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Historical Overview of V/STOL Aircraft Technology

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HISTORICAL OVERVIEW OF V/STOL AIRCRAFT TECHNOLOGY

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SUMMARY

For over 25 years a concerted effort has been made to derive aircraft that combine the vertical takeoff and landing capabilities of the helicopter and the high cruise speeds of conventional aircraft. During this time, over 60 V/STOL types have been studied and flown with varying degrees of success. The requirements for satisfactory characteristics in several key technology areas are discussed and a review is made of various V/STOL aircraft for the purpose of assessing the success or failure of each design in meeting design requirements. This survey shows that in spite of many problems revealed, special operating techniques were developed to help circumvent deficiencies. For the most part performance and handling qualities limitations restricted operational evaluations. Flight operations emphasized the need for good STOL performance, good handling qualities, and stability and control augmentation. The majority of aircraft suffered adverse ground effects. There is a continued need to update and improve flight test techniques and facilities to ensure satisfactory performance and control before and during flight testing.

1. INTRODUCTION

For over 25 years a concerted effort has been made to develop aircraft concepts that combine the vertical takeoff and landing capabilities of the helicopter and the high cruise speeds of conventional aircraft. During this time, approximately 60 types of V/STOL concepts (Fig. 1) have been studied and demonstrated in flight with varying degrees of success. Although a great deal has been learned from these programs, only one or two aircraft have been operationally accepted. The one outstanding exception is the Hawker AV-8A Harrier, a vectored-thrust V/STOL fighter in service with the British RAF, the U.S. Marines, and the Spanish Air Force. In the eastern bloc countries, the Russian Yakowlev YAK-36 lift-plus-lift/cruise jet VTOL fighter appears to be gaining operational status.

In the United States there has been a recent renewal of interest by the Navy and Marines in developing V/STOL aircraft, with particular interest in a V/STOL combat aircraft with supersonic capability. In addition, studies have led the USAF to examine STOL aircraft as an answer to the runway denial situation.

With all the background of V/STOL technology obtained from tests of a wide variety of V/STOL vehicles conducted by many NATO countries, the question remains as to how well the available V/STOL technology base can support the development of advanced V/STOL designs. One approach to answering this question is to review the historical development of V/STOL aircraft and to point out what is needed in several key technology areas to ensure a more successful future V/STOL design. The purpose of the presentation is to:

1. Examine the state of the art of V/STOL technology by means of a historical overview of V/STOL aircraft.

2. Identify problems that have persisted over the years in many V/STOL designs.

3. Reflect on what remains to be done to ensure future design success.

The importance to V/STOL designs of key areas including structures and materials, avionics, and guidance and navigation is recognized; however, this review concentrates on the following:

1. Aerodynamics and performance
2. Propulsion and propulsion-induced effects
3. Flight dynamics and controls
4. Operating problems
5. Testing techniques

A movie of many historical V/STOL aircraft designs is used in the oral presentation to illustrate what is desired (and lacking) in the aforementioned technology areas.

2. RESULTS AND DISCUSSION

In the following discussion, the requirements for satisfactory characteristics in several key technology areas are examined briefly in the light of known desired characteristics. Finally, a chronological review is made of various V/STOL aircraft for the purpose of assessing the success or failure of each design concept in terms of meeting certain technological design considerations.

2.1 Aerodynamic and Performance Design Considerations

2.1.1 Low- and high-speed configuration compatibility

The aircraft features that provide VTOL capability must not unduly compromise cruise performance. In general, achieving good cruise performance requires aerodynamic cleanness to minimize parasite drag, a wing of sufficient span with good load distribution to minimize induced drag, and the least compromise in propulsive efficiency.

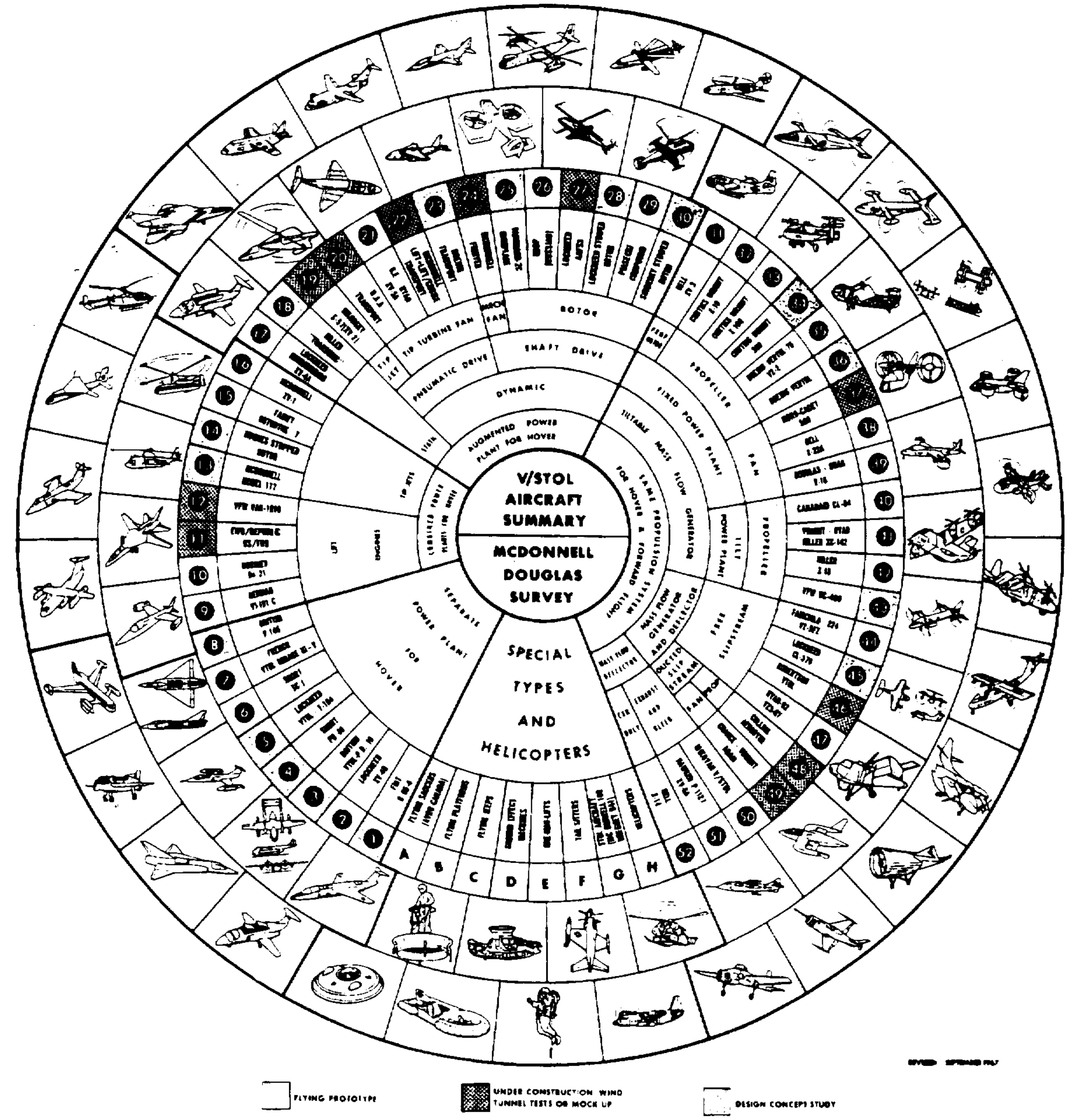

Figure 1. V/STOL aircraft summary.

The cruise performance of a given V/STOL configuration can be evaluated by making comparisons in terms of the airspeed obtained and the specific power (installed power divided by the gross weight multiplied by the velocity obtained). The cruise performance of various VTOL configurations is shown in Fig. 2. A good example of a competitive concept is the lift fan. The propeller-driven tilt-wing types have similar values of specific power but are limited by their propellers to lower speeds. Rotor types generally have poorer cruise efficiency for well-known reasons. The exceptions are the tilt rotor, the stowed-rotor, and the X-wing concept.

At the very low end of the speed range, hover performance can be an important consideration. We are aware that a lift system that imparts a high downwash velocity is less efficient because the engine power (and full flow required to produce the lift) varies as the cube of the air velocity. Obviously, jet-lift and lift-fan concepts, although efficient in cruise, are poor choices if extensive hovering is needed. A rotor or propeller configuration is obviously more efficient. An example of a good compromise in this regard is the XV-15 tilt-rotor concept, which has good rotor efficiency in hover and reasonably good propulsive efficiency in cruise.

2.1.2 STOL performance

A very important consideration for the productivity (usefulness) of a V/STOL concept is the potential improvement in range and payload when the vehicle is operated in the STOL mode. The inherent gain in STOL performance is highly configuration-dependent. Tilt-wing, propeller slipstream types (XC-142 or CL-84) achieve good STOL performance by using the propeller slipstream to increase wing and flap lift. In contrast, tail-seater types, such as the Convair XFY-1, have zero STOL performance gain because of the inability to effectively vector the slipstream.

The primary factor in achieving good STOL performance on a given VTOL concept is the placement of the inlet and exhaust of the lift-generator system. Proper exhaust location, such as that achieved on the AV-8B aircraft, can enhance flap lift considerably. The momentum drag associated with turning the inlet flow can have a pronounced effect, not only on increasing takeoff roll but also on limiting forward speed in transition.

2.1.3 Transition corridor

A further requirement for good aerodynamic and performance characteristics is in transition from powered lift to conventional flight. In going from powered lift to conventional flight, the drag and thrust relationship must be such that adequate margins in airspeed or flightpath angle or both are available. For example, the VAK-191B jet-lift-plus-lift/cruise concept could barely accelerate out to conventional flight due to the high induced drag and the high stall speed (approximately 220 knots) associated with the small span and wing area. In transitioning from conventional flight to powered lift, deceleration or descent capability can be severely limited by wing or duct stall when propulsive thrust (power) is reduced. Notable examples in this regard are the tilt-wing and tilt-duct VTOL concepts.

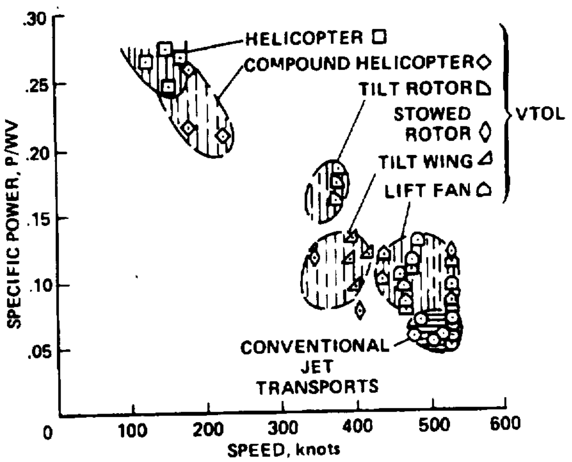

Figure 2. Comparison of power requirements and cruise-speed capability of various aircraft types.

2.1.4 Gust sensitivity

Although closely interrelated with stability and control aspects, the perturbations in speed or upset tendencies in gusty air are strongly influenced by the aerodynamic features peculiar to certain V/STOL concepts. For some aircraft, the change in pitching moment with airspeed and change in rolling moment with side velocity can be extremely troublesome. The aerodynamics of the propulsion-lift-generation system as exemplified by ducted fans, tilt wings, and fan-in-wing are influenced by the center of pressure migrations and momentum drag changes that occur with changes in speed, angle of attack, and engine power. The large drag forces with the tilt wing set at 90° (barn door effect) make this concept gust-sensitive.

In general, aircraft that are gust-sensitive cannot be expected to hover precisely; in addition, flightpath control, particularly in IFR conditions, can deteriorate to unsatisfactory levels. Because some V/STOL concepts are inherently prone to gust sensitivity, greater control power and a more complex stability and control augmentation system (SCAS) can become unwelcome additional requirements.

2.2 Propulsion and Propulsion-Induced Effects

A primary design consideration for V/STOL aircraft is the flow environment induced by the propulsion system during hover and low-speed operation. Although the type and severity of propulsion-induced effects can vary considerably, depending on the VTOL concept, their presence can dominate the behavior and operational limitations of an aircraft.

The downwash flow from the propulsion and lift-generating system can impose very serious design constraints on a VTOL aircraft. There are three major areas of concern:

1. Hot-gas recirculation (ingestion)
2. Induced pressures (forces and moments) on the vehicle
3. Ground (runway) deterioration

Every vehicle that has been tested has manifested, to some degree, a sacrifice in operational utility because of the aforementioned ground-proximity effects.

Hot-gas recirculation (ingestion) was, as expected, more of a problem for the jet-lift vehicles than with the lower-disk-loading types. Since the thrust output of the jet engine is sensitive to inlet (intake) temperatures, which for some VTOL concepts can be very high (namely, the VJ-101X2 afterburning version), the ingestion of only a small portion of the exhaust can result in large thrust losses or compressor stall or surge. None of the propeller or rotor aircraft experienced any detrimental hot-gas ingestion effects.

Major factors that influence hot-gas ingestion are engine inlet height, forward speed, and the aircraft configuration. Since reingestion is caused by the influence of the ground on the exhaust flow, it decreases rapidly with increase in altitude. At takeoff, the near-field (fountain) effect is the primary influence to about 10 ft above wheel height, after which the far-field (convective) effect predominates.

Forward (or rearward) speed progressively reduces the near-field ingestion and increases the far-field ingestion. At a critical forward speed, ingestion reaches a maximum; further increases in speed cause the exhaust to flow beneath the intakes, thus rapidly decreasing ingestion. The critical speed can vary widely, depending on the configuration (layout) of the power-plant exhaust and inlet system. Nozzle canting for the VAK-191B, high inlets for the VJ-101, and low inlets for the AV-8A resulted in critical speeds of 2 knots, 29 knots, and 58 knots, respectively.

Although there is a qualitative understanding of exhaust gas flow (ingestion), a suitable prediction technique for estimating gas-flow characteristics is not available. The situation is complicated by unknown effects of the ground (surface) condition and uncertain flow of the near-field gases.

Induced pressures caused by the influx and efflux of the lift generator system result in forces and moments that can significantly influence the lift and stability of VTOL aircraft in hover and transition flight. Although these induced effects may be present regardless of ground proximity, the effects are usually more severe close to the ground. At low speeds, the aerodynamic interference effects on the engine inlet, wing, fuselage, and tail can be of the same magnitude as the aerodynamic loads, thereby greatly influencing control-system requirements. The effects of induced flow are not limited to high-disk-loading vehicles, as was the case for hot-gas ingestion, but affect all VTOL concepts to a greater or less degree. Of concern, in hover are such factors as lift-loss, pitch-trim changes, roll instabilities, and control-power reductions. Lift-loss (suck-down) magnitude varies, depending on the configuration. In general, greater lift losses occur for configurations in which the lift jets are close together (e.g., X-14), and can be favorable (positive lift) for tilt-wing types (e.g., XC-142) or when the jet fountain effect can be "trapped" by judicious location of undersurface partitions, as used in the Harrier.

Both pitch and roll instabilities can be encountered in hover because of the reflection of the exhaust flow from the ground to the horizontal tail or wing surfaces. The upsetting moments can be very large, particularly in roll, if the vehicle is lifted from the ground in a banked attitude. The Harrier, VJ-101, and DO-31 are examples of configurations that have experienced pitch and roll instabilities.

In forward (or sideward) flight, induced flow can effect lift, pitching moment, and rolling moment to varying degrees, depending on the VTOL concept used and on the location of the lift generators. Severe rolling moments have been encountered in sideward flight for several configurations: for example, the Harrier, XV-5, SC-1, and Mirage III-V.

2.3 Flight Dynamics, Controls, and Handling Qualities

More than any other technical area, flight dynamics, controls, and handling qualities have dominated the success or failure of every V/STOL concept. In general, poor handling qualities have significantly limited the operational utility of most V/STOL concepts tested over the years. The following areas are of interest:

1. Control characteristics:
    - Mechanization
    - Control power and sensitivity
2. Stability:
    - Static
    - Dynamic
3. Stability and control augmentation
4. Trim characteristics
5. Flightpath control

2.3.1 Control system characteristics

We are aware that V/STOL aircraft impose several unique control system requirements beyond those associated with conventional aircraft. The lack of any significant dynamic pressures associated with forward flight precludes any inherent stability, and the powerful engine-power-induced flow effects dominate aircraft behavior (usually adversely) until sufficient forward velocity is obtained. For these and other reasons, V/STOL control systems require special attention for the purpose of minimizing unwanted excursions in aircraft attitude, speed, or flightpath. Of primary concern are the mechanical control characteristics, control power, and control sensitivity.

Important mechanical control characteristics include friction, preload, free play, force gradients, mass unbalance, inertia, nonlinear gearing, and rate limiting. These factors directly relate to the pilot's feel of the aircraft (and therefore to the handling qualities) and also affect his ability to rapidly and precisely position the aircraft in hover or along some desired flightpath. Many of the early V/STOL concepts suffered adversely because of poor mechanical control characteristics; for example, the Curtiss Wright X-19A tilt-prop aircraft.

2.3.2 Static and dynamic stability

The need for providing positive static stability in pitch, roll, and yaw is of special interest in the case of V/STOL aircraft because of the more complicated procedures used in transition and the more dominant effect of gusts. Instabilities greatly increase pilot workload and affect accuracy of flightpath control, particularly for IFR operation. Static stability is greatly dependent on aircraft geometry and induced flow effects of the powered-lift system. Pitch instability (pitch-up) was encountered on several V/STOL concepts in low-speed operation, occasionally with dire consequences. If pitch instability occurs at too low an angle of attack, the aerodynamic lift benefits of the wing cannot be used to full advantage, thereby comprising STOL performance. In contrast to pitch, the roll axis has frequently caused handling problems because of too much positive stability. In this case the large positive dihedral can saturate the capability of the control system quite insidiously if the pilot turns quickly out of a headwind or otherwise allows large sideslip angles to develop. Positive directional (yaw) stability has not been a virtue of any of the V/STOL concepts at low speeds; however, except for the need to aid those configurations with large dihedral effect, heading divergences in hover do not seriously affect safety of flight.

Dynamic stability can be a significant problem for V/STOL aircraft, one that requires complex autostabilization systems; such systems are costly, increase maintenance time, and require additional ground checkout equipment. Unfortunately, estimating damping and rotary derivatives is particularly difficult to establish for V/STOL aircraft because of nonlinear power-induced flow effects, aerodynamic lags in downwash, and the flow changes caused by ground effect. Poor Dutch-roll damping in the transition speed range has caused serious problems for several jet-lift aircraft. Although pilot-induced oscillations (PIO) in pitch have been encountered by V/STOL types, no serious flightpath departures have occurred.

Stability and control augmentation systems (SCAS) have necessarily been used in the development of V/STOL aircraft to reduce unwanted excursions in flightpath. Although several early V/STOL aircraft were flown without any form of stability augmentation system (SAS), operation was usually limited to steady hover (no maneuvering), calm air conditions, and very short duration flights. SAS additions have been needed not only to alleviate the effects of instabilities previously discussed, but also to alleviate the cross-coupling that is inherent in most V/STOL types, for example, engine gyroscopic moments, lateral and directional coupling, and pitch and height coupling.

2.3.3 Flightpath control

Flightpath control in the low-speed transition and hover-flight regimes is of special interest for V/STOL aircraft because of the need to satisfy requirements for height-control power (excess thrust margin), height damping, and height-control sensitivity (vertical acceleration per inch of control motion). The amount of height-control power, similar to the other angular axes control, depends on inherent damping of the vehicle, the amount of maneuvering demanded by the mission, and the tendency for gust upset. In contrast to tilt-prop rotor, ducted-fan, fan-in-wing, and tilt-wing types, the jet-lift aircraft exhibit far less vertical (height) damping. This condition, plus the interaction of engine thrust response (time lag), can affect the precision in height control desired by the pilot.

Perhaps the most important handling-qualities factor that has influenced the hover and low-speed operational evaluations of most V/STOL concepts is control power. It has received special attention because it is achieved at some expense of aircraft performance. In addition, if the levels of control power finally designed into a given concept are inadequate, they are usually difficult and costly to improve.

The amount of control power desired by the pilot is determined by three interrelated requirements: (1) how rapidly the aircraft must be maneuvered for a particular task, (2) the magnitude of the moments required for trim, and (3) the amount of control required to compensate for gusts, recirculation, or other disturbances. The amount of control power required for trim depends a great deal on the V/STOL concept and on the axis of interest. For example, the XC-142 tilt-wing requires relatively more pitch-control power for a given alpha range (as speed changes) than the Harrier jet-lift type. However, for lateral (bank-angle) trim, the Harrier needs relatively more lateral control power for sideward flight. Control power required to overcome gust upsets is also configuration-dependent. Finally, one conclusion, from flight-test experience, which may not be abvious at the outset, is that the major share of the total control power required for most V/STOL concepts is needed for trim and upset. Only a small amount (approximately 10%) is used for maneuvering.

2.4 Operating Problems

Several operational considerations peculiar to V/STOL aircraft are discussed in this section to point out how and where compromises in mission effectiveness could occur. These constraints in aircraft operation generally vary in degree, depending on the V/STOL configuration.

One of the most serious operational constraints encountered by most concepts is the restriction imposed by crosswinds. The jet-lift types were severely limited in crosswind operation because of large positive dihedral effect resulting primarily from engine-exhaust-induced flow. Aircraft with inherently large side forces, such as the ducted-fan types, also suffered in this respect, but to a lesser degree.

In some concepts, tailwinds can cause problems that result from hot-gas ingestion or from the need to hover nose-high for station-keeping, thus impeding forward visibility. Turbulence can also restrain operation for some V/STOL aircraft because of upset tendencies close to the ground, and add to the difficulty of achieving precise flightpath control.

Ground and surface erosion caused by hot gases can require specially prepared operating pads which can alter mission effectiveness and restrict vertical lift-offs such that some amount of forward roll is required for takeoff, or by making it necessary to start the lift engines during the takeoff run. The exhaust gases can also overheat aircraft tires, wheel struts, and fuselage skin.

Loss of an engine during takeoff or landing influences operation by virtue of the deadman's curve. Pilot escape is an important engine-out safety consideration, one that requires either large amounts of control power for trim or shuttling down an opposing engine to preserve symmetry.

Many of the foregoing problems that occur during operation in ground effect (IGE) — such as unsteadiness, exhaust heating of tires, and erosion of the ground surface — can be minimized by performing "jump" vertical takeoffs, which in turn require a larger margin of excess takeoff thrust. The ski-jump technique used so successfully by the Harrier also serves to minimize these problems, although its primary intent is to improve overload performance.

2.5 Testing Techniques and Facilities

To a greater extent than is the case for conventional aircraft, special testing techniques and facilities are needed to aid the development of V/STOL aircraft for several reasons. First, the higher cost of a complex VTOL design requires accurate prediction of flight characteristics; and second, less is known about safety of flight for these novel concepts. In general, the following purposes are served:

1. Check out controllability of vehicle before flight

2. Determine performance capability and propulsion system functions

3. Establish safety margins, particularly for failure-mode situations

4. Develop hardware for novel control systems and propulsion systems

In the early days of V/STOL vehicle development, tethered cables were a popular method for preflight checkout. In some special cases the aircraft was suspended by a vertical cable in addition to the fore and aft and sideward restraint methods. The main advantage of tethering is that a partial preflight checkout can be made for a relatively low cost. The disadvantage is that the pilot is unable to effectively assess aircraft controllability and response because of the limited amount of translational motion allowed. The cables must be relatively tight to prevent large excursions; otherwise, dynamic loads may be excessive. In addition, if one restraining cable breaks, a large overturning moment may develop. Further, unless propulsive system thrust is reduced quickly, it can add an appreciable down force that tends to crush the cockpit turnover structure.

A marked improvement in preflight checkout of V/STOL systems can be obtained by the telescope, or pedestal facility, made popular in Germany. In addition to constraining the vehicle's angular motions, the ground height can be readily changed, thus allowing an assessment of changes in induced-flow effects on lift and moments. The ability to check the effect of aircraft attitude is an important test function that is easily carried out on the telescope. Further, an open grid network can usually be made available to remove the propulsive system exhaust near-field recirculation effects, thereby providing longer test runs without overheating aircraft components.

The static test stand is in some way similar to the telescope, the principal difference being in vehicle mounting arrangement. The static test stand being developed at NASA-Ames Research Center is perhaps unique in that it utilizes a strut and balance system similar to that used in the large-scale tunnel, thereby greatly facilitating comparison of wind-tunnel results. Ground effects can be evaluated by adjusting strut length, and, by virtue of a proposed turntable base, wind effects can be studied in the real-world environment. Acoustical measurements can also be obtained with this facility.

Another popular German test facility is the hover rig. Its typical construction consists of an open tubular structure in which engines and cockpit are placed to match the geometric layout of the actual aircraft to be developed. In addition to its use in free hovering flight, it can also be used in ground and pedestal tests. By virtue of exposing the pilot, control systems, and propulsion systems to free-flight environment, valuable design and development information can be obtained on the functioning of such items as reaction control and flight control augmentation (SCAS) systems, the ground exhaust-flow footprint, and hot-gas ingestion characteristics.

2.6 Review of V/STOL Aircraft Technological Characteristics

The following paragraphs present a historical (chronological) review of a number of V/STOL aircraft. The purpose of these summaries — presented here in outline form — is to point out what has been learned about the technology areas discussed in the preceding subsections. Movie sequences of the aircraft are shown in the oral presentation to illustrate operational problem areas, desirable characteristics, and testing techniques. Most of the information presented herein was obtained from first-hand flight-test experience by the author.

Rolls Royce Flying Bedstead

First flight in Darby, U.K. in 1953, using two Rolls Royce NENE turbojet engines horizontally disposed to minimize gyroscopic effects. Inlets located fore and aft. Concept originated to examine control-system requirements for hover and air taxi. Initially tested in ground tether rig. An RAE pilot was killed when a restraining cable broke causing the vehicle to tip over. An overturn structure was added over cockpit area for safety. Tethered testing of V/STOL aircraft requires lines to be relatively tight for safety; however, this greatly reduces pilots' ability to "feel out" aircraft responses. Pilots complained of low control power about all axes (roll axis angular acceleration only 0.5 rad/sec^2). Could be operated only in calm air. Very low excess T/W for height control. Engine exhaust gas ingestion occurred for both forward or rearward flight.

Convair XFY-1 VATOL Aircraft

Conceived from a 1950 U.S. Navy design competition as an escort fighter to operate from limited ship deck space. Powered by one Allison YT40A-14 turboprop. Approximately 17,000 lb static thrust. "Vertical taxi" tests (approximately 280) made in hangar from overhead tether line attached to prop spinner. First vertical free flight in August 1954. Six transitions made to conventional flight, starting November 1954. Good configuration arrangement for low- and high-speed compatibility (high-speed potential of about 500 mph). Poor mechanical control system features including low actuator response rate. Tip-over tendencies noted when on ground in gusty air. Difficult to hover precisely over a spot. Control power about all axes reduced in ground effect. No hot-gas investion or aerodynamic suck-down. Gust sensitivity bothersome to pilot during takeoff and landing phases. Landing approach transitions from conventional flight made by vertical climb (altitude gain of approximately 3,000 ft). Pilot believed level flight transitions could be attempted in spite of wing-stall buffet. Precision of flightpath control in landing approach poor because of unusual spatial orientation situation. Although SAS developed for low-speed operation, pilot was reluctant to use it. Concern for safe pilot ejection with VATOL concept. Poor STOL potential for this aircraft. Very high pilot workload during low-speed operation. Testing curtailed because of engine and gearbox reliability problems.

Ryan X-13 Vertijet VATOL

Started as an internally funded Ryan program in 1947 to demonstrate feasibility of a tail-sitting VTOL research aircraft. First flew with conventional landing gear. First hover flight of USAF-funded prototype made in May 1956; transition made in November 1956. High-wing delta planform. Powered by Rolls Royce Avon turbojet of 10,000 lb thrust. Good configuration for high- and low-speed compatibility. Mechanical control characteristics adversely compromised by complex control mixer system. No aerodynamic suck-down or hot-gas ingestion experienced with this inlet and exhaust location. Exhaust nozzle swiveled for pitch and yaw hover control, compressor bleed air at wing tips for roll control. Rate-damped SAS provided. Large engine gyroscopic cross-coupling moments resulted in loss of attitude control if large angular rates were allowed to develop. In transition, aerodynamic flow separation at high angles of attack resulted in heavy buffet, thereby limiting deceleration and descent performance. Large rolling moments (positive dihedral effect) limited crosswind operation, particularly at high angles of attack. Precision of flightpath control poor due in part to pilot visibility limitations in vertical hover mode. No favorable STOL performance potential possible with this tail-sitter concept.

Shorts SC-1 Lift Plus Cruise Engine Turbojet

First fixed-wing VTOL research aircraft built in U.K. First jet-lift VTOL aircraft to fly English Channel. First vertical flight October 1958 with complete transition in April 1960. Powered by five RR RB108 turbojet engines of 2,130 lb thrust. Four lift engines tiltable to improve acceleration and deceleration. Gross weight approximately 8,000 lb. V_{max} about 250 mph with fixed gear. Moderate low- and high-speed compatibility concept. Limited in high speed by low thrust from single cruise engine. Experienced aerodynamic suck-down and usual hot-gas ingestion problems. Reaction nozzles (bleed air) at aircraft extremities provided satisfactory control power. Quadraplex full-authority SAS improved precision of flightpath control. Good transition characteristics. Large (positive) dihedral effect in sideward flight which increased at high α, limited crosswind operation. High-velocity downwash and large footprint of turbojets caused ground erosion problems. No STOL performance advantage because of appreciable ram drag of lift engines, no favorable induced flow, and small cruise engine thrust. A fatal accident occurred in October 1963 due to lateral upset associated with SAS malfunction. Aircraft extensively tested at RAE Bedford, yielding useful research information.

Bell XV-3 Tilt Rotor

First tilt-rotor convertiplane, developed under joint Army-USAF contract initiated in 1951. First hover flight with three-bladed articulated rotors made in August 1955. Crashed in October 1956, due to "rotor weave" (mechanical dynamic rotor instability). No. 2 aircraft used two-bladed rotors. Underpowered by one Pratt & Whitney R-985 (450 hp) piston engine. Could not hover out of ground effect (OGE). Positive aerodynamic ground effect. Tendency to dart randomly when hovering IGE due to unsteady reflected rotorwash. No SAS made hover precision poor and high pilot workload was required to hover in gusty air. First complete transition made in December 1958. Good (rapid) transition characteristics with small pitch trim changes and wide speed (angle of attack) corridor. Maximum (cruise) speed limited by pitch and yaw dynamic instability associated with destabilizing (side) forces as rotor (prop) blade angle was increased. Low- and high-speed compatibility rated good. Good STOL performance. Downward seat ejection escape system not too popular with pilots. Had potential to be autorotated for power-off landing.

Bell Air Test Vehicle ATV

First tilt-jet VTOL aircraft to fly in the United States. Hover and low-speed tests conducted in 1953 at Buffalo, New York, to explore feasibility of reaction nozzle bleed-air control system. Aircraft had marginal control power with no SAS. Single (upper) surface airfoil limited high-speed flight. Operated from platform to reduce hot-gas-ingestion effects. JT-9 turbo engines (two) could be tilted for conventional flight. Never went through transition, because program was dropped in favor of pursuing X-14 VTOL design.

Bell X-14 Jet Deflection VTOL Aircraft

Concept built under USAF contract to explore potential of a twin-engine deflected turbojet (Bristol Siddeley Viper engines) (cascase thrust diverters) using reaction bleed air for hover control. First hover flight in February 1957 and first transition in May 1958. Open cockpit, no ejection seat, wings from a Beech T-34 aircraft simplified construction. Very low control power (and low control sensitivity) about all axes and no SAS resulted in marginal hover characteristics. Engine gyroscopic cross-coupling, aerodynamic suck-down (10% lift loss IGE), and hot-gas ingestion severely restricted hover operation. Aircraft damaged during checkout of Hawker-Siddeley P.1127 pilot in an uncontrolled (sideward) crash landing due primarily to low roll-control power and no SAS. Refitted with GE J-85 turbojet engines by NASA-Ames Research Center in 1960 and converted to an in-flight simulator to study various control system concepts. Flown in May 1965 by Neil Armstrong in simulated (vertical) lunar landing from 1,500 ft. Aircraft could be safely hovered with roll-control power reduced to approximately 0.6 rad/sec^2 OGE, but required 1.8 rad/sec^2 to compensate for upsets in takeoff and landing. Cascade thrust diverter system did not produce favorable lift-induced flow for STOL performance; in fact, partially vectored thrust caused random flow disturbances that greatly curtailed low-speed flight. Aircraft still on flight status at Ames Research Center. Has survived three hard landings, one in which an Italian Air Force captain lifted off without turning on the bleed-air valve for the reaction nozzles. Aircraft currently equipped with digital fly-by-wire control system to study advanced systems.

Ryan VZ3-RY Deflection Slipstream

Sponsored by U.S. Army to evaluate the deflected slipstream principle for V/STOL operation. First flew in December 1958. Powered by a single Lycoming T-53-L-1 turboshaft engine. Large (40% chord) double-slotted flaps deflected the slipstream for hover operation, and pitch and yaw control was obtained by a universally jointed exhaust jet deflector nozzle at the tail-pipe outlet. Roll control was provided by differential propeller pitch. Marginal turning of slipstream and random upset disturbances caused by slipstream recirculation prevented vertical lift-offs or landings. Addition of a full-span wing leading-edge slat permitted hover OGE; however, recirculation effects limited IGE operation to speeds greater than 10 knots. Excellent STOL performance achieved ($C_{L_{max}}$ of 10) with this concept with moderate to good cruise speed potential. Static pitch instability could be encountered at high lift coefficients and large pitch trim changes occurred with flap deflection and power changes. Transition required careful technique to avoid pitch-up. Although adequate, descent performance limited in the extreme by low roll-control power and airflow separation on wing when power was reduced to descend. Aircraft severely damaged twice and rebuilt. In one case the pitch-up boundary was exceeded during transition to low-speed flight and the pilot ejected safely; other accident occurred as a result of a propeller pitch control malfunction and insufficient L/D was available to flare for landing.

Hiller X-18 Tilt Wing

Funded by USAF. Aircraft first flew conventionally in November 1959. Powered by two Allison T40-A-14 turboprop engines and 16-ft diameter six-bladed contrarotating propellers and one J-34 turbojet engine, which provided exhaust gas reaction pitch control in hover. Aircraft never flown below the speed corresponding to an α of 50°. Piloted motion base simulator studies indicated a potentially catastrophic roll upset if one engine failed in hover (no cross-shaft interconnect). Concept had good STOL performance potential. Marginal transition corridor because of the lack of high-lift devices to prevent wing airflow separation when power was reduced for descent.

Boeing-Vertol VZ-2 Tilt Wing

Conceived from a jointly funded U.S. Army/Navy contract. Aircraft first flew in August 1957 with first transition in July 1958. Powered by a single Lycoming YT53-L-1 turboshaft engine with cross-shaft to two 9.5-ft-diameter three-bladed rotor/propellers. Lateral control provided by differential collective pitch which was very powerful (too sensitive) and pitch and yaw control provided by two ducted fans at the tail (marginal control power). Concept offered moderate low- and high-speed compatibility. Good STOL performance provided by slipstream induced lift. Yaw control power was too weak, resulting in random deviations in heading. No appreciable aerodynamic lift change IGE. Flow reflections from ground caused buffeting and unsteady aircraft behavior with poor hover precision. Because of low pitch-control power, no SAS, and low inherent pitch damping, hover operation was restricted to calm air conditions. Transition to wing-supported flight was satisfactory with little pitch-trim change. Deceleration or descent was severely restricted, however, by wing stall when power was reduced; in addition, lateral-directional damping decreased to unsatisfactory levels. Directional instability was encountered when slowing down IGE at a wing tilt angle of 70°.

Doak VZ-4 Ducted Fan

Developed under U.S. Army funding. First flight in February 1958. Powered by a Lycoming YT53 turboshaft engine with cross-shafting to tilting ducts at each wing tip. Variable inlet guide vanes in the ducts provided roll control in hover; pitch and yaw control were provided by reaction nozzles, using engine exhaust gas at the rear of the fuselage. No SAS and weak control power about all axes made the aircraft difficult to hover. Large side forces associated with large ducts and large (positive) dihedral effect restricted operation to calm air conditions and no crosswinds. No STOL performance benefit noted with the wing-tip-mounted fans. Transition to conventional flight could be made quite rapidly (17 sec from 0 to 200 knots); however, deceleration or descent restricted by duct-lip stall as power was reduced. Large nose-up pitching moment due to ducts required careful speed and duct-angle programming. Aircraft served to indicate feasibility of tilt-duct concept; however, control power improvements and SAS were needed to make this concept operationally acceptable.

Curtiss-Wright X-100 Tilt Prop

Built as a company-funded research aircraft to develop a "radial-lift-force" propeller V/STOL concept. First STOL flight in March 1960. Aircraft was powered by a Lycoming YT53-L-1 turboshaft engine driving two interconnected, highly tapered fiberglass propellers mounted on the wing tips in tilting pods. Because the propellers were designed to support a large share of lift, the wing area was relatively small, resulting in a high stalling speed. Good stall characteristics were reported in conventional flight. Hover IGE was characterized by a random flow fountain causing unsteady behavior. Hover precision was demanding for the pilot because of attitude upsets, roll and height coupling, and lack of SAS. A large nose-up trim change at low forward speeds required full nose-down pitch control. Only one complete transition was made. The aircraft was tested in the 40- by 80-Foot Wind Tunnel at Ames Research Center. Having proved the feasibility of the propeller "radial-lift-force" concept, the flight program was abandoned in favor of pursuing a four-poster (X-19A) arrangement, which would provide improved low-speed control capabilities.

AVRO VZ-9AV Flying Saucer

Funded in part by the USAF. This 18-ft diameter UFO concept first flew in 1960. Hover lift was obtained from a 5-ft-diameter fan mounted at the center and tip-turbine driven by exhaust from three J-69 turbojets by the mixed exhaust ejected downward around the circumference of the disc. The efflux could be vectored aft for forward acceleration and spoiled differentially for roll, yaw, and pitch control. The fan was to be used to provide gyroscopic stabilization for hover, but this feature was never incorporated. High-speed performance was estimated at 300 knots at 30,000 ft. Maximum performance attained was 30 knots at 3 ft. Concept had positive aerodynamic cushion at low heights. Above 3 ft the vehicle became dynamically unstable in pitch and roll with a motion aptly described as "hub capping." This was due to random separated flow on the undersurface of the vehicle and reflected flow from the ground impinging on the vehicle. Large control cross-coupling was evident at all forward speeds. Large nose-up trim change occurred with increased speed, no directional stability, and no directional damping created a high pilot workload situation. One engine out caused serious pitch and yaw trim changes. Large internal duct losses greatly reduced lift and control moments. This concept had poor overall performance potential with a basic

L/D of approximately 3.5. In essence, it turned out to be a ground-effect machine capable of leaping over 10 ft ditches with comparative ease.

Hawker Siddeley XV-6A, P.1127, Harrier

Started as a company-funded venture in 1957. First tethered hover in October 1960, untethered hover in November 1960, and first transition in September 1961. Swept wing (32° at the quarter chord) tactical fighter, powered by a single Bristol Siddeley Pegasus 5 vectored thrust turbofan of 15,200 lb thrust. Bleed-air reaction nozzles used for hover attitude control. Concept designed to be 'simple,' and initial configuration had no SAS. Tethered tests were conducted but not considered to be advantageous to "feel out" aircraft response. Low control power about all axes, aerodynamic suck-down, and marginal height control power created a high pilot workload for the early version of this aircraft. In addition, directional instability was noticed in turning out of the wind, yaw control power was low, but not considered unsafe, and pitch-trim changes occurred when leaving ground effect. Usual hot-gas ingestion problem can be circumvented by maintaining a low forward speed in takeoff and landing. Static pitch instability is encountered at alphas greater than approximately 15°. Large (positive) dihedral effect limits crosswind operation. Transition characteristics are outstanding with only small trim changes, simple cockpit procedures and only 17 sec to complete. Low- and high-speed performance is excellent. Dutch-roll damping is low (typical of swept wing) at altitude requiring a yaw damper. Good STOL operational capability using vectored thrust ski-jump technique to achieve added STOL capability (easy to execute with this concept). Large favorable propulsion-induced lift is obtained on the Harrier AV-8B by relocating flap/jet exhaust. In addition, positive aerodynamic lift was obtained by means of capturing the "fountain effect."

Dassault-Balzac Jet Lift Plus Jet Cruise

First flew in 1962. This delta wing concept built from the original Mirage III prototype airframe. Used eight RB-108 turbojet lift engines mounted in the fuselage and a single BS Orpheus turbojet for cruise. Bleed-air reaction nozzles located at the aircraft extremities for hover attitude control. This concept possessed aerodynamic lift-loss in ground proximity, hot-gas ingestion, and random disturbances during hover IGE. Moderate high-speed potential due to limited thrust available from the single cruise engine. STOL performance limited because of large ram drag associated with flow turning through eight lift engines, even though mounted at favorable (forward) pitch angle. In addition, no favorable aerodynamic lift benefits resulted from this lift-engine exhaust location. Large (positive) dihedral effect. This concept was studied extensively in wind-tunnel tests which indicated that 90% of the large C_{l_β} was due to lift-engine-induced flow over the leading wing and 10% due to the usual aerodynamic swept-wing effect. Dutch-roll damping was low in transition. A French pilot was killed in a "falling leaf" crash during early attempts at transition.

Dassault Mirage III-V Jet Lift Plus Jet Cruise

A larger VTOL aircraft similar to the BALZAC. Powered by eight RB-162 turbojet lift engines and one TF-106 cruise engine (later replaced by P&W TF-30 turbofan). Possessed hover and low-speed problems similar to those of BALZAC (large positive dihedral effect), but had improved control power and damping. For transition, pilots preferred to get through "quickly" allowing no sideslip to develop. In general, this VTOL concept, in common with the Shorts SC-1, has several inherent performance limitations: (1) large cluster of lift engines produces aerodynamic lift-loss (suck-down) IGE; (2) ram drag effects are large, limiting transition corridor; and (3) no favorable induced flow for STOL operation. Good high-speed capability (Mach 2) by use of afterburning thrust and lift-engine location (buried in fuselage) that results in low-profile drag. Aircraft destroyed (pilot ejected) when visiting USAF pilot "ran out of gas" during low-speed/hover operation.

Lockheed XV-4A Augmentor Concept

Sponsored by a U.S. Army contract. The XV-4A (Hummingbird) made its first conventional flight in July 1962 and first transition in November 1963. A 7,200-lb, two-seat, twin-engine (JT-12 turbojet) vehicle which used the engine exhaust directed into an augmented jet ejector system contained in the fuselage to provide increased vertical lift. Three-axis jet (bleed-air) reaction controls were used for hover. Good low- and high-speed performance potential existed for this concept (estimated 530 mph), because the vertical lift capability was completely enclosed in the fuselage and full engine thrust was available for conventional flight. STOL performance was poor, however, because of the large ram drag associated with turning the airflow through the augmentation system; flow exhausting from the bottom of the fuselage provided no favorable induced flow over the wing to increase lift. Hover performance was compromised by inadequate augmentor efficiency, aerodynamic suck-down (approximately 5%), and hot-gas ingestion. The trim aircraft position in hover was nose-up which increased the possibility of hot-gas ingestion as forward speed was increased. Flow mixing in the augmentor reduced gas temperature from 1,200°F at the engine exit to 300°F at the augmentor exit. Ground effect was evidenced by high-frequency (rumbling) of the airframe which increased in intensity in crosswind operation. Rate-damped SAS was used about all axes and attitude stability provided in pitch and roll. Positive dihedral effect in sideward flight was large enough to completely saturate roll-control power resulting in a loss of roll-rate damping and a hard (uncontrolled) landing. An increase in roll-control power and elimination of attitude SAS improved hover controllability. A strong pitch-up was encountered at 60 knots in transition flight. The operational procedure used to alleviate this problem was to reduce engine power when the pitch-up occurred and then to add power as the aircraft was in the dynamic process of pitching down. This procedure was not a panacea for this pitch problem and the aircraft (and pilot) were lost during transition in June 1964.

Lockheed XV-4B Lift Plus Lift Cruise

This concept evolved by modifying the second XV-4A prototype to include four GE YKJ-85 lift engines in the fuselage center section (previously used for the augmentation system) and a 90° thrust-vectoring capability for the two cruise engines (which were moved forward). Wind-tunnel tests indicated a severe deep stall pitching moment problem at alphas exceeding 12°. Alleviated by aft-mounted fuselage strakes. During ground and tether tests severe tail buffet occurred when the engine thrust was vectored 20° aft.

The jet downwash from the six turbojets resulted in ground erosion, tire overheating, and hot-gas ingestion severe enough to induce engine stall. Conventional flights were made to explore high-speed flight and transition down to 95 knots where control sensitivity was judged to be sluggish. Vertical flight was never accomplished with this concept due to the loss of the aircraft in a divergent phugoid oscillation in conventional flight in 1969. Both of these aircraft were helped in their development by an iron bird hover rig, a telescope test rig, and a tether system which used a 300-lb lead ball attached at the c.g. to restrict vertical freedom.

EWR VJ-101 Lift Plus Lift Cruise

Funded by the German Ministry of Defense to assist the development of a Mach 2 VTOL fighter. Concept used six Rolls Royce RB-145 jet-lift engines arranged in pairs at each wing tip and in the fuselage directly behind the cockpit. The wing-tip pod engines were tilted for transition, and thrust modulation was used for pitch and roll attitude control in hover. Engine failure was compensated for by automatic power reduction on the opposite side. First free-flight hover in April 1963 and first transition in September 1963. Excellent low-and high-speed compatibility. First VTOL aircraft to exceed Mach 1 in level flight. Aerodynamic suck-down (approximately 2%) occurred at hover lift-off, decreasing to a positive net buoyancy value of 4% with increased ground clearance. Far-field exhaust effects necessitated a rapid (jump) VTO technique. Good handling qualities were noted. No appreciable C_{ℓ_β} effects in sideward flight were reported for this wing-tip engine location design. The VJ-101C-X1 aircraft was destroyed in a conventional takeoff in September 1964 (pilot ejected as aircraft rolled through 360° position) due to a roll-rate gyro that was installed with reversed polarity. The VJ101C-X2, an afterburner-equipped version of the X1, had a high-speed potential of Mach 1.6. Extensive damage to the concrete runway would occur if VTO was attempted with afterburner. The operational technique used was to apply afterburner power as the engine pods were going through 75° resulting in a takeoff run of about 10-13 ft. This RVTO was short enough to prevent excessive skin or tire temperature increases. Vertical takeoff with afterburners was possible using a ground-elevated thrust deflector system. On one occasion when the aircraft approached the thrust deflector stand for a landing, the reflected exhaust flow was re-ingested in the rear-engines resulting in a large thrust loss and a hard landing (which broke the main landing gear). Transition was straightforward with small trim changes and good acceleration. Deceleration from forward flight to touchdown took about 90 sec. No attempts were made to operate STOL, although favorable induced flow over the wing would occur with this concept. Extensive use was made of ground-test facilities including a "Wippe" or "see-saw" mechanism to check out thrust modulation control, a flying hover rig consisting of three RB-108 turbojet engines arranged in a triangular pattern, and by a telescope permitting control system checkout even with afterburning.

Ryan XV-5A&B Fan-in-Wing

This VTOL concept was a 9,200-lb twin-engine, tri-fan, midwing turbojet-powered research aircraft funded by the U.S. Army. Hover flight first achieved in June 1964 with first transition in November 1964. Control in hover was compromised by several adverse factors, including tip-over tendencies with the narrow tread landing gear, upsets due to unsteady reflected flow, and control and altitude coupling. Hover roll control was obtained by spoiling thrust on one side in the exit of the wing fans, pitch control was obtained by thrust reversing of a front (fuselage) fan, and yaw control by differentially vectoring the exhaust of the wing fans. A moderate dihedral effect due to side velocity and low available roll-control power limited crosswind operation to 12-15 knots. Although positive aerodynamic lift is inherent in this concept due to a favorable fountain effect, hot-gas ingestion from the exhaust of tip-turbine fan drive degraded lift-off thrust by as much as 15% until a wheel height of 10 ft was attained. Operational techniques to minimize ground effects included lifting off in a slightly nose-high attitude, keeping the tail to the wind, and gaining height as rapidly as possible. No STOL performance was evident for several reasons: (1) large ram drag due to flow through the three fans, (2) inability to obtain large enough horizontal acceleration due to limited turning of exhaust flow (maximum fan thrust vector angle was 45°), and (3) low thrust-vector rotation rate. Transition corridor was marginally adequate because of limited forward thrust and the need to abruptly increase angle of attack (about 12°) to gain aerodynamic lift when the wing fan doors were closed. Due to a strong nose-up moment with fan start-up, a large change in alpha was required, and fan overspeed tendencies made conversion difficult. In aerodynamic flight, good high-speed performance was possible (550 mph estimated). Low-speed stall characteristics included a deep stall problem. The first prototype was destroyed (pilot killed) in a conversion from conventional flight. The aircraft was observed to pitch down abruptly from level flight (about 45°) with the pilot ejecting just prior to ground contact. The accident was attributed to inadvertent selection of full nose-down stabilizer position (normally programmed to relieve trim change in transition) at too high an airspeed. The second prototype was also damaged (pilot killed) but rebuilt by NASA to XV-5B configuration. This accident occurred when a hook from the rescue winch system was ingested into the wing fan during a low altitude hover. The pilot ejected as the aircraft hit the ground; however, the seat trajectory was tilted away from the vertical by the ground angular acceleration. Ironically, the recorded data indicated that the cockpit crash accelerations were low enough for survival. NASA tests of the XV-5B disclosed several flightpath control problems in steep (up to 20°) decelerating approaches including: (1) power management compromised by dual height-control methods (lift spoilage or engine speed) (pilot prefers one lever power management), and (2) need to minimize aerodynamic lift effects because longitudinal static stability changed from negative to neutral to positive as speed decreased.

Ling-Tempco-Vought XC-142 Tilt Wing

A tri-service funded tilt-wing concept using four TG4-GE-1 engines with cross-shafting to four propellers and a tail propeller for pitch control. First conventional flight in September 1964; hover in December 1964; and transition in January 1965. Some mechanical control characteristics were unsatisfactory: (1) Directional friction and breakout forces varied with wing tilt angle, (2) nonlinear control gearing, (3) possibility of control surface hard-over, and (4) collective control had to be disengaged manually from throttles in transition. Hover handling qualities were good with SAS on with no adverse flow upsets, resulting in precise spot positioning. Propeller thrust in hover was 12% less than predicted. No adverse lateral-directional characteristics noted in sideward flight to 25 knots. In slow forward flight, a long-period (20 sec) oscillation was apparent which could lead to an uncontrollable pitch-up. On one occasion full forward stick did not arrest the pitch-up, whereupon the pilot reduced engine power, the nose fell through, and the aircraft was extensively damaged in a hard landing because the pilot did not add sufficient power to arrest the high sink rate for fear of starting another pitch-up. STOL performance was not as good as predicted and controllability compromised IGE by several factors: (1) severe recirculation of slipstream for wing tilt angles in the range 40° to 80° (speed range 30 to 60 knots) producing large amplitude lateral-directional upsets; (2) weak positive, neutral, and negative static longitudinal stability; and (3) low directional control power. Transition corridor was satisfactory with ample acceleration and deceleration capabilities. Conventional flight performance was less than predicted (11% less) due to large boat-tail drag-cruise. Stability and control deficient in several areas: (1) low to neutral pitch stability, (2) nonlinear stick force per g gradient, and (3) tendency for pitch PIO during recovery from rolling maneuvers. A failure of the drive shaft to the tail pitch propeller in low-speed flight caused a fatal crash which essentially curtailed further development of this concept.

Canadair CL-84 Tilt Wing

Funded jointly by the Canadian Government and Canadair. Two-engine, propeller-driven tilt-wing aircraft made its first hover flight in May 1965, and first conventional flight in December 1965. Aircraft powered by two Lycoming T-53 free-turbine engines and two four-bladed cross-shafted propellers. Hover handling qualities were satisfactory with ample control power and no appreciable trim or upset effects. Ground erosion was minimal, but hot-gas ingestion was experienced, and a positive ground effect prevailed up to a wheel height of 5 ft. STOL performance was excellent with no ground-effect instabilities encountered as on the XC-142; this was attributed to a higher wing position and improved flap angle programming. Transition outbound was very rapid and easy to perform. Decelerations were limited by wing buffet caused by flow separation on the inboard portion of the wing when power (slipstream velocity) was reduced for descent. Flightpath control during deceleration and descent was more difficult due to a speed-altitude instability somewhat similar to a "vortex ring" condition experienced by helicopters. Low directional stability was noted at high α. Cruise performance was limited due to the high basic profile drag inherent in this concept. Two nonfatal but catastrophic accidents occurred due to: (1) failure of propeller pitch control on one propeller resulted in an uncontrollable yawing moment, and (2) engine gearbox failure in conventional flight with the loss (separation) of one propeller from the aircraft.

Curtiss Wright X-19A Tilt Prop

The program started with only company funds; funding was later augmented by the USAF to develop two six-passenger aircraft consisting of a twin-engine, intershafted tandem high-wing, using four tilting propellers. The propellers were large-chord designed to develop large radial (lift) forces in conventional flight, thereby reducing wing-area requirements. First hover flight in November 1963. Transition tests progressed to about 120 knots. Aircraft never completed transition. Poor mechanical control system characteristics severely penalized low-speed operation. Large friction and break-out forces, hysteresis, and free play (slop) made precision hover impossible. Lack of SAS and upsets due to random flow IGE further increased pilot workload in hover. A positive ground effect was observed up to wheel heights of 4 to 5 ft. Low downwash velocities and lack of hot-gas ingestion were favorable features of this concept. Control and height coupling was a problem in part due to sluggish height control response (engine rpm could be used instead of collective prop pitch). A PIO tendency in height control was encountered due to these poor characteristics. A moderately favorable STOL performance could be expected with this configuration because of the relatively short span and small wing area. Good high-speed performance would be expected because of the clean design and small wing area. One prototype crashed due to a fatigue failure of a gearbox mounting which caused the left rear propeller to separate from the aircraft during transition tests. The two test pilots ejected safely from an inverted aircraft position at an airspeed of 118 knots and 390 ft above ground level.

Bell X-22A Ducted Fan

Under a U.S. Navy contract, two dual tandem ducted fan/propeller aircraft were built as half-size transport vehicles. From the start, variable stability and control features were incorporated for flight research on V/STOL handling qualities. Power was supplied by four GE T-58 turboshaft engines interconnected to the ducted fans such that in the event of an engine failure the remaining engines would drive all four fans. First hover flight in March 1966, and transition completed in June 1967. Hover operation OGE in no wind was rated excellent with more than ample control power and with no perceptible hot-gas ingestion. A 12% positive thrust cushion was generated IGE by the favorable fountain as evidenced by airframe shaking and buffeting at wheel heights up to approximately 15 ft. Wind effects were quite noticeable, however, because of the large side forces generated by the ducts. Vertical crosswind landings required an excessive bank angle to avoid lateral drift. STOL performance was rated good by virtue of the increased duct lifting forces. High-speed performance was limited by relatively high drag associated with the four large ducts. Transition to conventional flight could be made safely due to a wide transition corridor; however, damping was low and both a lateral/directional and longitudinal PIO were encountered. Deceleration and descent at low engine powers caused undesirable duct "buzz" due to flow separation on the lower duct lips. Vortex generators appreciably improved this flow separation problem. The first aircraft was destroyed in a nonfatal hard landing accident in August 1966. Accident was a result of complete hydraulic system failure and the attempt to execute a vertical landing. The high rate of sink (20 ft/sec) could not be arrested with the altitude and power available. The second prototype has generated significant VTOL handling qualities and is currently on flight status.

Dornier DO-31 Lift Plus Lift/Cruise

Under a German Defence Ministry contract, two aircraft were constructed. First conventional flight was made by No. 1 aircraft in February 1967, and first hover flight by No. 2 aircraft in February 1968. Two underwing vectored-thrust Pegasus 5 engines and eight RB-162 lift engines in wing-tip pods provided vertical thrust. Hot-gas ingestion to the main (cruise) engines was a primary problem in vertical hover operations. Ingestion could be circumvented in takeoff by limiting the main-engine nozzles to no more than 85°, which resulted in a takeoff distance of one fuselage length (about a 5-knot forward speed). In vertical landings hot-gas ingestion resulted in a lack of wave-off capability below a wheel height of about 15 ft. A small amount of forward motion greatly alleviated the inlet temperature rise. Induced propulsion flow effects were significant in that aerodynamic lift loss of 3% existed OGE, increasing to 8% at ground contact. Hover control was excellent OGE, using an attitude-hold rate-damped system in pitch and roll and main engine thrust for height control. No large rolling moments were encountered in sideward flight with this concept. In forward flight, lift-losses of the order of 10% were experienced out to 80 knots and then gradually decreased. About 80% of the available pitch-control power was needed to trim at midtransition speeds because of induced flow effects. A wide transition corridor existed with ample acceleration capability. High-speed performance potential was good but not outstanding (cruise at 400 mph) because of the drag resulting from the sizable lift-engine pods. Deceleration and descent characteristics were satisfactory with ample downward flightpath angle capability. In spite of the requirement to handle 10 jet engines, good cockpit procedures and the grouping of all eight lift engines on one throttle level resulted in a satisfactory pilot workload in approach and landing. It is of interest to note, however, that aerodynamic lift was minimized ($\alpha = 0°$) to avoid L/D changes during approach. STOL performance was not investigated. It would be expected, however, that some favorable power-induced flow over the wing-flap system would occur from the main-engine exhaust, offset to some degree by the ram drag produced by turning the flow through the lift engine pods. The success of the concept from the control standpoint can be attributed to extended use of a flying test rig and telescope checkout stand. Aircraft now resides in the Munich Deutches Museum.

VFW VAK-191B Lift Plus Lift/Cruise

The VAK-191B VTOL aircraft originated in response to a NATO military requirement for a high-performance tactical reconnaissance fighter capable of delivering a nuclear warhead from a high-speed (Mach 0.9) low-level dash mission. The ride qualities for this low-level operation were made tolerable by a low-aspect-ratio swept wing, with high wing loading (134 lb/ft^2). The conventional takeoff and landing performance associated with this small wing area (134 ft^2) would require speeds in excess of 200 knots if not taken care of by the VTOL capability. The program initially was a joint effort with Fiat of Italy and VFW of Germany in 1964; Italy withdrew in 1968 for several reasons, one of which was their preference for a tricycle landing gear design instead of the tandem (bicycle) type main landing gear pursued by VFW. The first flight was made in September 1971 and first transition in October 1972. Good precision for spot hovering and low pilot workload were achieved OGE due in large measure to the excellent attitude-command control system. Hover IGE was unsteady due to recirculation and hot-gas ingestion. A positive fountain impingement produced a noticeable cushion in descents at a gear height of 10 ft. A negative (suck-down) induced flow effect of about 2% persisted OGE in hover. Nonlinear pitch-attitude response was objectionable in hover; this occurred as a result of mixing thrust modulation of the lift engines with reaction bleed air forces. In addition, hovering in a tailwind caused hot-gas ingestion which commanded reduced thrust on the front lift engine for balance, creating pitch and height control coupling. Because of serious ground erosion caused by the high-temperature, high-velocity jet efflux, vertical takeoffs were not allowed from the concrete runway area; instead rolling takeoffs were made by starting the lift engines during the takeoff roll. This procedure resulted in a high pilot workload and would not be acceptable operationally. The (overload) STOL capability was very poor because no favorable induced flow over the wing existed and the ram drag (flow turning) through the lift engines was large. During takeoffs, in the speed range between 30 and 40 knots, the lift-engine exhaust could be ingested into the cruise engine inlets, depending on the position of the cruise-engine nozzles. In addition, a pitch-up was encountered in the speed range of 20-80 knots requiring about 50% of the pitch-control power for trim. This was not a workload problem for the pilot since the attitude command control system automatically compensated. Aircraft experienced high dihedral effect in low-speed sideward flight, limiting crosswind operation to 15 to 20 knots. In one case the SAS completely saturated roll command leaving the pilot with no maneuvering control power. In transition, the cruise-engine nozzle angle, lift-engine power, and aircraft angle of attack could be varied over a wide range with minimum control management efforts; however, at nominal gross weights, acceleration performance in the upper transition speed range was barely adequate due to the high induced drag associated with the low-aspect-ratio swept wing, the large momentum drag due to lift engine flow turning at the relatively high required transition speeds (over 200 knots), and less than rated thrust available from the cruise engine. Although closing the lift engine doors reduced drag to improve forward acceleration, this could not be done until after the lift engines had cooled down. In high-speed conventional flight, handling was rated satisfactory out to the allowed limit of 300 knots, beyond which further flutter clearance was needed. Although conventional takeoffs were not attempted due to the concern for pitch-up after leaving the ground reaction moment, a conventional landing was successfully made in an emergency caused by a lift engine malfunction.

There was considerable preflight preparation for this concept, including wind-tunnel tests; sonic and thermal-load distribution static structural testing; an iron-bird control system rig; a telescope (pedestal) test apparatus; and a five-engine hover rig capable of free-flight hover. From an overall standpoint, the VAK-191B was designed well; however, in retrospect, several concept questions remain, foremost of which is the serious performance penalty associated with losing any of the three engines, and the lack of high supersonic potential by virtue of the limited cruise-engine thrust.

YAKOVEV YAK-36 (Forger) Lift Plus Lift/Cruise

Evolved from the VTOL 1967 "Freehand" delta wing concept, the YAK-36 strike/reconnaissance aircraft first appeared on the Russian Kiev carrier/cruiser in 1976. The midset wings are small in area by virtue of the VTOL capability, having 45° sweep, considerable anhedral (to reduce positive dihedral effect). Wings fold upward for stowage. No leading-edge devices are used; however, low-speed performance is improved by a large Fowler-type flap. Gross weight is about 22,000 lb. Main engine is a Lyueka AL-2H-3 turbofan of about 18,000 lb dry thrust exhausting through a single pair of vectorable nozzles aft of the wing. Two Kalieson lift engines (about 6,000 lb thrust) installed in tandem in the fuselage aft of the cockpit provide pitch balance for hover and low-speed flight. Ram drag is reduced slightly by virtue of tilting the lift engines aft. A positive fountain effect should result from the flow reflection of the three engines, although hot-gas ingestion may also occur for some operating conditions. Hover and vertical takeoffs appear satisfactory with minimum upset tendencies observed. This concept undoubtedly would have an inherently large positive dihedral effect, limiting crosswind operation. Landings appear to be precisely controlled with no apparent effort to hurriedly set it down on the deck to avoid hot-gas ingestion. Although no STOL or RTO operations have been observed, some moderate STOL potential is inherent in the favorable induced flow from the main-engine exhaust in the proximity of the Fowler flap, offset somewhat by the ram drag of the lift engines. Transition characteristics would be expected to be similar to those of the VAK-191B, lacking a wide speed transition corridor. High-speed flight potential is good by virtue of clean aircraft configuration (low fineness ratio). Only slightly supersonic capability is estimated because of limited cruise-engine thrust.

Bell XV-15 Advanced Tilt Rotor

The XV-15 research aircraft was developed under U.S. Army and NASA funding as a modern version of the Tilt Rotor XV-3 concept. Powered by two Lycoming LTC 1K-4K engines rated at 1800 shaft horsepower, it first hovered in May 1977. Two interconnected 25-ft-diameter three-bladed rotors are used with a blade twist of 45° from root to tip. Hover and low-speed control obtained from collective and cyclic blade angle changes. Ground-handling characteristics include some tendency to lean into the turns due in part to the narrow gear; a tight turn may be limited by "bottoming out" differential cyclic control. Hover characteristics similar to other tandem rotor helicopter configurations in that wind direction does change rotor-span loading somewhat; however, this detracts very little from hover precision. Hover envelope of 25 knots sideward and 10 knots rearward has been explored with no handling-qualities limitations. There is an unsteadiness hovering close to the ground which disappears above wheel height of 6-12 ft. SCAS provisions by a three-axis rate-damped system greatly reduce pilot workload. Attitude retention features in pitch and roll do not appear to help hover precision. Transition to conventional flight is easily accomplished with a wide speed and power "bucket" and good (0.4 g) acceleration capability. Trim changes are small and stability and damping are adequate to minimize unwanted flightpath excursions.

In conventional flight a unique aircraft longitudinal response (which has been called "chugging") occurs in gusty air. Attributed to gust-induced angle of attack changes on the propeller blade. No undesirable limits in stability or damping (which restricted high-speed flight in the XV-3 aircraft) have appeared to speeds of 300 mph. Stalling behavior mild with ample warning and no roll-off. In event of an engine failure, the aircraft can be either landed at low speeds with the propellers windmilling or brought to a hover-type landing in an autorotative mode. Engine-out hover performance is not possible. Reconversion characteristics permit slow or fast decelerations with adequate descent rates and a wide speed corridor. A variable tilt rate for the rotors would appear to enhance operational flexibility.

This concept has shown the best potential for combining good hover performance with reasonable cruise efficiency. The favorable flight performance is due in part to the large-scale (40- by 80-ft) wind-tunnel tests of the complete airframe. It remains to be seen if the relatively complex propulsive system can achieve a low-cost maintenance record and high reliability.

3. CONCLUDING REMARKS

In spite of the many problem areas revealed in these summaries of V/STOL aircraft, the information accumulated from the design, development, and flight evaluations has provided a useful data base for future V/STOL designs. It is of interest to note that even though most of the aircraft were deficient – to some degree – in terms of aerodynamics, propulsion systems, or performance – it was always possible to develop special operating techniques to circumvent these problems. For the most part, this review would indicate that performance and handling-qualities limitations severely restricted operational evaluations for all types of V/STOL concepts. It has become quite obvious that V/STOL aircraft must be designed with good STOL performance capability to be cost effective, a virtue not shared by many of the aircraft covered in this review. Further, flight experience has shown that good handling qualities are needed, not only in the interest of safety, but also to permit the aircraft to carry out its mission in a cost-effective manner. It was apparent also that SAS was required to some degree for safely carrying out even simple operational tasks. The question of how much control system complexity is needed for various tasks and missions is still unanswered. Another area deserving of increased attention derives from the fact that most of the V/STOL aircraft studied suffered to some degree adverse ground effects. In this regard better prediction techniques are needed to avoid costly aircraft modifications or restricted operational use of the V/STOL concepts. Finally, there is an important continued need for good testing techniques and facilities to ensure satisfactory performance and control before and during flight testing.

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16. Abstract

For over 25 years a concerted effort has been made to derive aircraft that combine the vertical takeoff and landing capabilities of the helicopter and the high cruise speeds of conventional aircraft. During this time, over 60 V/STOL types have been studied and flown with varying degrees of success. The requirements for satisfactory characteristics in several key technology areas are discussed and a review is made of various V/STOL aircraft for the purpose of assessing the success or failure of each design in meeting design requirements. This survey shows that in spite of many problems revealed, special operating techniques were developed to help circumvent deficiencies. For the most part performance and handling qualities limitations restricted operational evaluations. Flight operations emphasized the need for good STOL performance, good handling qualities, and stability and control augmentation. The majority of aircraft suffered adverse ground effects. There is a continued need to update and improve flight test techniques and facilities to ensure satisfactory performance and control before and during flight testing.

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