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NASA Technical Memorandum 81328

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(NASA-TM-81328) V/STOL AIRCRAFT AND FLUID
DYNAMICS (NASA) 8 p HC A02/MF A01 CSCL 01C N82-10029

Unclas
G3/05 27729

October 1981

National Aeronautics and
Space Administration

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V/STOL AIRCRAFT AND FLUID DYNAMICS

by

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SUMMARY

A recent AGARD Flight Mechanics Panel Symposium on the "Impact of Military Applications on Rotorcraft and V/STOL Aircraft Design" (Paris, April 1981) is summarized with respect to fixed-wing aircraft. The influence of the mission needs on the configurational design of V/STOL aircraft, the implications regarding some problems in fluid dynamics relating to propulsive flows, and their interaction with the aircraft and the ground plane, are summarized.

1. INTRODUCTION

A recent AGARD Flight Mechanics Panel (FMP) Symposium on the "Impact of Military Applications on Rotorcraft and V/STOL Aircraft Design" (April 1981) summarized the military mission needs and their influence on the configurational aspects of V/STOL aircraft design; identified several classes of V/STOL aircraft that are in various phases of research and development; and recognized that, with projected advances in technology, a number of practical V/STOL aircraft now appear feasible.

To achieve the desired performance of the V/STOL aircraft under consideration requires further progress in several technical disciplines including structures, materials, controls, propulsion, and aerodynamics. Of particular interest to this symposium is how the fluid-dynamical aspects of propulsive flows interact with aircraft surfaces and with the ground plane, thereby affecting performance.

It is the purpose of these remarks to summarize some of the conclusions of the previous symposium and to discuss areas of additional research in fluid dynamics that can contribute to an improvement in performance of V/STOL aircraft.

2. MISSION NEEDS

The need for military V/STOL aircraft results primarily from the potential vulnerability to enemy attack of main airbases in Europe and elsewhere, and of large aircraft carriers at sea. In the event of such attacks, V/STOL aircraft could conceivably operate from damaged runways or damaged carrier decks while continuing to utilize the logistics and support capabilities of those major assets. Alternatively, with the introduction of dispersed operations on land and at sea, V/STOL aircraft could operate without the necessity for long runways or large ships.

With respect to land-based aircraft it is argued that the dispersed site operational capability of V/STOL aircraft provides the advantage of quick response to requests for close air support with higher sortie rates, lower detectability on the ground, and a lower probability of concentrated attack. It is important here to distinguish between the need for improvements in short landing as opposed to short take-off capability. Most modern fighter aircraft, by virtue of their high thrust-to-weight ratio, already have the capability of taking off in relatively short distances (say 2,000 ft), whereas, landing on a 2,000 ft runway is a much more difficult problem, given the allowable errors in touchdown point and a limited means of reducing touchdown speed of conventional fighters. Also, for transport aircraft, the need is for shorter landing capability at dispersed destination points (long runways are generally available at the major supply points and the return takeoff is generally easier after the cargo delivery has been completed, since the aircraft is then lightly loaded).

With this emphasis, STOL, in some applications, can be refined to CTOSL; i.e., conventional takeoff and short landing. It may be feasible to design such CTOSL aircraft with essentially the same thrust-to-weight ratio as their conventional counterparts (i.e., $T/W \sim 0.9$ for fighters and $T/W \sim 0.3$ for transports), thus avoiding the engine-weight penalty usually associated with high T/W STOL aircraft. The technical challenge is to find ways of using propulsion-induced flow to augment aerodynamic lift, thereby reducing landing speed and obtaining good flightpath control to assure minimum touchdown dispersion.

In the event that operation from very short runways is required (say, 500 to 1,000 ft), thrust-to-weight ratios higher than those for conventional aircraft become necessary and landing speeds become sufficiently low that special consideration must be given to aircraft stability, control, and handling qualities. The resulting configuration effectively has all the essential characteristics required for vertical landing (i.e., high T/W and a control system integrated with, and dependent on, the propulsion system). Again, the landing task places the greatest demands on the design; as a result, the best compromise to satisfy mission needs may be a STOVL aircraft (short takeoff and vertical landing) rather than a VTOL aircraft. Payload and fuel-load capabilities of such an aircraft for short takeoff will be substantially better than for vertical takeoff.

For sea-based operations, V/STOL eliminates the need for catapult and arresting gear and allows greater flexibility in ship operations obviating the need to steam into the wind; e.g., during launch and recovery of aircraft. The more compelling reasons for V/STOL, however, is the concern regarding the vulnerability of large carriers to the threat of long range missiles. V/STOL aircraft would permit the smaller, less vulnerable ships to be deployed as a distributed force. The optimum size and number of such ships is the subject of much study but there appears to be a growing belief that a new generation of aircraft carriers having deck lengths of approximately 600 to 800 ft would be a logical complement to, and ultimately substitution for, the current generation of large carriers.

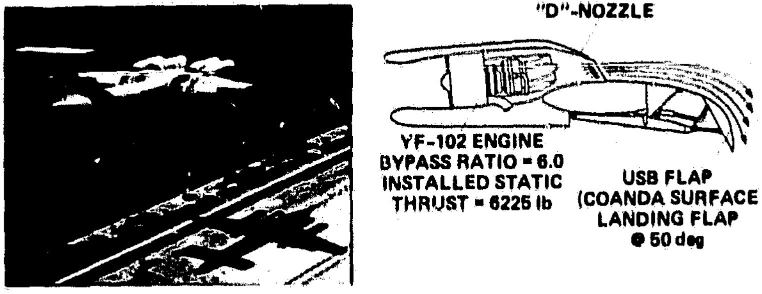
For the present generation carriers and a next generation smaller carrier, the STOVL aircraft may be the correct choice. Such aircraft would have substantial payload and fuel-load capability by virtue of short takeoff (rather than vertical takeoff) and would permit greater flexibility in ship operation through vertical landing (at the reduced weight associated with mission return). Although several types of STOVL and VTOL naval air missions are currently under study, including carrier-onboard-delivery, close support/attack, and supersonic interception, no formal V/STOL aircraft requirement within the U.S. Navy has yet emerged. It seems likely that such a requirement will evolve, in conjunction with new weapon and ship requirements, as part of an integrated systems approach that addresses the problem of replacing the current generation of large aircraft carriers.

3. V/STOL AIRCRAFT CONFIGURATIONS

A number of fixed-wing V/STOL aircraft configurations were reviewed at the FMP Symposium. Those selected here for discussion are (a) the upper surface blowing (USB) STOL aircraft, (b) the turbofan subsonic V/STOL aircraft, and (c) the direct jet-lift supersonic V/STOL interceptor. They represent a broad range of aircraft concepts covering CTOSL, STOL, STOVL, and VTOL. They also incorporate the use of propulsive flows in a variety of ways. Therefore, they form a good basis for the subsequent discussion of several areas in fluid dynamics which need to be better understood with a view to optimize proulsive induced-flow effects.

3.1 Upper Surface Blowing (USB)

The upper-surface blowing concept uses the engine exhaust, usually from a high-bypass-ratio engine, in conjunction with a trailing-edge flap to improve the wing lift through Coanda flow turning and increased wing circulation. The schematic engine-wing-flap geometry for a recent demonstration program (the Quiet Short-Haul Research Aircraft program conducted by NASA and Boeing) is shown in Fig. 1. Maximum lift coefficients above 10 have been demonstrated in flight, compared with lift coefficients of the order of 2 that are usually achieved by aerodynamic means on a typical transport aircraft wing-flap combination. With various flight safety margins, values of C_L and the corresponding low approach speeds (60 knots) and landing distances (500 ft) for moderate thrust-to-weight ratios (~0.5) clearly indicate the value of incorporating the propulsive-aerodynamic interactions into the design of STOL aircraft.



(a) Quiet STOL Research Aircraft with Upper Surface Blowing (NASA-Boeing).

(b) Engine-Wing Schematic.

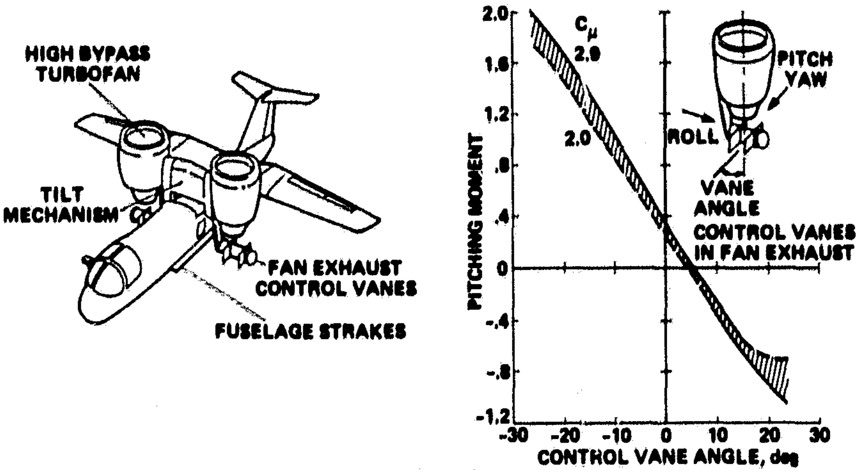
Figure 1. Upper Surface Blowing.

This work is now being extended to examine configurations of conventional thrust-to-weight ratios (T/W = 0.3) — characteristic of military transport aircraft — and to determine whether effective flow turning can be maintained under these lower thrust conditions. The high speed (transonic) characteristics of this engine-wing combination are also being investigated to determine whether positive interference between the wing and the exhaust flow can be realized that will lead to improved cruise efficiency. These results will have important implications regarding the questions of whether CTOL aircraft can achieve short landing performance (i.e., CTOSL aircraft) simply by changing the engine placement and flap design. Several fluid dynamic areas are of interest for this concept.

3.2 Vectored Turbofan

This STOVL or VTOL concept has also been the subject of extensive research (by Grumman and NASA), including full-scale static- and wind-tunnel tests, and small-scale model flight tests in transition and hover. It employs two high-bypass-ratio engines (which can be tilted to change the thrust vector) integrated with controllable inlet guide vanes and a system of control vanes in the engine exhaust flow (Fig. 2). The effectiveness of these vanes in deflecting the exhaust flow to provide control moments in hover and transition is of particular interest. The vane pitching moment was found to be linear over a deflection-angle range of ±20°, whereas only ±5° of deflection was required to provide trim moment for the aircraft. Evidently, substantial margin remained for maneuvering and gust compensation.

The influence of the ground plane on aircraft lift is also of extreme interest. Aircraft lift for a given thrust was found to depend on aircraft height above ground because of the exhaust impingement and the resulting fountain effect. Ground effect was positive (i.e., lift/thrust > 1) and increased typically to a maximum of about 1.08 at a height equal to twice the engine inlet diameter. However, substantial changes in lift associated with meandering of the fountain were observed. Further research is needed for this unsteady phenomenon to be fully understood.



(a) Tilting Turbofan VTOL Aircraft (NASA-Grumman).

(b) Variation of Pitching Moment with Control Vane Angles.

Figure 2. Vector Turbojet.

3.3 Direct Jet Lift

Direct jet lift has been successfully applied to the Harrier VTOL aircraft and is now being considered for application to supersonic fighter and interceptor aircraft. The Harrier aircraft employs a "four poster" Pegasus engine in which four rotatable nozzles direct the flow downward for vertical flight. The two forward nozzle exhausts are relatively cool since they use by-pass air, whereas the two rear exhausts are hot. In some applications it is necessary to maintain a nominal aircraft forward speed in order to avoid damage to the ground plane due to excessive heating. Despite the exhaust impingement problem, the Harrier has operated successfully from various ground surfaces including road segments, grass fields, dirt strips, and aluminum matting. It is therefore natural to seek ways of adapting this successful form of propulsion to supersonic aircraft.

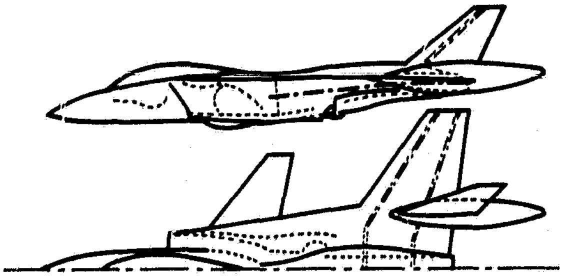


Figure 3. Supersonic VTOL Configuration with Plenum Chamber Burning (Rolls Royce).

Two general variants of the Pegasus approach to direct jet lift applicable to STOVL and VTOL are currently under study (by BAE and Rolls Royce). The first of these (Fig. 3) adds plenum chamber burning (PCB) to the two front nozzles to increase the thrust and combines the two rear nozzles (to reduce supersonic drag) into a single nozzle which also rotates into a vertical thrust position. While extensive testing has been conducted to prove the PCB concept, questions remain regarding the effects of the three hot exhausts on the ground plane and on the underside of the aircraft. Also the fountain produced by the three exhaust streams may be less stable than that of the more symmetric four-poster configuration of the Harrier and may produce adverse effects from hot-gas ingestion into the engine.

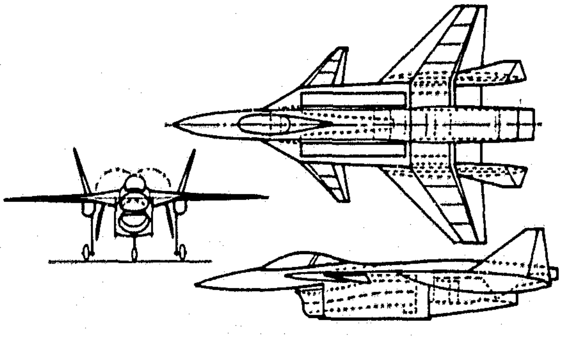


Figure 4. Supersonic VTOL Configuration with Fuselage Thrust Augmentor (de Havilland).

The second broad variant of the Pegasus approach (under investigation by de Havilland of Canada) is to augment the thrust of the forward nozzles by using ejectors located in the fuselage (Fig. 4). This has the advantage of retaining the cold front exhausts (thus avoiding the adverse effects of hot gas ingestion) and providing a relatively low impingement velocity on the ground plane. The two rear hot nozzles are again combined into a single nozzle as in the previous discussion. Uncertainties that remain to be resolved include (a) the extent to which thrust can be improved by cold flow augmentation within the geometrical constraints of a practical supersonic aircraft design, and (b) the effect of the fountain caused by the impingement of exhaust flows (in this case heating effects should not be a problem due to extensive use of cold air; however, the fountain may cause upset moments on the wing and fuselage).

4. PROBLEMS IN FLUID DYNAMICS

The practical problems touched upon in the previous discussion represent only a limited cross-section of those that fall within the scope of this symposium on the "Fluid Dynamics of Jets with Application to V/STOL." Two general areas of interest to fluid dynamics seem to occur and recur whenever V/STOL aircraft configurations are discussed, namely: (1) the mixing between a propulsive stream and a parallel flow in producing thrust and lift, and (2) propulsive flows issuing from, and impinging upon, neighboring surfaces.

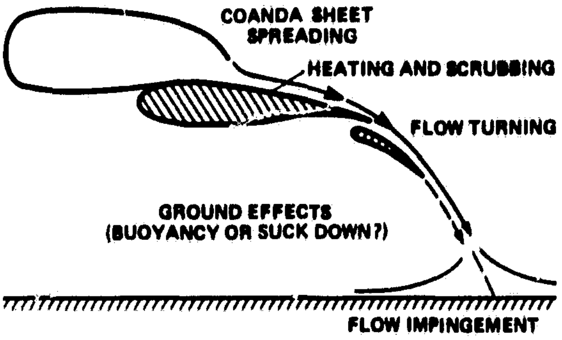


Figure 5. STOL Fluid Dynamics Phenomena.

First, with respect to the mixing of the propulsive flow with a near parallel stream (Fig. 5), although there is extensive analytical and experimental work reported in the technical literature, additional work is required on the lateral spreading of jet flows over curved surfaces (e.g., the upper surface of a wing) and on the subsequent turning from the stream direction of Coanda surfaces. Such redirection of the flow is, in principle, one of the simplest ways of increasing wing lift without attendant duct losses and without complex mechanical devices. The application of this principle to increasing or controlling the circulation around wings and other lifting devices is receiving attention in both the fixed-wing aircraft and helicopter industries, although the basic phenomena are not yet fully understood.

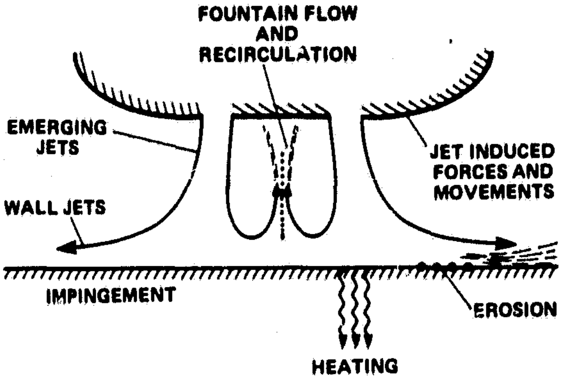


Figure 6. VTOL Fluid Dynamics Phenomena.

Second, regarding propulsive flows issuing from, or impinging upon, neighboring surfaces (Fig. 6), a wide variety of fluid dynamical phenomena in two and three dimensions remain to be fully explored and explained. These include: augmentor mixing, internal vorticity within jets in a crossflow, the influence of a closely placed ground plane on the thrust performance of augmentors and jets, flow spreading over the ground plane, stability of fountain flows in the presence of neighboring surfaces, etc. In contrast to the near-parallel flows discussed earlier, this class of flows may be characterized by convection and the generation of shear stress in several directions so that thin layer approximations to the flow are not valid. There has been some progress through the use of computer models of the flow, but these invariably depend on assumptions relating to the nature of turbulent transport of momentum and energy which are not generally based on definitive experiments that pertain to the particular geometry in question. A concentrated effort is needed to combine careful experimental measurement with intelligent computer modelling in order to gain a better understanding of some of the controlling phenomena in V/STOL related fluid dynamics.

5. CONCLUDING REMARKS

The mission needs for V/STOL aircraft are again receiving critical attention for both land-based and sea-based forces. The traditional disadvantages of V/STOL aircraft in terms of payload and range are now being reduced by advances in technology and offset by the introduction of new operational modes for the deployment of these aircraft. The successful operational experience of the Harrier lends credibility to the mission value of V/STOL aircraft.

Improvements in the use of propulsive forces, involving the engine airflow and its interaction with the aircraft aerodynamic flow, are evolving as the critical element in many of the V/STOL aircraft configurations under consideration. In particular, for CTOSL and STOL aircraft, it appears that substantial reductions in takeoff and landing speeds and resulting field lengths can be achieved by placement of the engine exhaust above the wing (upper-surface blowing) without the necessity for increasing the installed thrust of the aircraft. For VTOL aircraft new developments in thrust augmentation (plenum chamber burning or the use of cold-flow ejectors) now permit the consideration of STOVL supersonic fighter/interceptor configurations having little penalty in propulsion system weight when compared to their CTOL counterparts.

The performance and operational effectiveness of these configurations, however, will depend on the successful integration of propulsion and aerodynamics; i.e., a more complete understanding of the fluid dynamics of the propulsive flow and its interaction with the airframe and the ground plane. It seems most likely that this improved understanding, when applied to the most promising configurational concepts, will result in a new generation of V/STOL aircraft that will add a new dimension to the development of air defense forces.

ADDITIONAL READING

The papers below were presented at the AGARD FMP Symposium on the Impact of Military Applications on Rotorcraft and V/STOL Aircraft Design; Paris, France, April 6, 1981.

Andrews, D. R., "Is it Worth Providing Military Aircraft with a V/STOL Capability?" Defense Operational Analysis Establishment, U.K.

Hazen, David C. (Executive Director), "U. S. Military V/STOL; Who Needs It? Wants It? Can Afford It?" Assembly of Engineering, National Research Council, Washington, D.C.

Lewis, W. J. and Simpkin, P., "Multi-Mission STOVL with Vectored Thrust Engines." Rolls Royce Ltd.

Roberts, L., Deckert, W., and Hickey, D., "Recent Progress in V/STOL Aircraft Technology," NASA-Ames Research Center, Moffett Field, California.

Whitley, D. C., "V/STOL Aircraft Technology in Canada," de Havilland Aircraft of Canada.