Journal of Aircraft

VOLUME 6 JULY-AUGUST 1969 NUMBER 4

VTOL—1968

AIAA VTOL Systems Committee

Lifting Systems

THE basic characteristic of any VTOL aircraft is its ability to hover and maneuver at low airspeeds. The most important parameter related to the hovering performance of a VTOL aircraft is the disk loading (vertical thrust per unit of actuator disk area) which characterizes its lifting rotors, propellers, fans, jets, or other devices. This parameter is the principal determinant of the power required in hovering flight, which, in turn, usually establishes the total installed power required for a given design.

A primary concern of any VTOL lifting system is the associated stability, control, and handling qualities in various flight conditions and maneuvers. The characteristics of helicopter rotor systems and fixed wings are well known; however, the characteristics of some proposed VTOL lift systems are not as well defined.

Fundamental Considerations

Vertical lift principles

Disk loading establishes the size of the vertical lift device and, therefore, affects the size of the aircraft, fuel consumption, downwash velocity in hover, and translational flight characteristics. The typical helicopter has a disk loading of 5 to 15 psf, the propeller-lifted tilt-wing VTOL has a disk loading up to approximately 50 psf, whereas jet and lift-fan VTOL types may have effective disk loadings up to 500 psf or higher.

Influence on vertical lift system design

Figure 1 shows the trend of optimum disk loading with hover time for a VTOL mission. The effects of design disk loading on installed power requirements, Fig. 2, show that low disk loadings are more efficient in terms of power required to lift a given weight.

Secondary profile power losses account for approximately 30 to 40% of the power required to hover. Proximity to the ground, or ground effect, usually decreases induced power. Other factors that affect performance of a lifting system are tip losses, root losses, interference, and vertical drag.

Lift in forward flight

As the VTOL aircraft moves into forward flight, the induced power required decreases, since a larger mass of air is encountered, and the induced velocity that must be imparted to the air is smaller. At higher speeds, power must be supplied to overcome parasite drag as well as rotor lift and drag forces.

This VTOL state-of-the-art paper was prepared by the VTOL Systems Committee. It is based on a series of papers which together were too lengthy for presentation at a technical session. The digest prepared by the editors is intended to meet the time restrictions of a technical session and yet fairly represent current conditions. It offers a hazy yet considered view of the future and considers the technological base, the missions required, and the operational environment. Many proposed concepts and configurations were omitted simply due to space limitation and not to lack of technical excellence. Several problem areas are identified, suggesting that some development or research is advisable. Hopefully, the technical precepts set forth will serve as a good guide to those interested in VTOL aircraft systems.

The paper was edited by Ralph B. Lightfoot, Engineering Manager—Production, Sikorsky Aircraft Division of United Aircraft Corporation, Stratford, Conn. and William T. Immenschuh, Technical Director, Ryan Aeronautical Company, San Diego, Calif. Principal contributors were Robert Lichten and Robert Foster, Bell Helicopter Company; Harvey Nozick, General Electric Company; John Buehler, The Buehler Corporation; Norman Taylor, The Boeing Company, Vertol Division; Jack Ford, North American Rockwell Corporation; Dr. E. R. Wood, Georgia Institute of Technology; Dr. K. Hohenemser, Washington University; Lawrence Kaufman, Teledyne Systems Company; Paul Theriault, Lockheed-California Company; Charles Kuehne, U.S. Air Force; Paul Williams, WOFAC Corporation; Robert Decker, Sikorsky Aircraft; Franklin Kurt, Grumman Aircraft Engineering Corporation; Theodore Dumont, Sikorsky Aircraft; Robert Stange, U.S. Army; Mrs. Joan Barriage, Federal Aviation Administration; Clarence Belinn, Los Angeles Airways, Inc.; and John Borger, Pan American World Airlines.

Presented as Paper 68-977 at the AIAA 5th Annual Meeting and Technical Display, Philadelphia, October 21–24 1968; submitted October 3, 1968.

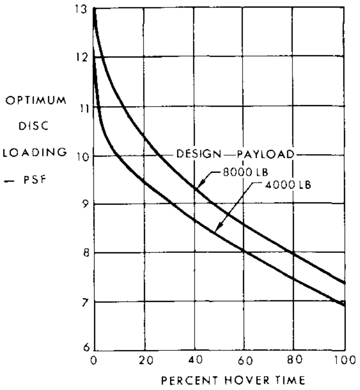

Fig. 1 Effects of required hover time on disk loading for minimum takeoff gross weight. Single-rotor helicopter optimum disk loading for minimum gross-weight, 4-hr mission; hover out-of-ground effect for $x\%$ time, cruise at 150 knots for remainder.

Some VTOL aircraft are equipped with wings to supplement the lift produced by the VTOL system when in translational flight. The sharing of lift between the vertical lift system and the wing must be achieved over a wide range of c.g. position, speed, flight-path direction, and ambient conditions. The wings assume all the lift in high-speed flight of those machines designed for speeds in excess of 300 knots.

Rotors

Types

The three types of rotors in general use are the fully articulated, the seesaw or semirigid, and the hingeless or rigid. The fully articulated rotor is designed to minimize dynamic coupling between components of blade motion. Characteristics of this sytem are: 1) blade root moments are small, 2) vibration can be alleviated by varying the number of lightweight blades to avoid fuselage resonance, 3) the articulating hinges can be offset from the center of rotation to produce large control moments, thus permitting large travel of the center of gravity and fuselage stability feedback to the rotor, and 4) lead-lag dampers are usually required to avoid mechanical instability.

The semirigid rotor system has blades rigidly connected to a hub which is gimbal-mounted to provide angular freedom relative to the fuselage. Features of this sytem are: 1) blade centrifugal force is not carried by the flapping bearings, 2) two-bladed versions are mechanically simple, and 3) rotor rigidity avoids mechanical instability.

The rigid rotor can be the simplest system mechanically since it requires no hinges. Features of this sytem are: 1) high control power, 2) rapid control response, and 3) reduced blade-to-airframe clearance requirements. However, the rigid rotor is subject to high structural loads and imparts large steady and vibratory moments to the airframe due to severe blade bending under maneuvering, high speed, and "off-design" c.g. locations. Therefore, it tends to be heavier than the other systems.

Configuration

The most familiar rotor configuration is the single main rotor with antitorque tail rotor arrangement. The advantage of this type is the relative simplicity, with the saving in weight compensating for the small power loss due to the tail rotor. The tandem rotor configuration offers the advantage of large fuselage volume. Disadvantages are high transmission and shafting weight and a loss in efficiency in forward flight. The side-by-side configuration is more efficient in forward flight, because of the aspect ratio effect, but suffers from fuselage drag and/or high structural weight. This configuration also requires extensive gearing and shafting. In the coaxial machine, the net rotor torque is largely eliminated by using two superimposed rotors, rotating in opposite directions. The coaxial design offers the advantage of compact over-all dimensions defined only by the rotor diameter and the directional control configuration. The rigid rotors, hub, and controls become more complex. Intermeshing rotors are essentially equivalent to a side-by-side design with a high degree of overlap and are quite similar to coaxial types. Some lifting efficiency is sacrificed for compactness and transmission simplifications.

The proposed variable-diameter rotor is extended to its full diameter for hovering at a low disk loading. For high-speed flight, the rotor is retracted to its minimum diameter and is unloaded by a wing and auxiliary propulsion. The retracted rotor can be rotated 90° and used as a propeller. The blade retraction-extension system adds a degree of mechanical complexity.

Rotor aerodynamics

New airfoil and planform shapes are being developed to improve lift and drag characteristics. Thin airfoil sections can be used at the rotor tip where high Mach numbers are encountered.

Propellers and Proprotors

Since lifting propellers are normally designed for high-speed flight, the resulting hovering disk loading is high, precluding autorotation. Lifting efficiency is poor, as shown in Fig. 2, resulting in high fuel consumption and undesirable downwash velocities. The proprotor is a large-diameter propeller with lower downwash and design compromises to increase the autorotational and lifting efficiency. If the tip speed in the propeller mode is reduced to approximately half of the hovering tip speed, the propulsive efficiency approaches that for conventional propellers.

Fans, Ducted Fans, Shrouded Propellers

The aerodynamic characteristics of lift fans mounted externally or faired into fixed wings have generally acceptable characteristics. Since they are not capable of autorotation, appropriate wings or multiengine installations are required for flight safety.

Direct-Lift Jets and Augmented Jets

Pure or augmented jet engines can be used for lift either by diverting the exhaust downward or by mounting the engine vertically. In either case a multiengine installation is required to minimize the effect of loss of an engine.

Combinations with Wings

All of the lift systems can be combined with wings to unload a rotor in forward flight and relieve stall and compressibility effects. The speed potential can be increased further with auxiliary propulsion. The tilt proprotor transfers all of the lift to the wing in high-speed flight and then continues as an airplane with the proprotor serving as a propeller. Stop-

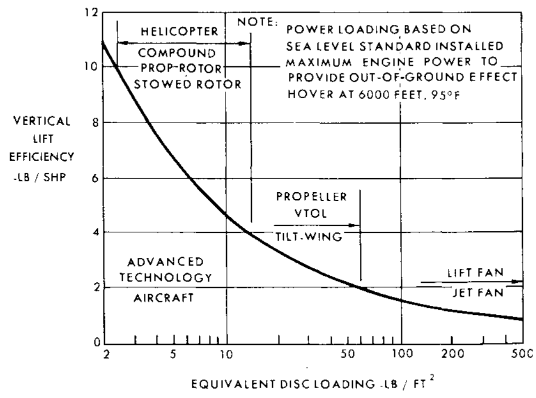

Fig. 2 Hovering lift efficiency (power loading) variation with design disk loading.

pable rotor systems also transfer all lift to the wing in high-speed flight, using auxiliary propulsion for forward flight. After the rotor is stopped, it can be feathered, faired, or retracted to reduce its drag, indicating the speed potential of a fixed-wing airplane. The lifting fans may be independent of the wing and rotate 90° for propulsion in high-speed flight. Alternatively, the fans may be buried in the wing and faired over for high-speed flight with an auxiliary system for propulsion. The direct jet lift devices with a wing are similar to the fan combinations.

Propulsion

The sustained installed lift-to-takeoff weight ratio in any realistic VTOL design is 1.2, with loadings as high as 1.6 under consideration to include reserve for maneuvering control and altitude operation. Advanced propulsion technology will contribute to the development of more efficient helicopters as well as other useful and economically sound VTOL designs.

Trends and Projections

In the following brief discussion it is convenient to consider lift and cruise propulsion separately.

Lift engines

In the lift mode, the engines of greatest interest are the turboshaft, direct-lift turbojet, direct-lift turbofan, and the pneumatically or mechanically coupled lift fan.

Turboshaft

The turboshaft engine is used primarily in a helicopter drive system. Current turboshaft engines of reasonably high cycle pressure ratios have a power-to-weight ratio ranging from 4 to 6, Fig. 3. In the higher-horse-power range, power-to-weight ratios approaching 7–9 are feasible. Improvements in power-to-weight ratios have resulted from combinations of advanced aerodynamic design, improved materials, and increased turbine inlet temperature. Turbine inlet temperature has increased an average of 35–40° per year. Increased reliability and further growth in output per pound of air are foreseeable through continued advancements in cooling techniques. Use of titanium and composite materials has resulted in reduced engine weights, whereas improved aerodynamic and mechanical design of components contribute to lower weights by reducing the number of turbomachinery stages required for a given engine cycle. The band indicated in Fig. 3 reflects variations in design parameters as well as size effects. The larger engines of high pressure ratio will generally employ axial flow compressors, whereas the smaller engines may require mixed flow compressor design because of practical limits of clearance control. Advancements in temperature, materials, and design will also improve the SFC characteristics of advanced engines. Specific fuel consumption trends for turboshaft engines are shown in Fig. 4.

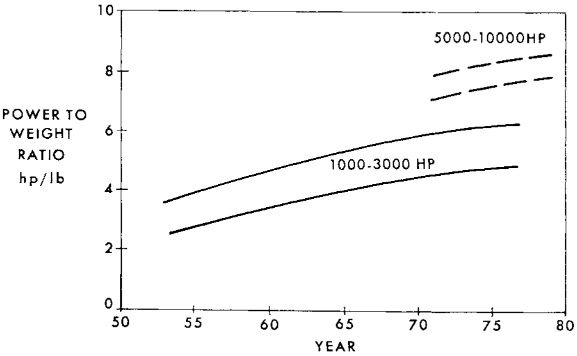

Fig. 3 Turboshaft power/weight ratio vs year of model qualitative test.

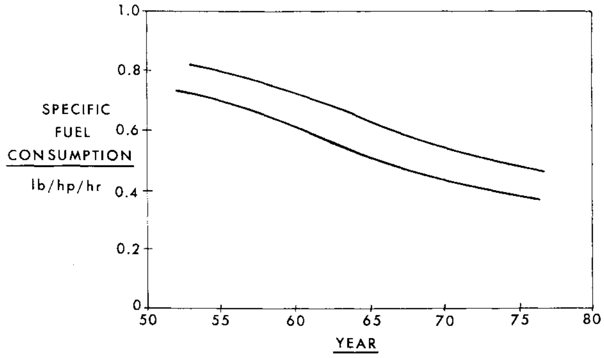

Fig. 4 Turboshaft engine specific fuel consumption vs year.

The weight trend for transmission gearing, Fig. 5, indicates that light weight and high efficiency (97%) of this type of gearing make it superior to other methods of energy conversion for most applications.

Direct-lift turbojets

As an indication of the potential of direct-lift turbojets, Fig. 6 shows a predicted trend of thrust/weight through 1980. The high thrust/weight ratios look promising, particularly for supersonic aircraft for which the requirement for hover flight time would seem to be minimal on the order of one minute. This short-time hover requirement (due to fuel limitations), coupled with the noise and exhaust velocity implications, has lessened enthusiasm for direct lift-turbojets in recent years.

Direct-lift turbofans

Emphasis is currently being focused on direct-lift turbofans despite a less favorable thrust/weight ratio, Fig. 7. The recognition of more realistic hover requirements has led to study of turbofans with bypass ratios of 8 to 1, resulting in specific fuel consumption values approaching 0.4 lb/lb-hr. The high-bypass-ratio fan design offers a potentially better (although not necessarily acceptable) noise solution. It may be necessary to adopt a coaxial fan turbine gear transmission, provided the thrust-to-weight ratio remains competitive.

Lift fans

The fourth lift propulsion element is the gas coupled lift fan used on the U.S. Army XV-5A research aircraft. The general characteristics foreseen for the lift fan suggest an applicable bypass ratio range of 6 to 12, fan pressure ratios of 1.1 to 1.4, and specific fuel consumptions ranging from 0.30 to 0.40 lb/-lb-hr, depending on the exact cycle and design selected. The lift/weight characteristics of the lift fan are shown in Fig. 8.

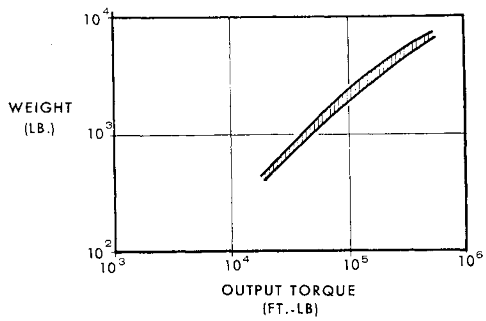

Fig. 5 Helicopter main transmission weight-torque relationship.

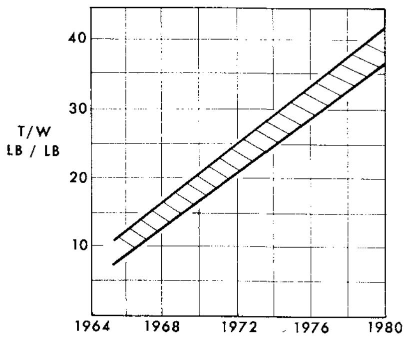

Fig. 6 Lift turbojet engine thrust/weight vs year.

Geared lift fans have also been studied for weight, mechanical complexity, and fuel consumption tradeoffs.

Cruise engines

In the cruise mode, the turboprop, turbojet, and turbofan engines are of interest. Developments in turboshaft technology as discussed previously would apply equally to the turboprop engine.

Although the turbojet as a cruise engine for subsonic applications is generally considered less attractive than high-bypass-ratio turbofans, modern turbojet cycles may be competitive on an engine weight and fuel-burned basis for short ranges, particularly at high subsonic speeds.

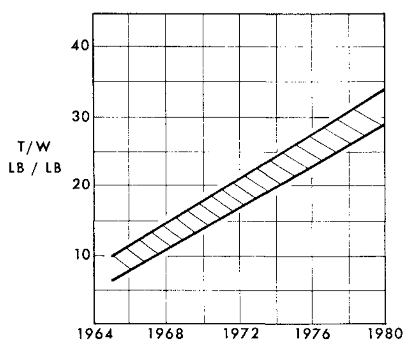

Fig. 7 Lift turbofan engine thrust/weight vs year.

Where significant cruise legs are essential in the aircraft mission, the high-bypass turbofan offers significant improvements in specific fuel consumption. Figures 9 and 10 show the projected trends for both turbojets and turbofans at static conditions.

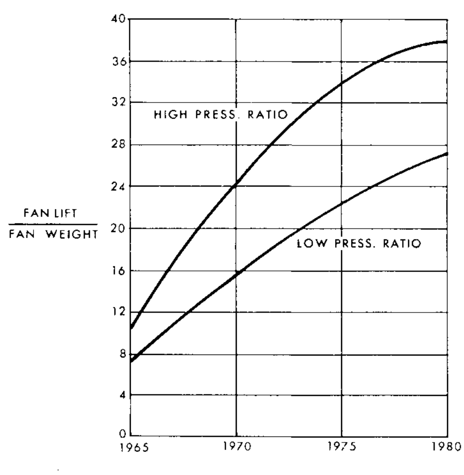

Fig. 8 Lift-fan thrust-to-weight vs year.

Table 1 Design considerations

● Thrust match	● Product cost
● Hover SFC	● Availability
● A/C control	● Simplicity
● VTOL site preparation	● Maintainability
● VTOL noise levels	● Reliability
● Installation penalties	● Vulnerability
● Engine-out safety	● Ground effects
● Development cost	

Other Propulsion Systems

Convertible engines, which provide shaft power for rotary wing takeoff and thrust for cruise with the rotor stopped and/or stored, are currently in the intial concept stage. Although tip jet propulsion appears to eliminate the transmission, some gearing is needed for control, and the theoretical jet efficiency is not obtained, due to the fluctuating tip velocity in forward flight, high fuel consumption, noise, and poor aerodynamic efficiency.

Other Design Factors

Of paramount concern to VTOL operation is the need for rapid lift and power response. The demand for full power in less than 0.3 sec without instability is not unusual.

The aircraft designer must also consider the desired performance and operating characteristics when one engine suddenly becomes inoperative, especially on a hot day at altitude in a confined area. This normally requires multiple power plants totaling 50% more power than required under standard conditions with all engines operating.

Other significant propulsion design considerations are summarized in Table 1.

Airframe Structure

Structures effectiveness depends upon 1) percentage of aircraft weight attributed to structure, 2) manufacturing cost, and 3) maintenance and reliability.

Weights

Helicopter airframe weight remains approximately 12% of total weight, even though helicopters are flying at higher speeds, with less vibration and improved safety. Trends in component and system weights are illustrated in Fig. 11 for the crane configuration. The designer is generally guided by four requirements: strength, stiffness, resonant frequencies, and minimum practical sizes. Weight will be reduced by use of new materials, such as titanium, boron, and beryllium.

Manufacturing Costs

The average manufacturing cost of helicopters is similar to the cost of World War II fighters, as indicated in Table 2. The trend in manufacturing costs with respect to size is shown in Fig. 12.

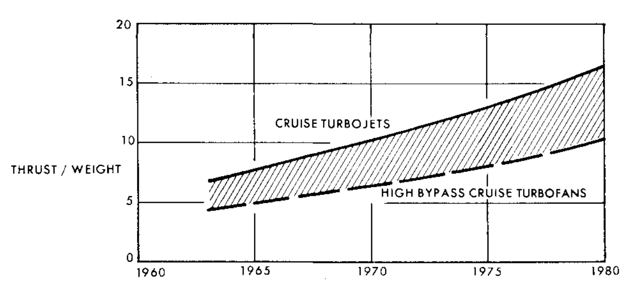

Fig. 9 Cruise engines thrust/weight projection vs year sea-level static takeoff.

Table 2 Manufacturing costs

Quantity of aircraft	10	100	1000
Manufacturing man hr/lb fighters	11.5	4.8	2
Helicopters	10	4.5	2.5

Maintenance and Reliability

For both the airplane and the helicopter, the airframe accounts for about 14% of the maintenance. Because of the vibratory environment in most VTOL aircraft, materials must have the highest degree of resistance to fatigue.

The designer has a limited choice of materials when considering fatigue and crack propagation. On an equal weight basis for the time to fracture, Table 3, titanium is 75% better than aluminum and approximately 250% better than steel.

Current and Future Design Practices

In primary tension applications, 2024 aluminum is used because of its superior fatigue performance, fracture toughness, and slow crack propagation rate. Structural fiberglass is corrosion-free, has good fatigue resistance, and is easily repaired. Vacuum-melted steel increases fracture toughness appreciably and improves reliability. Flashless closed-die forgings are preferred and should be examined metallurgically to insure the greatest structural integrity.

Dynamic and Aerodynamic Characteristics

Rotary Wing Aircraft (up to 15 psf Disk Loading)

Achieving greater speed, range, and payload at lower costs and with better crew environment entails new solutions related to the dynamic and aerodynamic characteristics of the rotorcraft. Higher disk loading (approaching 15 psf) increases downloads on the fuselage. As the number of rotor blades is increased, a blade is more likely to encounter vorticity shed by the preceding blade, leading to aerodynamic losses and interference, particularly in the blade tip region.

Blade-vortex interaction is a major source of vibratory excitation to both blades and fuselage, Fig. 13. Excitation originates in the flowfield, where the primary contributor is the strong tip vortex left by each blade. The succeeding blade passes near this vortex resulting in an inpulse-type loading. Since the blade is restrained at the root, the blade response results in root forces which feed from the rotor head into the fuselage as vibratory shears and moments.

The asymmetrical lift produced in forward flight causes all orders of harmonic loading on the blades. The dynamic pressure q at a particular blade station varies as $(\Omega r + V\sin\psi)^2$. The angle of attack, in turn, contains all orders of blade flapping as well as steady and first-harmonic pitch change. The loading resulting from the product of angle of attack and q consequently contains significant higher (2nd–6th)-order forces which must be predicted if vibration and stresses are to be controlled.

Optimum rotor efficiency is obtained when the advancing blade operates just below critical Mach number and the retreating blade operates just below stall. This requires rotor unloading or reduced rotor speed and increased solidity. The inherent fluctuating loads in the rotor system are largely attenuated by the hinged rotor blade. For chordwise design of hingeless systems, tuning is especially important due to the possibility of detrimental coupling of the inplane modes. For the hinged blade, maximum vibratory moments generally occur at about $\frac{2}{3}$ blade radius, and maximum centrifugal stress at the blade root. The hingeless blade does not have this separation of design points; both maximum steady and maximum vibratory stresses occur at the blade root.

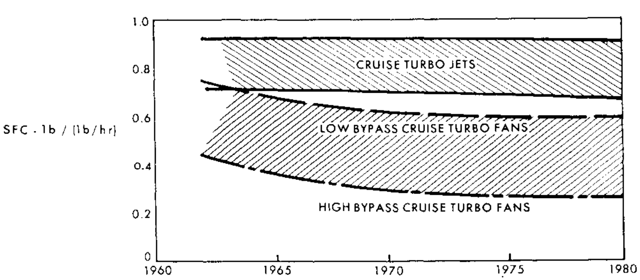

Fig. 10 Cruise engines specific fuel consumption projection vs year sea-level static takeoff.

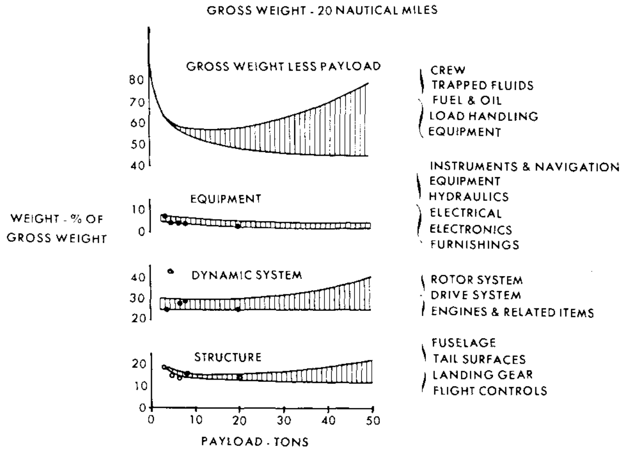

Fig. 11 Weight trends.

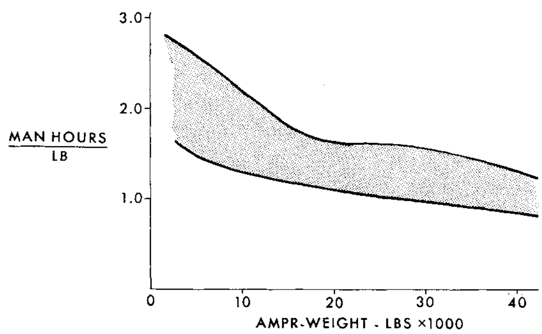

Fig. 12 Manufacturing cost (man hours/lb).

Helicopters

Forward speeds of helicopters are limited by increasing dynamic loads and vibrations, by a loss of propulsive force, and by a loss of controllability due to the increasingly asymmetric disk loading as the rotor advance ratio is increased. By reducing fuselage drag and using more blade area despite

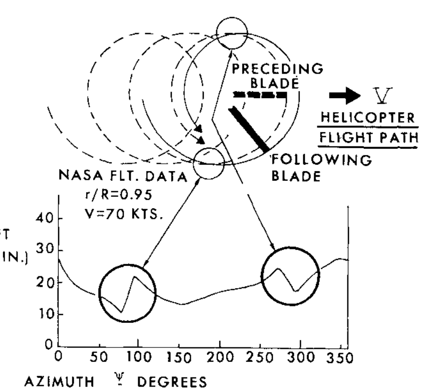

Fig. 13 Vortex interaction.

Table 3 Relative fatigue and crack propagation characteristics of materials[a]

	% endurance limit	Time of fracture referred to aluminum
Steel	65.2	0.72
Aluminum	100.0	1.00
Titanium	38.3	1.75

[a] Relative stress (% of endurance limit) in equal weight components and relative time to fracture from a $\frac{1}{8}$ initial crack size.

a penality in hover efficiency, a continuous forward speed of 180 knots becomes feasible.

Vibration can be reduced to acceptable levels by such methods as 1) dynamically and aerodynamically balancing blades and rotors, 2) unresponsive matching of airframe dynamics to rotor system dynamics, 3) dynamic isolation of rotor systems and transmissions, and 4) incorporating tuned dynamic absorbers on rotors and/or fuselage.

Compound helicopters

By adding a fixed wing which unloads the lifting rotor in forward flight and adding auxiliary propulsion, a further increase in forward speed is achievable. Although the fixed wing is beneficial in level flight, it is detrimental in hover and in climb because it then produces vertical drag rather than lift. A continous forward speed of 250 knots is considered feasible with a basic compound helicopter.

Studies and flight tests of compound helicopter designs have shown several important advantages. Blade vibratory stress and vibratory control loads at high forward speeds are markedly reduced as the lift and thrust of the rotor system are reduced. The additional lift of the wing and the auxiliary propulsion system also provides for improved performance under maneuvering and gust conditions.

Composite aircraft

In a basic compound helicopter, rotor pitch and roll control is retained in the entire flight regime using normal rotor speed. In a composite aircraft, cruising flight is performed in airplane fashion with airplane-type lift, propulsion, and controls. The lifting rotor can either be idled or stopped and positioned as a fixed wing, or it can be stopped, folded, and possibly retracted.

Idling rotor

In cruising flight, the rotor speed of the composite aircraft-idling rotor is $\frac{1}{2}$ or less of the rotor speed used in the helicopter. To avoid large dynamic blade loads, the idling rotor must be equipped with a mechanism to prevent buildup of rotary wing lift in gusts and maneuvers. The idling rotor requires high bending and torsional blade stiffness to allow large advance ratios without aeroelastic instability. A continuous forward speed of 300 knots is considered feasible with an idling rotorcraft.

Stowed rotor

Aeroelastic instability and excessive reversed flow is avoided in the stowed rotor. Conversion can be performed at relatively low flight speed with adequate aeroelastic stability margin. In principle, therefore, the stowed rotor is the most desirable composite. Once the rotor is folded, it may be stowed within the aircraft contour, thus indicating speed potentials of fixed-wing aircraft including supersonic flight.

Proprotor

The main aerodynamic requirement of the proprotor is to combine good rotor efficiences in helicopter flight with good propeller efficiencies after conversion. A reasonable compromise is achievable by reducing rpm in proprotor flight as compared to helicopter flight. Another aerodynamic compromise concerns the blade twist, since different optimal values exist for proprotor and helicopter flight. Dynamic conditions in proprotor flight require the suppression of excessive flapping in gusts and maneuvers, with negative pitch and yaw damping and the associated whirl instability, and with flap-lag aeromechnical instability.

Proprotors are configured for the side-by-side configuration, yielding an aerodynamic span effect. However, the wing blocks part of the slipstream, leading to vertical drag. 350 knots continuous forward speed is considered feasible with proprotors.

Based on a takeoff hovering capability out-of-ground-effect at 3000 ft and 90°F ambient temperature, weight-empty over takeoff-weight ratios for gear-driven rotors range from 0.50 for the pure helicopter to about 0.70 for the stowed rotor aircraft, with the idling rotor and the proprotor aircraft having intermediate values.

Tilt-Wing VTOL Aircraft (15 to 50 psf Disk Loading)

With the tilt wing submerged in the propeller slipstream, stall may be avoided at large angles of attack. A critical flight condition exists in partial power descent. At a given wing setting, the flight speed range is quite limited. Acceleration and deceleration must be performed by operation of the wing tilt mechanism.

Because of its higher propeller disk loading, the tilt-wing VTOL aircraft requires installation of greater engine power per pound of aircraft weight, with correspondingly high fuel consumption in hover. Dynamic response loads due to transient and steady-state excitation must also be taken into account. Tilt-wing VTOL have shown outstanding short-field takeoff performance with overloads, and cruising speed extends to the maximum speed practical for propeller operation of about 400 knots.

Propeller and Fan VTOL Aircraft (50 to 200 psf Disk Loading)

Because of the more intensive downwash of propeller and fan-type VTOL aircraft, such aircraft must hover at greater heights above the ground than the lower disk loading rotorcraft. Their "critical height" region (the height below which the aircraft cannot be recovered safely after failure of one engine in hover) extends to several hundred feet above ground. By contrast, the critical height region of multi-engine helicopters may be zero.

Characteristic of most propeller and fan VTOL aircraft are the interconnecting drive shafts to transmit power from all engines to all propellers and fans. For this application it is desirable, in order to transmit more power for less weight, to use high-speed, lightweight, hypercritical-speed shafts in which the drive shaft is operated above its fundamental critical speed.

Lift-fan VTOL aircraft

The lift and thrust characteristics of lift fans will vary as a function of disk loading, fan area to wing area relationship, exit louver position, ram drag, and transition velocity to fan flow velocity, i.e., crossflow velocity ratio. All of these ultimately affect the net lift, horizontal thrust, and power requirements, which are allowable or required to produce lift in excess of aircraft weight and a velocity beyond the conventional stall speed of the aircraft to insure conversion from fan-supported flight to wing-supported flight.

In well-matched lift and cruise propulsion systems, VTOL and hover are obtained with the same jet engine output necessary for the thrust required for conventional flight at maximum cruise speed. This permits smaller, less costly engines and results in lower hover fuel consumption. Fan installations can take many forms in addition to fan-in-wings, such as fold-out fuselage fans and platform fans on wings or fuselages.

With effort to develop thinner fans or configurations to retract fans, supersonic VTOL aircraft are considered feasible.

Hot gas distribution, duct sizing, valve leakage, and system volumetric considerations require careful attention in these configurations.

Lift-Cruise Fan VTOL Aircraft

Multiple use of the high-bypass fan technology for both vertical lift and cruise propulsion leads to attractive configurations for large transports. Both gas coupling and shaft coupling methods are under development. More uniform axial fan inflow reduces dynamic and aerodynamic considerations and, as in all fan systems, the rpm is low as related to turbine compressor technology.

Jet VTOL Aircraft (High Disk Loading)

Direct-lift jet VTOL aircraft, such as in military fighter aircraft, have the highest acceptance when mission hovering time requirements are minimized. Combinations of direct-lift engines and deflected thrust of the primary propulsion systems have been developed, with the direct-lift engines shut down for cruising flight. High ground impingement velocities with attendant high gas turbine temperatures further limit hovering times close to the ground unless prepared sites are used. Arrangements must accommodate engine-out cases, and installed volumetric considerations must receive special design attention.

Acoustic

No discussion of VTOL aerodynamics and dynamics would be complete without emphasizing the important design considerations which must be given to acoustics. Each type of VTOL aircraft will have its own sound signature. For both military and civil applications, engineering efforts must be directed to reduce this signature to an acceptable noise level.

In general, for VTOL aircraft, aerodynamic noise constitutes the major contributor to the external noise field. In particular, certain tip speed and power combinations can yield significantly high sound pressure levels and, if sufficiently high, can cause the structure to respond dynamically and ultimately reduce structural life.

VTOL Control Systems

Flight control systems enable pilots to maneuver in six degrees of freedom. Requirements related peculiarly to VTOL aircraft are as follows: 1) adequate control power throughout the flight envelope, especially hovering, 2) adequate damping in relationship to control power for statisfactory handling qualities, 3) simple control system to transform pilot inputs to control device outputs, 4) boost actuators to handle the actual control loads, 5) trim devices for furnishing desired

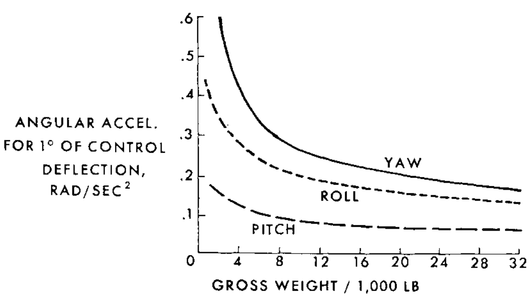

Fig. 14 Minimum angular acceleration capability for visual flying.

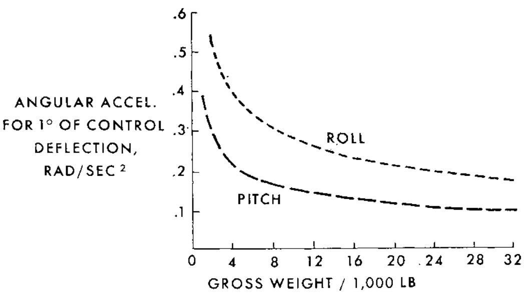

Fig. 15 Minimum angular acceleration capability for instrument flying.

feel characteristics, 6) automatic features to exploit useful VTOL flight characteristics.

The helicopter is probably the only VTOL is which these requirements have been resolved sufficiently to permit an operationally useful vehicle. In almost all other VTOL configurations developed to date, one or more of the foregoing problems has either remained unsolved or, at best, been marginally covered.

Control Power Requirements

The VTOL control system must produce control moments down to zero forward velocity, and even at modest rearward and sideward velocities. The criteria for control power requirements, Specification MIL-H-8501A, written initially for helicopters, established boundaries for control power requirements for three main classes of helicopters in terms of gross weight. Stability requirements in terms of response to pulse inputs about the three rotational control axes suggested by Tapscott are shown in Figs. 14 and 15.

Damping

Adequate damping is a corollary requirement to control power, Fig. 16. Some damping is inherent in the helicopter. Increased damping is obtained by synthetic feedback of vehicle motion and transformed into a damping moment.

In early helicopter designs, synthetic feedback was achieved by mechanical means. The stabilizer bar used on Lockheed, Hiller, and Bell helicopters consists of a mass rotating with the rotor blades and acting as a mechanical gyroscope. Precessional torques, proportional to angular rates, are induced to produce blade pitch change inputs to the rotor that oppose the angular motion of the vehicle. In Sikorsky and Boeing-Vertol designs, the stabilizer bar has been synthesized electronically, eliminating some of the inherent weight and power disadvantages.

On the Lockheed H-51, H-56 series, a component of control is also achieved which is approximately proportional to angular displacement. This innovation goes one step beyond furnishing the minimal damping in relationship to control power.

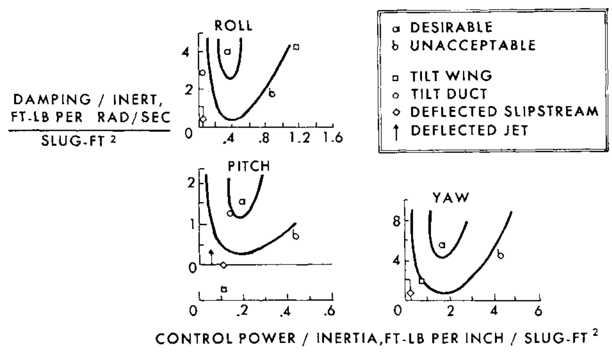

Fig. 16 VTOL configuration characteristics.

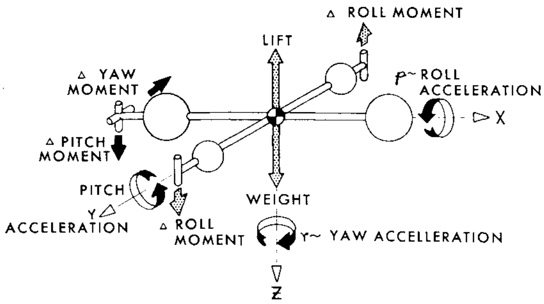

Fig. 17 Inertia representation of V/STOL in hover condition with no damping or aerodynamic springs.

Stability augmentation is a fundamental requirement for VTOL aircraft. Figures 17 and 18 show how such devices transform a vehicle whose response to pilot input is an angular acceleration into one in which there is damping of angular motions, thereby reducing the anticipatory pilot control otherwise required.

Figures 19 and 20, corresponding to Figs. 14 and 15, present control power requirements. Utilizing artificially derived damping moments, these requirements may be achieved easily within the present state-of-the-art.

Automatic Controls

Stability augmentation devices are essential in achieving good handling qualities. The ability to incorporate higher-level mission-oriented control functions is enabled by use of hydraulic actuation as an element of the primary flight control system. Achievement of the desired functions is then dependent upon provision of suitable sensing devices to input the system computer and then processing the data in the computer. Table 4 is a compilation of functions that have been incorporated in a variety of helicopters and VTOL aircraft. Control stick-steering refers to that feature which enables the pilot to effect control system reference point changes through his own primary controls.

For future applications, new automatic control functions will be exploited. Perhaps the most interesting of all of these possibilities will be the Automatic Take-off and Landing (ATOL) System, which will program and execute the optimal flight path required for a VTOL to minimize the duration of time expended in low-speed flight, especially hover, in order to curtail expenditure of fuel.

Another interesting possibility for the future is the exploitation of "fly-by-wire" systems for VTOL aircraft. Assuming appropriate reliability, the fly-by-wire electrical system offers a substantial weight saving. Elimination of complex linkage systems would materially reduce mechanical friction and hysteresis, permitting a more optimized control system. Automatic stabilization and control features can easily be coupled to the system. The next generation of VTOL control systems may very well exploit the fly-by-wire principle with a mechanical backup system to establish the desired reliability.

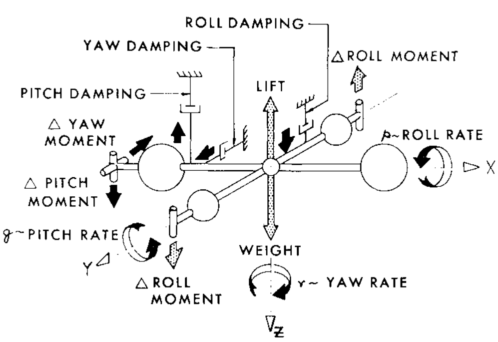

Fig. 18 Inertia representation of helicopter in hover condition with damping but no aerodynamic springs.

VTOL Missions and Transportation Systems

Military Missions

One of the first military missions for helicopters was replacement or supplementation of the light observation aircraft of World War II. They proved capable of assisting in reconnaissance and direction of artillery fire.

Medium or light utility VTOL aircraft have found use in such missions as ICBM missile site support, early warning radar support, and the movement of critical personnel and equipment between units of fleet. The ability of the helicopter to transport specialized personnel and equipment to otherwise practically inaccessible locations and without the necessity of constructing numerous airfields has proved cost effective. Security patrol requires aircraft with a high in-commission rate, speed, and range capability as well as the ability to operate vertically from high-density altitude and in all environments.

Helicopters equipped with sonar detection gear and weapons have proved valuable in antisubmarine warfare. This mission presents severe demands on endurance, navigation, and precise hovering capability. True twin-engine hovering capability is highly desirable.

Although air-sea rescue and the evacuation of wounded have long been a major mission application for VTOL aircraft, the combat aircrew recovery role has become even more important. Higher speeds and range and low downwash velocity are important aspects of this mission. Aerial refueling techniques have done much to extend range and loiter time. In order to accomplish some of these missions, fire power and armor are musts. Much yet remains to be done in improved survivability in a hostile environment and to give these aircraft true night and all-weather capability.

The vertical envelopment concept employing helicopters has provided great flexibility in the movement of troops, equipment, and supplies. Medium and heavy transport helicopters of various types are widely used in such operation. They have proved their ability to operate in the field with the troops. Improved reliability of equipment and survivability are important advances that must continue. The squad carrier and the vertical gunship are integral parts of this expanding concept. The helicopter equipped as an aerial

Table 4 Outer-loop functions

Function	Mission	Data source
Attitude/heading	Weapon launching, radar surveillance, long-duration flights	Vertical gyro, compass system
Heading (only)	Weapon launching (SS-11)	Compass system
Ground velocity	Long periods of low-speed flight (aerial crane)	Doppler radar, inertial navigation system
Terrain following	Nap of the earth flight	Forward scanning radar; radar altimeter
Altitude control	Transport/utility—long-duration flights	Barometric altitude sensor
Station keeping	Tight-formation flights	Station-keeping radar
Approach and landing systems	All-weather flight	VOR/ILS (stateside)
Hover control	Cargo sling loading, sonar dunking	Cable angle sensor
Control stick steering	Nap of the earth flight	Force transducer
Approach and flare to hover	ASW	Rad. Alt. A/S Nav. Pt.

firepower platform has opened new horizons in limited war operation and battlefield tactics. Newer models with increased speed and improved weapon accuracy will further the development of these concepts. The heavy lift or "flying crane" helicopter is used in construction work and for moving heavy equipment over otherwise impassable terrain, as well as for retrieval of downed aircraft and helicopters.

Civil Missions

The small helicopter has been adapted to such missions as power line patrol, police work, news reporting, fire patrol and fighting, disaster relief, and personnel transportation. Larger helicopters have found wide application in construction work and utility missions. One of the most outstanding missions is that of supply and transfer of personnel to offshore drilling operations. The heavy-lift helicopter is finding expanding uses in construction and ship-to-shore movement.

Scheduled and unscheduled personnel transporation systems have been established in many cities using small and medium-sized helicopters. These operations are hampered at present by the relatively high operational costs of rotary wing aircraft. However, the increase in heliport construction and the location of jet airports farther from the city center are sure to increase their application and acceptance for such uses.

The evolution of missions for the helicopter is certain to continue as advanced types are achieved with improved night and all-weather capability and reduced maintenance and reliability. A requirement exists for a heavier lift helicopter. Such an aircraft could accomplish important tasks of commercial transport, industrial construction, ship-to-shore movement of equipment and supplies, movement of heavy equipment to remote sites, and off-loading of large transport aircraft. The compound helicopter opens the way for additional missions requiring speed and agility.

Safety and Airworthiness

Safety pervades the whole process of design, construction, and operation. The basic design of an aircraft must acknowledge the human factors and incorporate appropriate handling qualities, strength of materials, and reliable components. Although a certain design may offer improved performance, it must be safe to fly. Sufficient testing has been done on several VTOL configurations, especially the helicopter types, to provide reasonable knowledge of the details of the flight maneuvering, fatigue, and landing loads. Testing techniques are established to select proper materials, methods of construction, and assembly of components to warrant adequate strength. Reliability testing and analysis has progressed to the point where mission reliability and system reliability can be predicted. Manufacturing procedures and quality control methods are sufficiently advanced to permit high production rates of equally reliable VTOL aircraft. Both operators and pilots have sufficient understanding of the potentials and limitations to use helicopters safely and effectively. Maintenance practices and designs for no maintenance have also progressed, but both areas need constant attention and development. Development of safe and reliable features and configurations is a long, specialized process. It has reached a reasonably high level in the helicopter configuration, and similar diligence will be required in other VTOL configurations.

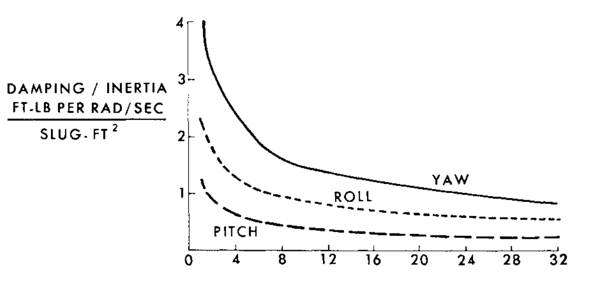

Fig. 19 Minimum angular velocity damping for visual flying.

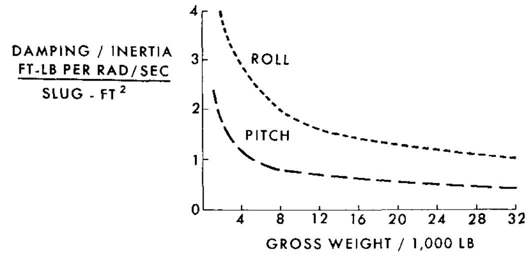

Fig. 20 Minimum angular velocity damping for instrument flight.

The pattern of development of airworthiness standards for VTOL aircraft essentially reflects the state of technical development of that category of aircraft. Airworthiness standards for helicopters—airline transport, utility/executive types, and military designs—are reasonably refined. They require amendment from time to time as additional knowledge is accumulated, and there continue to be specific areas that are controversial between the government agency, operators, and manufacturers, but their basic framework has been tested by experience. This process of evolution has been functioning since 1940.

In 1966 the Aerospace Industries Association initiated a new effort directed at development of a complete set of airworthiness standards (flight, structural, powerplant installation, systems, etc.) for the VTOL and STOL family. The transport category was considered to have the first priority, with comparable standards for air taxi, utility, corporate, business, etc. to follow, based upon the specific needs of the industry and the experience gained in development of the transport category standards. These "Tentative Airworthiness Standards for V/STOL Aircraft" were coordinated with the Federal Aviation Agency and subsequently issued by that agency in July 1968. These will not have the stature or restraints of a set of formal "Federal Air Regulations" but will provide a basis upon which manufacturers can design and operating standards can be developed. It is an objective and necessary step in the evolution of more formal criteria. Until these tentative standards have been substantiated by experience, the current Federal Air Regulations and Military Specifications are adequate, with special interpretations required for advanced designs.

VTOL State-of-the-Art Configuration

Mission requirements and cost effectiveness determine the configuration. For modest speed up to 180 knots where the mission requires about 10% of time in the hover mode, the helicopter is the minimum-cost aircraft. The helicopter is unique in its ability to hover, translate in all directions, and land safely on unprepared surfaces as compared to a fixed-wing aircraft. A comparison of a 10-yr system cost of the helicopter with other VTOL types is shown in Fig. 21.

With several compounds flying effectively over 200 knots today, the technology indicates the potential of 250 knots in the basic compound-type VTOL. Further performance improvements as a composite may be accomplished by a reduction of rotor speed to idling during high-speed flight. The composite is more cost effective than the helicopter at speeds between 180 and 300 knots.

The cost trends for the tilt wing/tilt rotor are more effective between speeds of 300 and 400 knots. However, if any extensive time is required in the hover mode, the high fuel consumption may restrict the mission effectiveness. The

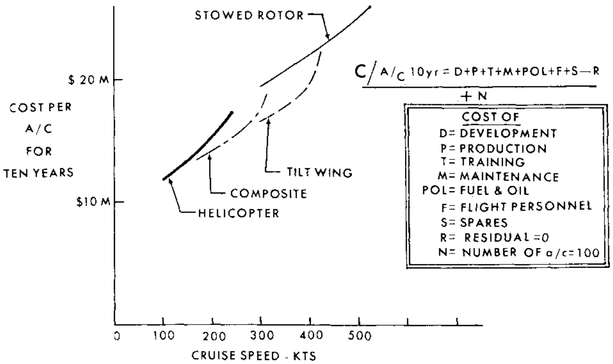

Fig. 21 10-yr total system cost; 10-ton payload, 100-mile radius.

stowed rotor with low disk loading and retracting blades offers the speed potential of the airplane and its cost effectiveness over 400 knots is indicated on Fig. 21.

The other configurations, such as stopped rotor, lift fan, and direct-lift jet must also be considered for mission requirement and cost effectiveness. Comparable studies are not currently available. Just as the helicopter has established new aircraft missions, so too, will other missions involving high speed demand the special attributes of these VTOL aircraft.

VTOL Environment—Ground and Air-Space Facilities

Intercity VTOL aircraft are expected to operate much like conventional aricraft except in the terminal area. Advancements being made or under study that will benefit everyone using the air space include area navigation, improved VORTAC accuracies and performance, and collision avoidance. Direct point-to-point flight, instead of radials between VORS, is under operational trial by several airlines. Eastern Air Lines is trying it on the Washington, D.C. to New York to Boston shuttles.

For intra-urban VTOL operations, flight at much lower altitudes may necessitate increased navigation accuracy and quality. LORAN C/D and Rho-Rho are among the systems being investigated. Increased ground/airborne accuracies and the capability of point-to-point navigation may lead to new air traffic control techniques and procedures.

A number of guidance systems for approach and landing now under development for the military should prove useful as Civil equipment. If coverage of a complex of facilities is to be successful, the routes of ingress and egress must be flexible or many of the advantages obtained through use of the VTOL aircraft will be lost. The approach angle should be selectable and/or adjustable to allow for variation in weather conditions and obstruction clearance considerations.

Automation of cockpit functions and design of instrumentation and presentations specifically for VTOL use will facilitate instrument operation.

A major key to the advancement of the VTOL system is the landing area. For the military, it may mean quick surfacing of a forward area with fast-setting lightweight fiber resinous materials. For the civil, the location, size, and arrangement of airports will be governed by the available passenger market, the in-and-out operation of the aircraft, and compatibility to surrounding land use.

Whether undertaken by municipal governments or by air transportation services, VTOL port facilities must be constructed concurrently with aircraft and airspace facilities. If VTOL systems are to be a significant factor in transportation, current thinking on VTOL port size and location must allow for future growth to a large volume of traffic, perhaps 45 to 60 operations at a peak hour handling 60–120 passenger vehicles and serving several million passengers annually. Costs may be of the order of 25 to 50 million dollars per facility, depending on land costs.

The most desirable facility would be the transporation center. Combining services in this way would reduce individual costs, and complimentary services would insure the passenger some effective mode of transporation to the greatest number of points. Locating VTOL ports over or immediately adjacent to major highways and railroads would provide easy access for passengers, insure clear way control, and serve a large market with few locations. Waterfront locations could prove worthwhile for cargo and passenger operations to offshore shipping when a city does not have port facilities.