased from about 0.4 for STOL to a value in excess of 1.0 for VTOL.

Generally, it is found that a body with semi-circular base provides good free-air efficiency but a rather weak ground cushion. Conversely, a body with a flat base provides a powerful cushion effect but exhibits poor "free-air" efficiency. Typical flow patterns for each case are illustrated in Figure 7. There have been two main attempts at a suitable compromise, one is to fit small trip wires or spoilers on a circular fuselage, the other is to fit doors which open to extend the fuselage closer to the ground and to form a fairly narrow flat base. The latter solution seems to be the more promising because it causes an early separation of the jets as the body approaches the ground and allows the cushion to become effective before wing "suck-on" effects become appreciable. However, the study of both configurations is continuing and tests are being conducted with the addition of a central jet to the round bottom fuselage. The effect of body shape on the strength of the ground cushion is shown in Figure 8.

Mixing between the primary and secondary flow in the ejector results in a relatively low velocity and temperature of the resultant jet. This is one of the more important reasons for choice of an ejector design. Figure 9 shows the variation of maximum dynamic head of the flow near the ground with height of fuselage above the ground. It can be seen that the ground is subjected to dynamic pressures of about 10% of primary jet dynamic pressure. These experimental measurements were made using the reflection plane model with cold primary jet.

Static Tests of Complete Model Fuselage

There remained the need to investigate ground proximity effects in a more representative and comprehensive manner without the limitations imposed by the reflection plane technique. Therefore, a complete model fuselage was built together with an integrated air-supply and balance rig as shown in Figure 10. The rig was fitted with a "ground board" which could be raised or lowered by remote control. The balance is capable of measuring

MAXIMUM HORIZONTAL JET DYNAMIC HEAD BENEATH MODEL

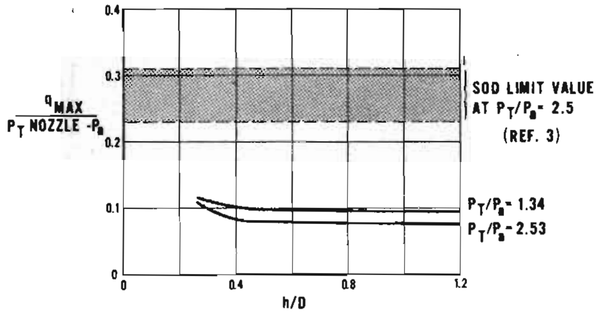


FIGURE 9

FIVE-COMPONENT BALANCE FOR VTOL MODEL TESTS

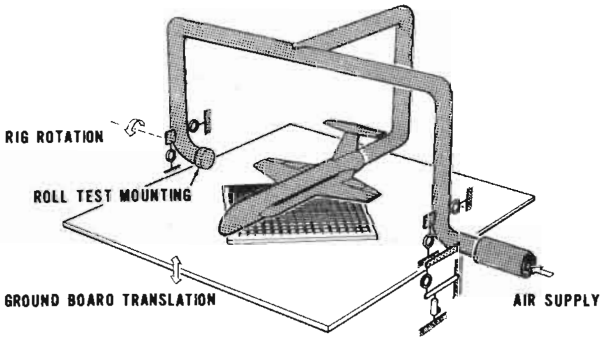


FIGURE 10

forces in two axes and moment about one axis but since the model can be mounted on the rig in two positions, a total of five components can be recorded. When mounted in one position, measurements can be made of lift, drag and pitching moment with variation in angle of attack whereas mounted in the other position measurements can be made of lift, side force and rolling moment with variation in angle of roll. Thus the VTOL testing rig permits investigation of static stability as well as a broader study of the effect of ground proximity on lift.

MODEL FOR HOVERING GROUND EFFECT TESTS

MID-WING CONFIGURATION

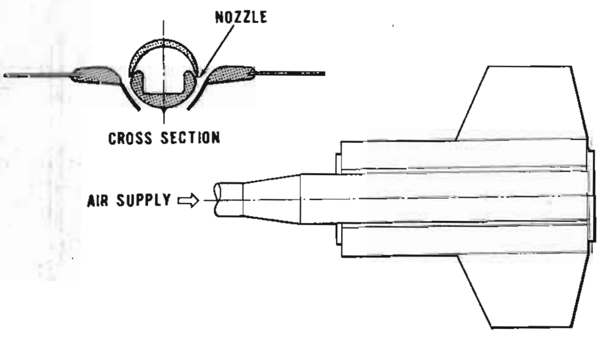


FIGURE 11

The model which was built for the rig is shown in Figure 11. For reasons of simplicity and cost, the fuselage was used as a plenum chamber and the jets made to issue from two slot nozzles located in the sides of the fuselage. The model was constructed so that flat plates could be added to represent wings of various planform shapes and the design was such that the main fuselage/nozzle assembly could eventually be incorporated into a wind tunnel model for the 6 x 9 foot tunnel at the National Aeronautical Establishment in Ottawa. Provision was made for two nozzle sizes (thickness t = 0.075" and 0.125") and the model was stressed for operation at values of pressure ratio up to three.

Figure 12 shows the analysis of a collection of data in which the lift loss due to the wing and wing root sponsons was isolated and related to the height above ground as measured to the underside of the wing. Results of tests from "fuselage plus wing" and corresponding "fuselage only" configurations were used to isolate the effect of the wing. It can be seen that the "suck-on" tendency is quite severe and in all probability requires the combination of a deep fuselage and a powerful ground cushion to offset the loss of lift.

LIFT LOSS DUE TO WING NEAR GROUND

MID-WING CONFIGURATION

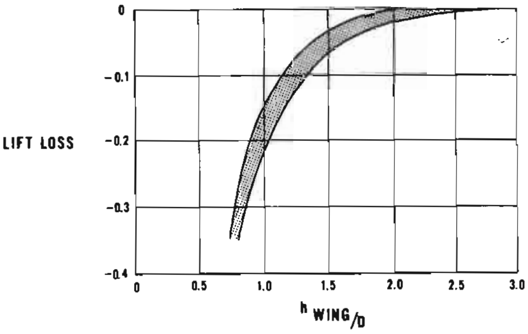


FIGURE 12

Figures 13 and 14 show some measurements of pitch and roll stability in close proximity to the ground. As might be expected, the ground cushion provides positive stability in pitch which increases as the model closes with the ground (Figure 13). In

PITCH STABILITY NEAR GROUND

MID-WING CONFIGURATION

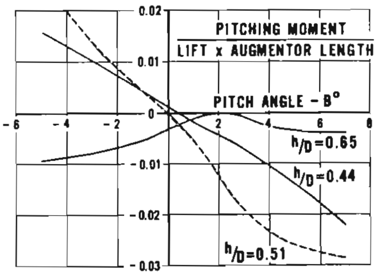


FIGURE 13

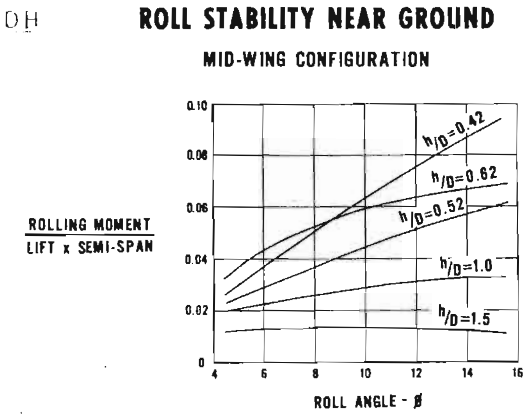


FIGURE 14

roll, as the down-going wing comes closer to the ground, the "suck-on" tendency is intensified and this results in a roll instability which increases as h/d becomes less. This again emphasizes the need to keep the wing relatively high on the fuselage. The introduction of some dihedral on the wing helps to vent the area beneath the wing and thereby lessen the suction due to entrainment.

Some experiments were carried out to study the effect of surface grids which were placed on the ground board beneath the model. The effects were quite pronounced so that with a suitable choice of size and depth of grid the "suck-on" tendency could be eliminated and a powerful ground cushion retained, even with a mid-wing configuration having circular fuselage. Figure 15 shows the variation of lift with height above the ground for various grids and Figure 16 is a photograph of the model mounted in the VTOL rig with a grid located beneath the fuselage. An attempt was made to explore the reasons for this result by measurement of static pressures on the under surface of the wing. The practical usefulness or otherwise of such a grid device is open to debate and, for the present, is left to the speculation of the reader.

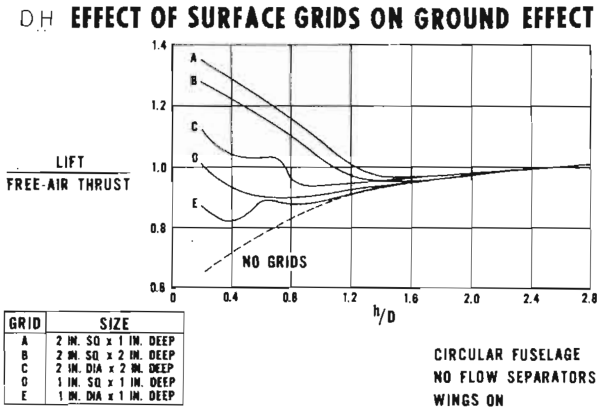


FIGURE 15

WIND TUNNEL TESTS

The basic fuselage/nozzle assembly of the hover test model described previously was used to form the wind tunnel model shown in Figure 17.

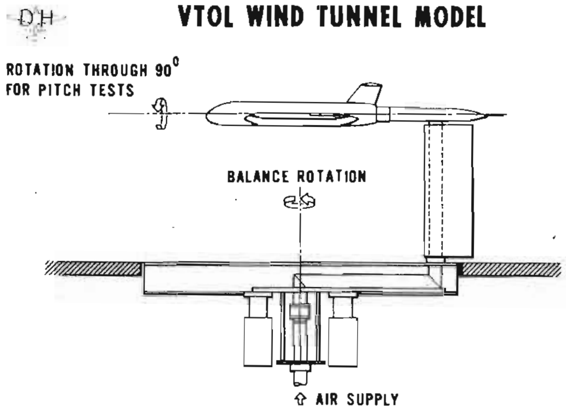


FIGURE 17

Once again, to save costs, the mounting was designed to utilize an existing ground-to-balance air-supply system. It is recognized that the combination of model and mounting is not an ideal one but it was considered satisfactory for initial exploratory tests. A photograph of the model is shown in Figure 18.

A fairly extensive tunnel program was carried out with four different wing planforms, two "Gothic"

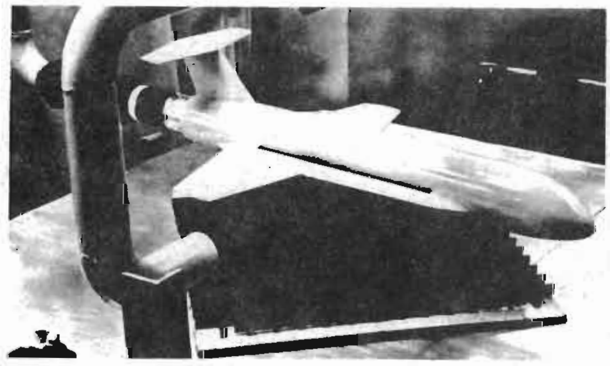


FIGURE 16

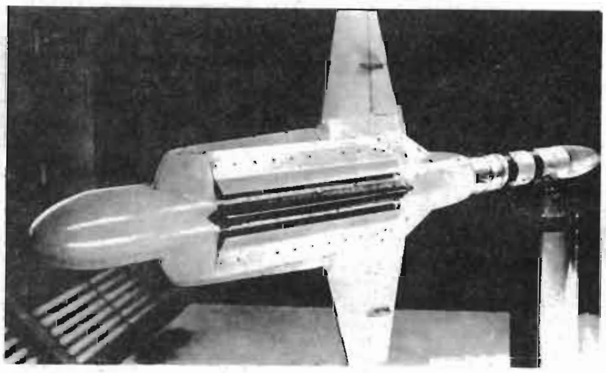


FIGURE 18

shapes (aspect ratio 0.48 and 0.96) and two "Draken" type planforms (aspect ratio) 1.16 and 2.06). The overall conclusion was that jet/wing interference effects were surprisingly small; for example, the model showed only slight loss of lift with forward speed; this effect is typically quite severe at low transition speeds for configurations with a cluster of circular jets centrally located beneath the fuselage. Therefore, in the present context, it was decided to highlight two interesting sidelines rather than attempt to present a large volume of rather mundane wind tunnel results.

Although the model aspect ratio was quite small (less than about two for all wings) it was noticed that the port wing stalled at $\alpha = 10^{\circ}$ (approx.) whereas flow over the starboard wing remained attached up to $\alpha = 20^{\circ}$ (approx.). Our aerodynamic staff suggested many ingenious explanations for this phenomenon until the true answer was found. It was pointed out that the model had a slight asymmetry such that the jet issued from the fuselage with an offset in the vertical plane of about 2°. This offset caused the jet to impinge on the tunnel floor and set up a corkscrew type of flow which, in turn, induced a vortex upstream of the model. The model was rotated on its sting support by 2° in roll and the stall asymmetry vanished. The model was then rotated a further two degrees in the same direction and the problem reappeared but this time it was the starboard wing which stalled first. This represents an excellent example of the need for larger wind tunnels for V/STOL testing, and, in Canada, we are fortunate that the new 30 x 30 foot low speed tunnel is now operational at the National Aeronautical Establishment in Ottawa.

The second phenomenon concerns the influence of the secondary flow into the ejector slot on wing characteristics and serves to explain, in part, why the configuration suffered so little jet interference effects. It is well known that the double-delta type of planform tends to exhibit poor stalling characteristics because the vortex which is shed from the highly swept leading edge at the wing-fuselage junction streams over the upper surface of the wing at about mid-span. This often leads to a premature stall on the outer wing and to disturbed flow over the empennage. In the case of the "external augmentor" configuration, the ejector slot ingests the vortex generated by the wing-root sponson and this leads to suppression of the normal non-linearities commonly associated with low aspect ratio wings. This phenomenon is illustrated in Figure 19 and was demonstrated in the tunnel by use of smoke for flow visualization. A simple illustration of the effect of vortex ingestion is given in Figure 20. It shows the $C_L - \alpha$ variation power-off and the corresponding C_{L_A} vs α power-on. In the power-on case the static jet reaction lift has to be subtracted from the measured lift to yield C_{L_A}, the aerodynamic component of lift. It can be seen that the power-off result exhibits the characteristic increase in lift-curve slope with α which is normally attributed to the existence of vortex-type flow on low aspect ratio, highly swept wings; whereas the power-on result is substantially linear, corresponding to fully attached flow typical of high aspect ratio wings.

VORTEX BEHAVIOR WITH AUGMENTOR

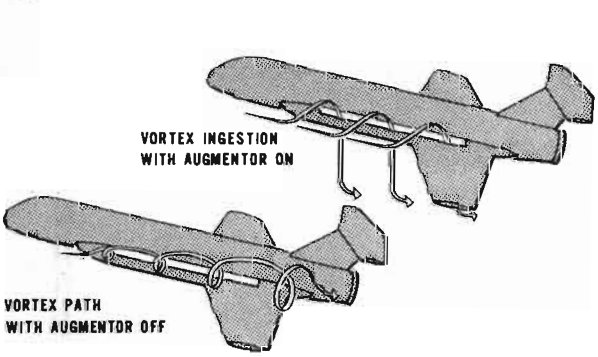
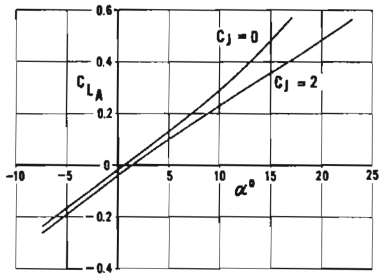


FIGURE 19

EFFECT OF AUGMENTOR ON AERODYNAMIC LIFT



ASPECT RATIO 1.16
FLAP ANGLE 0°
TAIL OFF

FIGURE 20

CURRENT AND FUTURE RESEARCH

The research work is receiving continued support from the Defence Research Board of Canada. The current model test program is directed toward the development of ejector configurations and fuselage shapes which combine to give a powerful ground cushion with the onset of cushion effects at relatively large values of h/d. This work will be followed by construction of a large scale model using a General Electric J-85 turbojet as the power source as shown in Figure 21.

This larger model will permit studies of the effects of temperature on thrust augmentation and jet mixing. The model will be mounted in a special stand to enable measurement of lift and thrust

LARGE SCALE VTOL MODEL WITH J-85 POWER PLANT

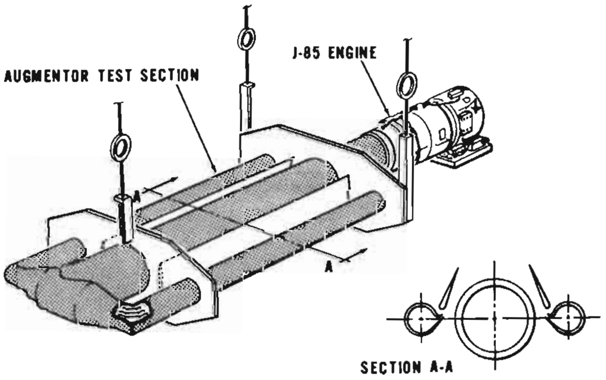


FIGURE 21

forces. The jet will be directed vertically upward to obtain measurement of thrust free of ground effect; and yet, by inverting the model and adjusting height, it will be possible to assess ground effects. In another configuration, the engine will be fitted with a conventional jet pipe and nozzle to obtain the basic characteristics of the unit for comparison purposes. The test program will include measurements of noise, re-ingestion and jet impingement effects.

CONCLUSIONS

Generally speaking, the development of VTOL aircraft has taken longer than was anticipated, say, 10 to 15 years ago. In recent testimony to the "Committee on Science and Astronautics" in Washington, Charles W. Harper of NASA stated:

> "In retrospect, it appears that this failure followed from an attempt to find a single concept suitable for all V/STOL missions. Recent experience indicates that such a solution is remote, if possible. In the past few years, NASA has focussed its research increasingly toward the objective of enabling development of several types of V/STOL aircraft, each directed at a single important mission".

The work described in this paper represents one further attempt to meet the demanding requirements of VTOL flight. Although illustrations have been presented showing the application of the concept to a variety of aircraft types, it is not implied that these ideas represent a general solution to VTOL but rather that the concept might eventually show to advantage and find application in a specific role or mission.

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