SUMMARY OF THE V/STOL STATE OF THE ART

By Charles H. Zimmerman

Langley Research Center

It is the purpose of this paper to summarize briefly the major points which have been presented in the preceding papers to aid the designer in forming an overall picture of the status of research on V/STOL aircraft and to present some of the needs for future research in this area.

The basic aerodynamic principles which govern aircraft design have been reviewed briefly and the mission capabilities of various V/STOL types have been presented in figures 1 and 2. It can be seen that the conventional helicopter, which was the only practicable aircraft capable of hovering when power plants were relatively heavy and bulky, remains the most desirable configuration when hovering is a major part of the mission. Because of considerations of rotor-blade stall, rotor-hub drag, and rotor instabilities, helicopters are not well suited to achievement of high speeds or large ranges. However, the power required in cruising can be greatly reduced by careful attention to drag reduction as compared with the power required when drag has been given little or no consideration. This decrease in drag will make possible both the achievement of a reasonably large ferry range for the helicopter and a substantial increase in its productivity in normal missions.

The speed limitation imposed by rotor-blade stall can be alleviated by transferring the propulsion function from the rotor to propellers and using a fixed wing to carry a large percentage of the weight in high-speed flight. The drag of the rotor and tendencies toward rotor instabilities remain serious problems and have caused many engineers to look for more suitable configurations where high speed and long range are the primary considerations and hovering is necessary only for the short time periods required to permit vertical take-offs and landings. Years of research, design, development, and experience have resulted in the conventional high-aspect-ratio, propeller-driven, subsonic airplane configuration as the one most suitable where range, efficiency, and operational flexibility is necessary and speeds greater than 400 knots are not required. It has been natural therefore to attempt to add to this configuration the capability of vertical take-off and landing.

Figure 3 shows a family of V/STOL aircraft which represent various approaches to this general solution. In this figure are four wing-propulsion systems which have been proposed. It has been assumed that a given load is to be carried in a given cargo-type fuselage. This fuselage requires substantially the same stabilizing and control means regardless of the wing-propulsion system and will obviously require the same lifting and thrust forces for its sustentation and propulsion. With the exception of the tilt-rotor aircraft, the aircraft shown have roughly the same effective span in cruising flight and the same downwash velocity when hovering if the same gross weight is assumed. The tilt-rotor configuration has a lower effective span and a lower hovering downwash velocity.

Test-bed aircraft representing in a general way each of these concepts have been flown. An aircraft for operational evaluation can be built based on any one of these concepts. This does not mean that sufficient information is available to build the optimum aircraft of any one type or that the answers are known to all the problems that will be encountered. A great deal of research and development will be required before a completely satisfactory service aircraft of any of these types can be built.

The main problem now is to decide where research should be concentrated in order to proceed most efficiently and rapidly toward the final service aircraft. Unfortunately, a rational answer to this question can come only from operational experience which will provide answers to such questions as:

(1) How much downwash velocity can be tolerated?

(2) How much emphasis should be placed on speed?

(3) How important is good hovering capability?

(4) What is the acceptable pilot work load?

Operational experience will not, however, give all the answers. All of these machines have deficiencies which must be eliminated by careful design and development or at least reduced to tolerable levels. As pointed out in previous papers these machines all have, to a greater or lesser degree, special problems inherent in placing the fuselage in the upwash generated by pairs of lifting jets operating about a plane of symmetry. They all are subject, to a greater or lesser extent, to unpleasantness associated with wing stalling at some point in their flight envelopes. They each present a problem in connection with the requirement for adequate center-of-gravity travel. And, finally, they each present a problem of compromise between design requirements for static lift and high-speed propulsion.

As shown by figure 1, the requirement for high speed strongly indicates the use of a jet propulsion system. Here the problem is one of finding a configuration suited to jet propulsion at high subsonic or supersonic speeds with a jet lifting system compatible with those high-speed requirements. Some of the aerodynamic problems associated with jet and fan lift arrangements have been presented. The major problems are thrust loss near the ground, pitching moments in transition, and high jet velocities.

These problems are not considered unsolvable except for the basic problem of high lifting jet velocities which will preclude use of such aircraft over many types of unprepared soils. It is expected that research directed toward solution of these problems will continue but it is believed that the future of jet V/STOL aircraft hinges largely on the availability of jet engines, or engine combinations, which can meet the requirement for extremely low weight and for both low drag and low specific fuel consumption at high speed.

The preceding discussion has concerned aerodynamics and, to a certain extent, propulsion problems; however, flying and handling qualities must also be considered. As pointed out and discussed previously, experience with conventional helicopters and airplanes plus that gained from the various test-bed vehicles and from studies with variable-stability helicopters and simulators has made possible specification of handling-qualities requirements which will be entirely adequate for V/STOL aircraft suitable for operational evaluation. On the other hand, sufficient information is not available to permit specification of detailed requirements for a service V/STOL aircraft and such specification should not be attempted until operational experience has been gained with suitable aircraft of this type.

It is relatively easy to specify the handling qualities desired in an aircraft; it is much harder to define the degree of departure from perfection that can be tolerated; and it is still harder, in general, to build an aircraft which fully complies with these requirements. The handling qualities of various test-bed aircraft, the reasons for their deficiencies, and, in most cases, the corrective measures which can be taken have been discussed. It should be clearly borne in mind that the test beds are undeveloped aircraft with novel features, and actually the surprising fact is not that they have deficiencies but rather that they fly as well as they do. No attempt will be made to review the deficiencies and their remedies but rather to point out general areas for attention. These problem areas are as follows:

(1) Ground interference effects

(2) Stalling or flow separation

(3) Control power and damping

(4) Pilot work load

In regard to the behavior near the ground, it is very clear that careful attention must be paid to fuselage shape, wing placement, control-surface or control-rotor location, and to the possible use of auxiliary shielding surfaces to minimize undesirable effects and maximize desirable characteristics. A program is underway which should provide better understanding of these phenomena but it is strongly indicated that model tests representing hovering near the ground will, in a development program for this type of aircraft, be as essential as conventional wind-tunnel tests.

It has been indicated that the stalling of lifting surfaces can be avoided or reduced to acceptable levels in certain cases but there is still a great deal to be done in the investigation of wing-rotor, wing-propeller, and wing-fan combinations in order that optimum configurations may be evolved. The National Aeronautics and Space Administration expects to continue to prosecute vigorously research in this area.

The provision of adequate control power and damping is largely an engineering problem. In this area efforts will be directed toward evolution of configurations which minimize those undesirable moment characteristics which impose unnecessary loads on the control system and toward the determination, through experience with variable-stability aircraft, simulators, existing test beds, and future experimental and service aircraft, of realistic control and damping requirements.

There is also the very real problem of pilot work load due to the necessity for changing the configuration during transition. Research, design, and development effort should be devoted to minimization of this problem by increasing the ranges of speed and power through which the aircraft can be safely operated without a configuration change. It is probable that automatic programing equipment can be used to alleviate the pilot's load in most instances but the designer must be fully aware of and respect the limitations inherent in his aircraft which automatic equipment cannot overcome. Also, it is true that, in general, automatic equipment increases costs and introduces maintenance and reliability problems, all of which are generally agreed to be undesirable.

In the area of loads and structures several papers have indicated that cyclic loadings present a major problem for the designer of V/STOL aircraft. This problem is one which requires better understanding and means of estimating the extent of the cyclic loadings so that the designer can minimize these loadings as much as possible in his design approach and can design rationally for the greatest structural efficiency to bear those loads which cannot be avoided. Some of the available information was presented. Efforts are being continued in this area, aided to a very important extent by support from the armed services. Better analytical methods for estimation of dynamic loads have become available which also assist in making possible efficient rational design. However, it seems evident that despite all efforts to avoid or minimize them the cyclic loadings will continue to be a very important factor in the design of V/STOL aircraft and the problem of getting the greatest efficiency of design from a fatigue standpoint has been discussed.

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V/STOL aircraft will bring with them serious operational problems, many of which have been encountered with helicopters. The problem of steep descents in connection with all-weather operation has been discussed and the very important point made that all-weather operation with any type of V/STOL aircraft will not be feasible until means can be developed to provide the pilot with reliable and adequate cues to enable him to find and maintain the proper position and orientation for landing at a selected spot while being plagued by wind shears and shifts and turbulence.

There are very serious problems associated with the operation of V/STOL aircraft from unprepared sites, a necessary requirement if certain military missions are to be accomplished with the desired high degree of mobility and flexibility. The maximum disk loading of the supporting rotors or propellers will almost certainly be dictated by the amount of dynamic pressure which can be tolerated without excessive troubles due to erosion of the types of terrain over which such operations must be conducted as indicated in figure 4. This may well dictate the type of aircraft required, and can be determined only by realistic field experience with suitable aircraft. Both the NASA and the armed services are continuing investigations in this area to extend to larger scale the small-scale results presented in figure 6. Another major problem in this area, that of the effect of the hurricane velocities in the vicinity is a function of aircraft weight, as shown by figures 5 and 6, and is actually worse in some respects for machines supported by lightly loaded rotors. In this area it is undoubtedly true that operational practices will have to be adapted to the velocities created in the vicinity of heavy V/STOL aircraft of any type.

The noise of airplanes and helicopters is one of the very objectionable features of their operation both in civilian and military service. The noise associated with the high powers necessary for large V/STOL aircraft can be alleviated somewhat by careful design and by engineering compromises but will remain a serious problem which will have to be taken into account in operational procedures, some of which have been discussed. Intensive research may indicate methods of reducing the noise output of high-powered turbine engines and lifting rotors but it is unlikely that any completely effective solution will be found in this area.

The most important problem in connection with the development of practical V/STOL aircraft which can support themselves financially in the civilian field and on the basis of usefulness in the military field is indicated in tables I and II. These tables show that, with the exception of the conventional helicopter which uses the same rotor for support in both hovering and forward flight and can hover with a relatively high power loading, all V/STOL aircraft suffer from the fact that the useful load which can be carried in vertical take-offs is a relatively small percentage of the gross weight. These tables also indicate the areas in which the weight penalties of V/STOL exist and hence the areas in which research, design, and development effort will provide the greatest returns in increasing the productivity of the aircraft. The weight of propulsion and lifting systems for all these aircraft, including the helicopter, is a very large item compared with that for the conventional airplane and is tied up in items such as propellers, rotors, and power transmission systems, the stress levels of which are dictated by fatigue considerations. Basic research in metallurgy tending to raise allowable fatigue stress levels in metals otherwise suitable for these components could result in substantially increased productivity of V/STOL aircraft of all types. The high installed power and refined mechanical components necessary in V/STOL aircraft make these aircraft relatively expensive. Research, design, development, and manufacturing techniques which will reduce the cost in money and manpower of producing and maintaining these items is urgently needed and will pay off to a far greater extent than would be true for the conventional airplane.

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Tables I and II are based on weight breakdowns of existing aircraft and on manufacturer's estimates for the unconventional types. They are shown only to illustrate general points and are not suitable for close comparisons of competing types.

Conclusions which may be drawn in regard to the V/STOL state of the art are as follows:

1. With the information now available it is possible to build V/STOL aircraft suitable for operational testing and evaluation and, probably with some modification, useful as service aircraft.

2. A great deal of intensive research is still required to permit the construction of optimum V/STOL aircraft having the greatest utility and productivity.

3. In order that research may be properly guided and expended most productively toward the ultimate goal of practical, useful service aircraft, the type of information needed is that which can be obtained only from operational experience with V/STOL aircraft incorporating those features which on the basis of present knowledge and engineering judgment most nearly approach those which will finally be found most satisfactory.

4. There is no reason to expect a breakthrough which will materially alter this situation. Design and construction should proceed now of the best aircraft which the state of the art can produce.

TABLE I

WEIGHT BREAKDOWN FOR ROTOR-POWERED CONFIGURATIONS

PAYLOAD = 4 TONS; RADIUS = 300 NAUTICAL MILES

	HELICOPTER		COMPOUND HELICOPTER		TILTING ROTOR	
STRUCTURE AND EQUIPMENT		.30W		.37W		.38W
PROPULSION SYSTEM		.25		.29		.25
ROTOR	.11		.11		.11	
ROTOR DRIVE	.10		.10		.08	
PROPELLERS	-		.02		-	
PROPELLER DRIVE	-		.02		-	
ENGINES	.04		.04		.06	
USEFUL LOAD		.45		.34		.37
FUEL	.19		.14		.14	
PAYLOAD	.26		.20		.23	

TABLE II

WEIGHT BREAKDOWN FOR PROPELLER-POWERED CONFIGURATIONS

PAYLOAD = 4 TONS; RADIUS = 400 NAUTICAL MILES

	TILTING WING		TILTING DUCT		CONVENTIONAL AIRPLANE	
STRUCTURE AND EQUIPMENT		.41W		.34W		.43W
PROPULSION SYSTEM		.22		.27		.07
PROPELLER	.09		.05		.02	
DUCT	-		.07		-	
GEARING	.06		.06		.02	
ENGINE	.07		.09		.03	
USEFUL LOAD		.37		.39		.50
FUEL	.17		.19		.20	
PAYLOAD	.20		.20		.30	

HOVERING AND CRUISE PERFORMANCE

W_f = 0.03 GROSS WEIGHT

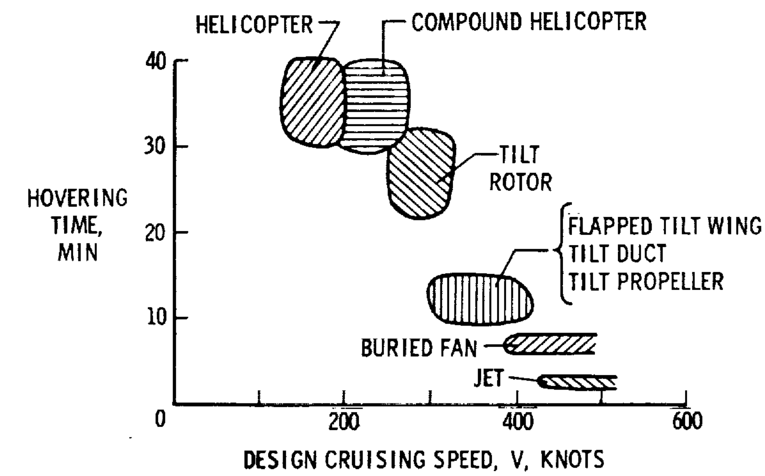

Figure 1

STOL PERFORMANCE

TAKE-OFF DISTANCE OVER 50-FOOT OBSTACLE;

$$\frac{W}{W_{VTOL}} = 1.2$$

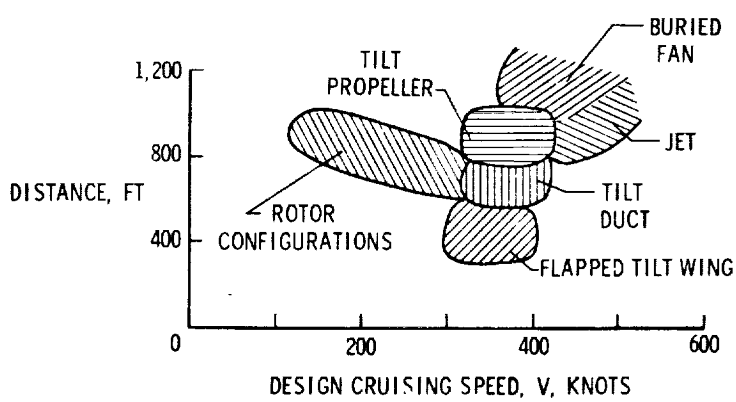

Figure 2

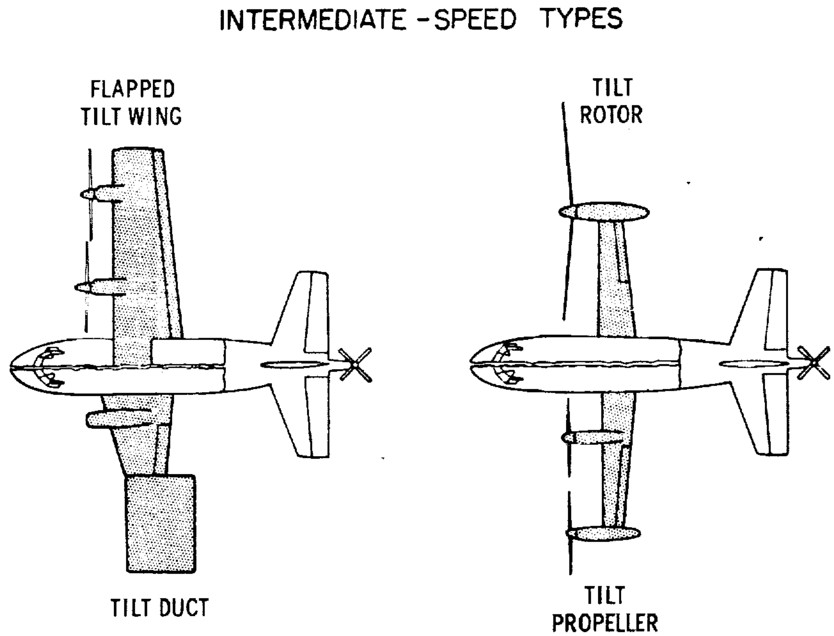

Figure 3

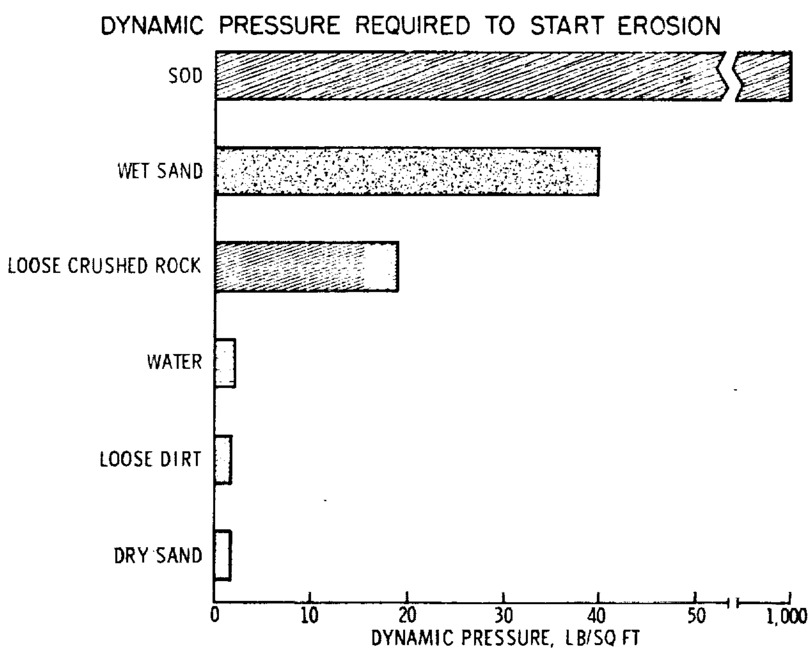

Figure 4

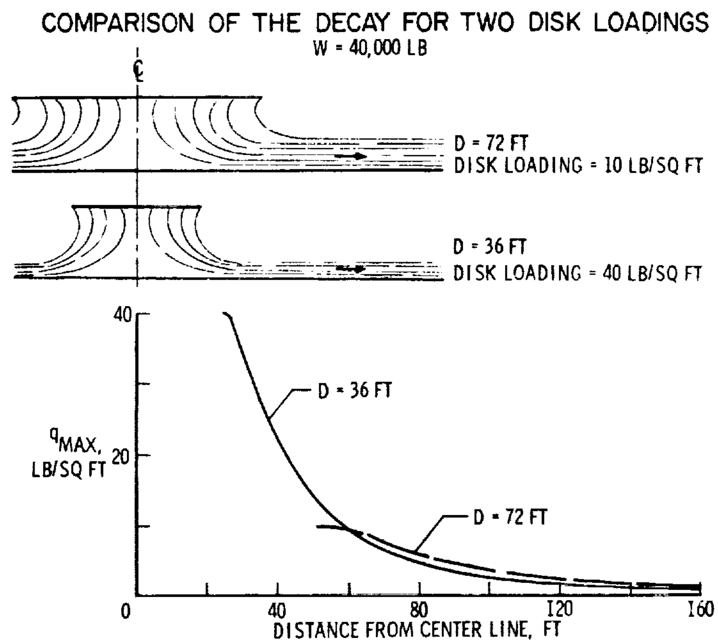

Figure 5

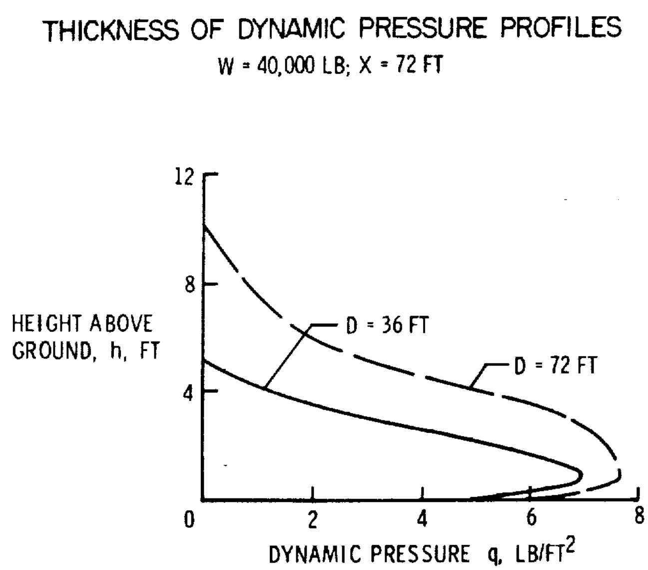

Figure 6

NASA - Langley Field, Va.