Tilt Wing Aircraft in comparison with other VTOL and STOL Systems

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PROFESSOR J A J BENNETT
(Chairman, Lecture Committee)
occupying the Chair

The CHAIRMAN, in introducing the Author, said that although it had in the past been the main concern of the Association to discuss the problems of the conventional helicopter, it was now proposed to include systems allied to it, and convertiplanes and other powered lift systems would be considered at this and future meetings of the Association There was now a whole spectrum of proposed direct lift aircraft ranging from the conventional helicopter of a few pounds per sq ft disc loading, to jet lift aircraft of hundreds of pounds per sq ft of jet area Between these two extremes there was a variety of convertiplanes and jet wing systems

The Author had been working on rotorcraft for a long time He had been Chief Aerodynamicist of the Vertol Aircraft Corporation and Director of Aeronautical Research there , he had written many papers relating to the helicopter especially on aerodynamics, and his books on the subject published by the Rotorcraft Publishing Committee had been very widely read, even on this side of the Atlantic It was understood that a long time ago he had been a contemporary student with Mr Ciastula at Warsaw University, and later he went to Canada to work for the de Havilland Company No better background was necessary for solving the difficult problems of tilt wing aircraft than his long experience in solving the more difficult problems of the tandem rotor helicopter

MR W Z STEPNIEWSKI

Introduction

A comparative evaluation of various VTOL concepts has been made in Ref 1 regarding their possible application to subsonic transport aircraft This study indicated that for the speed range of 300 to 360 knots, and 5 minutes of hovering time, the tilt wing propeller represents a very promising configuration due to both

(*a*) Relatively high payload to gross weight ratio for zero range, $(PL/W)_0$ (Fig 12, Ref 1)

(*b*) Relatively good fuel consumption in cruising flight (Fig 11, Ref 1)

The competitive position of the tilt wing with reference to other high speed VTOL concepts may still further improve if the required time in hovering is longer than the 5 minutes as assumed in Ref 1 This obviously results from the fact that the tilt wing configuration may be designed to operate at a lower value of vertical thrust generator loading than such concepts as the Aerodyne, Vertodyne, and especially the turbojet supported aircraft (see Fig 4 of Ref 2)

Because of its characteristics, application of the tilt wing concept to various military and civilian missions shown in Table I can be anticipated

It should be noted that the normal gross weight of a VTOL aircraft is based on hovering at ambient conditions (altitude and temperature) which

Table I

MISSION	NORMAL GROSS WEIGHT	HOVERING TIME	HOVERING ALTITUDE
Transport and Assault	≥ 30 000#	≥ 5'	4 000 - 6 000'
Rescue	3,000 - 30 000#	≥ 15'	10,000 - 12,000'
Observation and Liaison	≤ 10,000#	≥ 5'	4,000 - 6,000'
Light Liaison	3,000 - 5,000#	≥ 5'	4,000 - 6,000'
Business, Executive	10,000 - 30,000#	≥ 5'	4,000 - 6 000'

= lb ′ = feet

may be encountered under normal operation It should also include the fuel required for hovering, whose duration should reflect in turn the particular mission for which the aircraft is designed Actual flying weight can be increased considerably over the normal gross weight with a running take-off (Ref 2) It should be remembered, however, that sometimes in order to realize the largest benefits from a running take-off, design compromises may be introduced with a detrimental effect on the VTOL performance of the aircraft

The main design problems and the importance of various design parameters from the point of view of the overall performance will be discussed In this discussion the simplest possible analytical approach will be made believing that in this way the basic design philosophy of the tilt wing concept can be most clearly outlined

PERFORMANCE

General

From the overall performance viewpoint, design requirements of the tilt wing configuration, as of any other VTOL system, may be summarized as follows

(*a*) The ratio of minimum flying weight to the normal gross weight should be as low as possible In other words, the ratio of payload to gross weight for zero range $(PL/W)_0$ should be as high as possible

(*b*) In performing its basic mission the aircraft should use as little fuel as possible

The first of those requirements is completely general and equally applicable to all categories indicated in Table I, while the second one needs some additional qualifications For instance, for the transport, business executive, and similar categories the basic mission requires carrying the largest possible payload over a given distance This means that the relative amount of fuel (percentage of the gross weight) required per unit of distance flown (say 100 n miles) should be as low as possible On the other hand, for the observation and other aircraft required to stay aloft as long as possible, the relative amount of fuel consumed per unit of time becomes the criterion of their suitability In both cases, however, additional qualifications must be added regarding the acceptable cruising speed and range, or time of the mission Having all those requirements, it is necessary to select design parameters in a way leading to an optimization of the PL/W ratio for a given mission In this process, both the hovering and forward flight aspects should be considered

In all VTOL aircraft, the tilt wing being no exception, the power plant characteristics (specific weight, specific fuel consumption, loss of power with altitude and temperature, etc) are of prime importance In this study, however, attention will be concentrated on the airframe design parameters It is sufficient to assume that the aircraft are powered by turbo-shaft engines with the following characteristics accepted as representative of the present state of the art Specific installed weight 0 5 lb /SHP , specific fuel consumption (both in hover and in forward flight) 0 6 lb /SHP hr , loss of power with altitude and ambient temperature as in Fig 2, Ref 1 However, for the sake of simplification, only standard atmosphere conditions will be considered

As to the airframe design parameters, those most important in hovering are Rotor* disc loading (w_R), rotor geometry (planform, airfoil section, and twist distribution) and rotor tip speed (V_{t_h}) Wing loading (w_w), wing aspect ratio (Æ), aerodynamic cleanness of the aircraft (which may be expressed as the equivalent flat plate area loading, w_f) plus other parameters influencing the propulsive efficiency of the propeller, such as its geometry and tip speed (V_{t_f}), may be considered as the main design parameters in forward flight However, rotor disc loading in hovering cannot be considered as independent of the wing loading and aspect ratio

This results from the fact that in the transitional flight it is desirable to have the whole wing area submerged in the rotor-propeller slipstream It is true that this goal may be achieved by arranging rotor-propellers along the wing span with various amounts of the disc overlap and various amounts of the overhang of the rotor disc (up to one radius) from the wing tip However, in the present study it will be assumed for simplicity that the rotor-propeller diameter (2R) is equal to the wing span (b) divided by the number of rotor-propellers (n)

Then, the following simple relationship between the rotor disc loading (w_R) and the wing loading (w_w) exists

$$w_R = \frac{4n}{\pi Æ} w_w \qquad (1)$$

Eq (1) indicates that as far as low disc loading in hovering (at a given wing loading) is concerned, a combination of a high wing aspect ratio with a small number of rotors is desirable However, when running take-offs or landings are required some of those combinations may be eliminated because of ground clearance, regardless of their desirability because of the reduction of power required in hovering

Power Installed

In general it would be desirable that the installed power requirements resulting from hovering match those of forward flight

Assuming that the full normal rated power available at a given altitude is utilized for hovering, the installed power per pound of gross weight $(SHP/W)_{ins}$, (sea level rating) resulting from this flight regime can be simply expressed by modifying the relationships given in Ref 3

$$(SHP/W)_{ins} = \frac{K_{T_h}}{\eta_{T_h}}\left[\frac{k}{550}\sqrt{\frac{(4n/\pi Æ)w_w}{2\rho_h}} + \frac{3}{2200}\left(\frac{c_{d0}}{C_L}\right)_h V_{t_h}\right] \qquad (2)$$

where new symbols K_{T_h} is the ratio of sea level engine rating to that at hover-

* Rotor-propeller of the tilt wing will be called " rotor " when operating in hovering and " propeller " when in forward flight

ing altitude, η_{tr_h} is the ratio of rotor horsepower to shaft horsepower (it reflects transmission losses plus power required for accessory drive and hovering controls), k is the ratio of the actual induced power to the ideal one, $(\bar{c}_{do}/C_L)_h$ is the ratio of the average profile drag coefficient (in hovering) to the average rotor blade lift coefficient (in hovering)

Power installed, per pound of gross weight, based on forward flight can be expressed as follows

$$(SHP/W)_{ins_f} = \frac{K_{Tf}}{550\,\tau\ \eta_{tr_f}\ \eta_{pr}}\ \frac{V_f}{\varepsilon_v} \quad (3)$$

where new symbols are τ is the fraction of the normal rated power available at the flight altitude which is actually used (for V_{max}, $\tau = 1\ 0$, for cruising $\tau < 1\ 0$ is usually selected), V is the speed of flight (in fps) and ϵ_v is the aircraft lift to drag ratio corresponding to the flying speed

Matching Hovering and Forward Flight $(SHP/W)_{ins}$ *Requirements of Transports*

Tilt wing aircraft designed for maximum payload for a given distance (transport, business and some rescue types) will be considered as an example of matching $(SHP/W)_{ins}$ as determined by hovering with that, resulting from forward flight But in the aircraft category considered, fuel economy in cruise is very important Furthermore, cruising speed below some established standards (say 300 knots for transport and assault, etc) will not be acceptable This means the whole problem has three aspects (*a*) matching power installed requirements, (*b*) assuring the highest fuel economy, and (*c*) maintaining an acceptable cruising speed

Fuel required to fly a unit of distance of 100 n miles when expressed as a percentage of gross weight is

$$(W_F/W)_{f_{100}} \equiv \Upsilon = 30\ 8\,\frac{sfc}{\varepsilon\ \eta_{tr_f}\ \eta_{pr}} \quad (4)$$

where the new symbol η_{pr} is the propeller efficiency

It is obvious that from the point of view of fuel consumption it is desirable to fly at the optimum lift to drag ratio (ϵ_{max}) and have the lowest specific fuel consumption as well as the highest η_{tr_f} and especially η_{pr} under those circumstances The aircraft lift coefficient corresponding to ϵ_{max} can be approximated as (see Ref 4)

$$C_{L_{OPT}} = \sqrt{\pi A\!\!R\, e\, C_{D_{MIN}}} \quad (5)$$

(e being span efficiency)

Eq (5) can be rewritten in terms of the equivalent flat plate area loading (w_f)

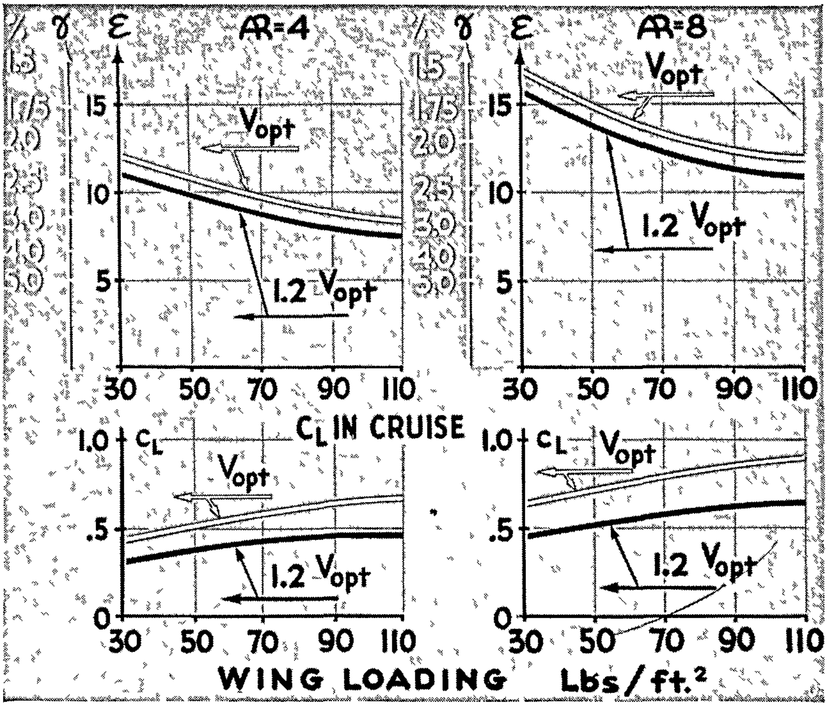

Fig 1 Lift to drag ratio (ϵ) relative fuel required per 100 n miles (γ) and wing lift coefficients in cruise

and the minimum profile drag coeffieicnt (referred to the wing area) of the wing itself plus the empennage ($c'_{do\,min}$)

$$C_{L\,opt} = \sqrt{\pi A\!\!R\, e(w_w/w_f + c'_{do\,min})} \qquad (5a)$$

and the maximum lift to drag ratio is

$$\epsilon_{max} = \frac{1}{2}\sqrt{\pi A\!\!R\, e/(w_w/w_f + c'_{do\,min})} \qquad (6)$$

Values of lift coefficient corresponding to the maximum lift to drag ratio and hence to the optimum cruising velocity, V_{opt} are shown at the bottom of Fig 1 against wing loading for $A\!\!R = 4$ and 8, while corresponding γ and ϵ values are plotted at the top of that figure

Since C_L required for optimum cruising speed is fixed (for given $A\!\!R$, w_w, w_f, and $c'_{do\,min}$), it is obvious that in order to make that speed as high as possible, it is necessary to fly the aircraft at the highest practical altitude Assuming flight altitude of 25,000 ft (which is generally accepted for turbine powered aircraft) the V_{opt} cruising speeds become as shown at the bottom of Fig 3

Power installed, based on hovering is computed from eq (2) under the following assumptions Hovering altitude, 4,000 ft standard atmosphere, $K_{Th} = 1\ 07$, $\eta_{tr} = 0\ 92$, $k = 1\ 1$, $(\bar{c}_{do}/\bar{C}_L)_h = 1/40$ and $V_{t_h} = 750$ fps

The results are shown in Fig 3 (as broken lines) against wing loading, for $AR = 4$ and 8 As can be expected a small number of rotor-propellers combined with high aspect ratios, leading to lower disc loadings, result in a much lower requirement of $(SHP/W)_{ins}$ for the same wing loading

Power installed, based on cruising is computed from eq (3) substituting for ϵ their maximum values as given by eq (6) and making the following assumptions Cruising is performed at 80% of power available at cruising altitude of 25,000 ft, $\eta_{tr_f} = 0\ 95$, $\eta_{pr} = 0\ 8$, $K_{T_f} = 1\ 6$ and $w_f =$ 4,000 lb /sq ft The results are shown at the top of Fig 2 as continuous lines marked V_{opt}

It can be seen from this figure that except for the two propellers and $AR = 4$, installed power requirements based on hovering considerably exceed those resulting from optimum cruise This means that in order to fly at V_{opt} it would be necessary to either operate engines at a much lower horsepower than the assumed 80% of normal rated power at cruising altitude and suffer rather high specific fuel consumption losses in turbines, or to turn some engines off and carry them as a useless ballast as far as cruise is concerned Another possibility is to take the advantage of the excess power and cruise at higher speeds, at the expense of a lower lift to drag ratio and hence higher γ values

Lift to drag ratio at a flying speed V different from V_{opt} can be expressed as

$$\mathcal{E}_{V} = \frac{2\,(V/V_{opt})^2}{1 + (V/V_{opt})^4}\,\mathcal{E}_{max} \qquad (7)$$

An increase of the cruising speed by 20% over its optimum value (V_{opt}) will result, hence, in a new lift to drag ratio in cruise only about 6 5% lower than ϵ_{max}, while γ values will be 6 5% higher than at their optimum values (Fig 1)

Shaft horsepower installed at 1 2 V_{opt} better matches the hovering requirements for $AR = 4$ and $n = 2$ and 4 But for $AR = 8$, only two propellers at high wing loadings produce the desired balance between the power installed requirements Should, however, STOL operations be required, the ground clearance difficulties in the airplane configuration could prohibit this solution

It may be stated, hence, that even for the tilt wing transport designed to hover at a relatively low altitude and to cruise at high altitude, the installed power will still be determined rather by hovering than other regimes of flight

For such aircraft as rescue, observation and liaison, where hovering at

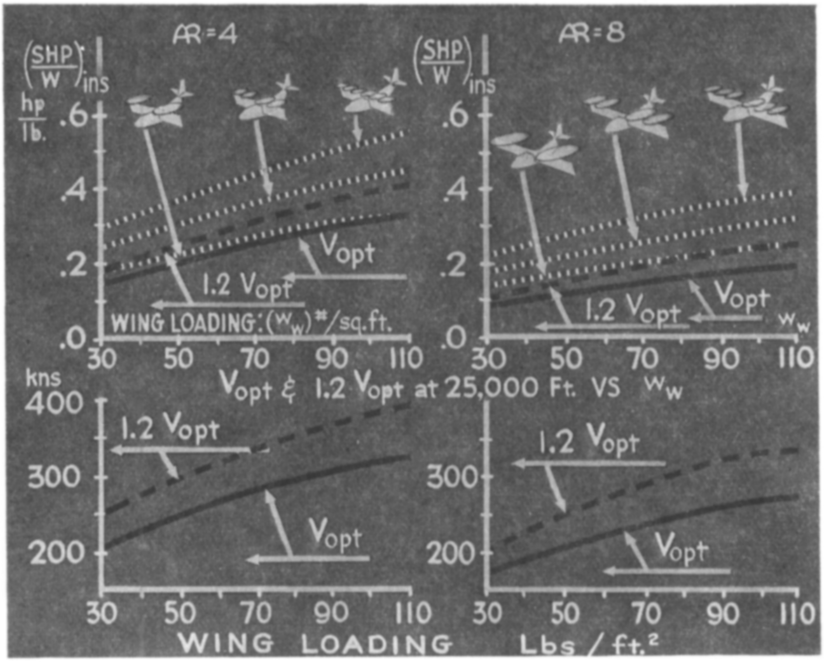

Fig 2 SHP/W installed, based on hovering (wings up) at 4,000 ft, and normal rated power SHP/W installed resulting from cruising (arrows) at 25,000 ft and 80% of power available

higher and cruising at lower altitudes and speeds (less than V_{opt}) may be required, even higher discrepancies between $(SHP/W)_{ins_h}$ and $(SHP/W)_{ins_f}$ may result This may require operating in forward flight with one-half of the installed engines turned off in order to optimize either the mission time or the distance flown

Weight Aspects

In order to indicate the influence on $(PL/W)_o$, of other factors than the horsepower installed, a more detailed weight analysis was performed by R H Swan* assuming a gross weight of 30,000 lb The results, presented on a relative basis as ratios of the particular group weight to the gross weight, may be considered as typical for this gross weight class In Fig 3 an example of a summary breakdown of the weight items is given

Assuming that a cruising speed of an order of 300—330 knots is required, one may notice from Fig 2 that for the two propellered—$\mathcal{R} = 4$ aircraft, this cruising speed can be realized at a maximum lift to drag ratio ($V_{cr} = V_{opt}$) and the corresponding relative fuel consumption per 100 nautical miles

* Chief of Weights, Research and Development, Vertol Aircraft Corp

(Fig 1) will amount to $\gamma = 3\%$ Furthermore, power installed based on hovering matches that required in cruising For the Æ $= 8$ aircraft the desired cruising speed is higher than the V_{opt} and for a wing loading of $w_w = 90$ lb /sq ft it will be equal to approximately 1 2 V_{opt} However, the power installed based on hovering will exceed by approximately one third that resulting from a cruise at 1 2 V_{opt} This obviously means that at this cruising speed it would be either necessary to operate at less than 60% of the power available, or to turn some engines off Another possibility is, of course, to fly at still higher speeds than 1 2 V_{opt} Assuming that cruising is performed at 1 2 V_{opt}, the correspondence value of γ is approximately 2 2% Since the difference between $(PL/W)_o$ of the two propellered, Æ $= 4$ and four propellered, Æ $= 8$ aircraft amounts to about 1 6% it is clear that for ranges in excess of about 200 n miles the higher aspect ratio aircraft will have better payload carrying characteristics

High Æ, four propellered aircraft at a lower wing loading, such as 50 lb /sq ft, may look still more attractive, because of the $(PL/W)_o$, than the previously considered $w_w = 90$ lb /sq ft The assumed cruising speed of 300—330 knots will amount to 1 43 to 1 57 V_{opt} with the corresponding $\gamma \approx 2$ 2 and $\gamma \approx 2$ 5% respectively But the wing lift coefficient would

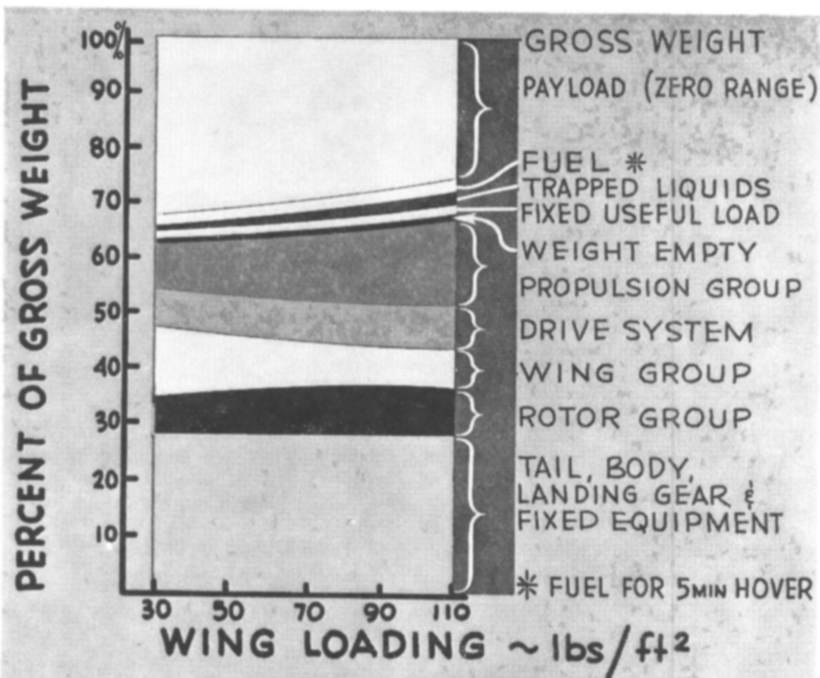

Fig 3 Example of the relative component weights and values of zero range payload for the four-propellered tilt wing aircraft of Æ = 8

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be approximately 0 24 and 0 20 respectively, which may be objectionable because of high gust loads

It may be concluded, hence, that where a cruising speed of 300—330 knots is required for short ranges (about 200 n miles) low aspect ratio two propellered aircraft with a high wing loading (about 100 lb /sq ft) may be

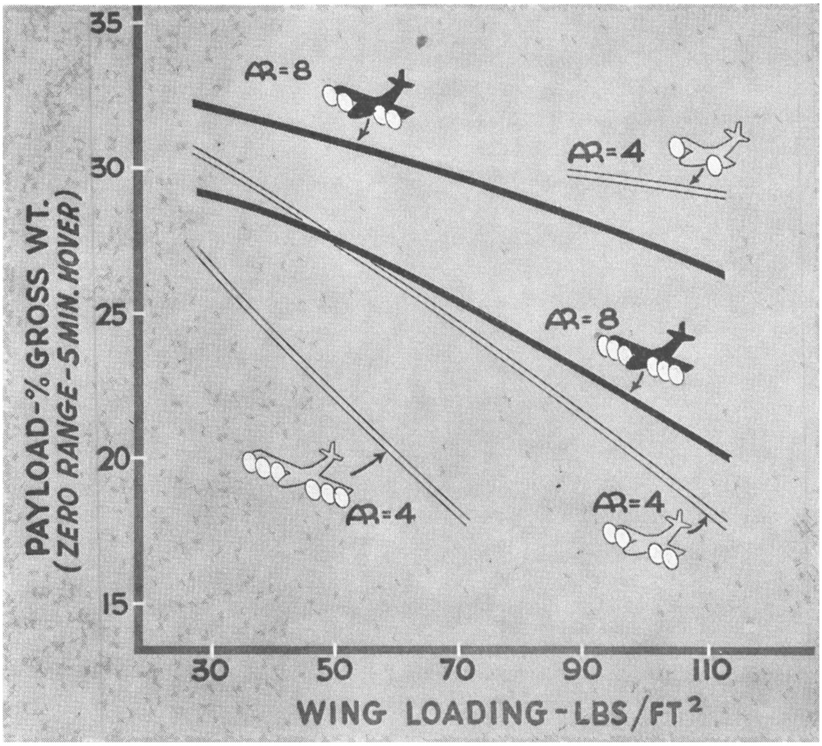

Fig 4 Zero range payload vs wing loading

attractive, while for higher ranges, high aspect ratio four propellered aircraft with a wing loading of about 90 lb /sq ft become more advantageous

In those cases, however, where propeller ground clearance requirements, resulting from the airplane type take-off and landings, can be eliminated the $(PL/W)_0$ values can be improved This can be done by either combining high Æ wings with two propellers of approximately 1/2 span diameter, or low Æ wings with two propellers located close to the tips and having their diameters almost equal to the wing span As in the previously considered cases, the low Æ would be more advantageous from the $(PI/W)_0$ point of view, while the high Æ would favour the cruising fuel consumption

General

The rotor-propeller of the tilt wing aircraft performs a dual task of a rotor in hovering and a propeller in forward flight It is necessary, hence, to make the same thrust generator the most efficient lifting and propelling device In addition, rotor-propellers in hovering and near hovering flight serve as a source of control forces and moments

The most important design parameters of the rotor-propeller are (*a*) disc loading w_R , (*b*) tip speed, V_t , and (*c*) geometry of the rotor-propeller (solidity, σ , blade planform , twist distribution, $\theta_x = f(x)$, airfoil section)

The very nature of the tilt wing dictates that the disc loading of the rotor-propeller in cruise amounts to a small fraction ($\text{Æ} = 8$ 1/17 to 1/11 , $\text{Æ} = 4$ $\frac{1}{12}$ to $\frac{1}{8}$) of that in hovering and the inflow conditions in the two regimes of flight are also quite different

A variable diameter rotor-propeller could partially alleviate those large variations of the disc loading However, the resulting mechanical complexity would probably overbalance the possible advantages of this approach It will be assumed, hence, in the present study that the geometry of the rotor-propeller remains the same throughout all regimes of flight and only collective pitch and tip speed may be varied

Selection of the tip speed in hovering (V_{t_h}) may be somewhat influenced by structural weight aspects, but usually compressibility and noise considerations will decide its value $V_{t_h} = 750$ fps will be assumed in the present study

In order to provide adequate control in hovering, there is an upper value of average rotor lift coefficient ($\bar{C}_L$) at which the aircraft should operate It is obvious that the maximum operational $\bar{C}_L$ will be determined primarily by the blade section $C_{l\,max}$ which in turn is dependent upon airfoil section, boundary layer control or circulation control and consequently may have a wide range of values Twist distribution and blade planform may also influence the acceptable values of $\bar{C}_L$ in hovering

However, in the present study it will be assumed that C_L, defined as for helicopters

$$\bar{C}_{L_h} = \frac{6 w_{R_h}}{\sigma \rho_h V_{t_h}^2} \leq 6 \tag{8}$$

Selection of the $\bar{C}_{L_h}$ and V_{t_h} values automatically establishes the rotor solidity for a given disc loading and hence a wing loading as well (eq 1) Some solidities resulting from $V_{t_h} = 750$ fps and $C_{L_h} = 0\ 6$ are quite high and may require contrarotating multibladed rotor-propellers

With solidity already established, the possible remaining avenues toward optimization of the rotor-propeller efficiency both in hovering and in cruising

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flight can lead through a proper twist and chord distribution of the blade and rpm (V_t) variation between the two regimes of flight Since for simplicity constant chord blades will be assumed, attention will be focussed on the twist distribution and rpm variation

Optimum Twist Distribution for Hovering

The most advantageous twist distribution in hovering is usually that which assures a uniform downwash over the largest part of the rotor disc This not only minimizes the induced power, but in general is also beneficial for the profile power as blade section lift coefficient (c_{L_x}) decrease toward

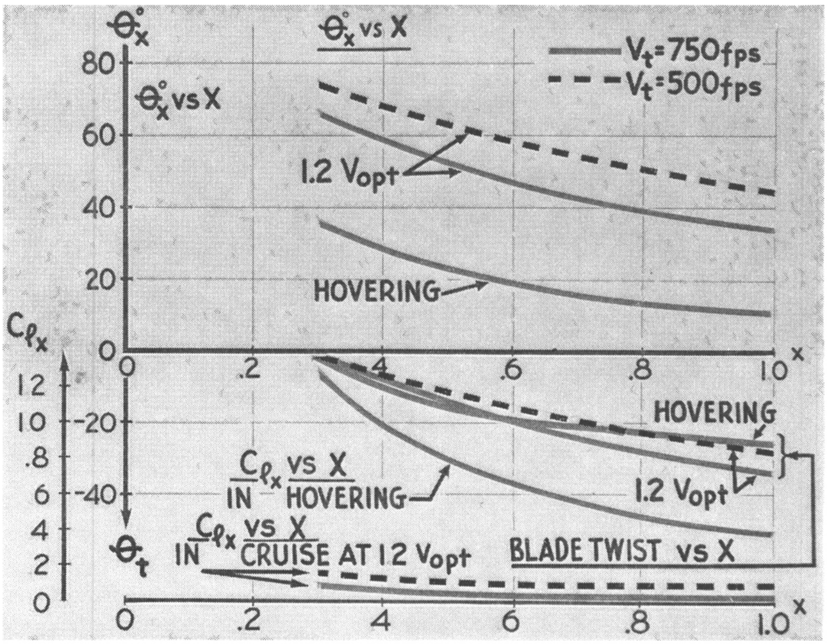

Fig 5 Examples of section pitch angle (θ_x) and twist (θ_t) distribution as well as the section lift coefficients (c_{l_x}) required for uniform induced velocity in hovering and at 1 2 V_{opt}

the tip This in turn reduces both the incompressible and compressible section drag coefficients in the high periferal velocity regions

Remembering that the ideal downwash velocity is $v_{i\alpha} = \sqrt{w_{Rh}/2\rho_h}$ the expression for the distribution of section lift coefficient, assuring a uniform downwash (see p 120, Ref 3) can be rewritten as follows

$$C_{\ell_x} = \frac{8}{\sigma x} \frac{w_{Rh}}{2\rho_h V_{t_h}^2} \qquad (9)$$

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or in terms of the average rotor lift coefficient ($\bar{C}_L$)

$$C_{L_x} = \frac{2\,\bar{C}_{L_h}}{3\,x} \qquad (9a)$$

while the blade pitch distribution ($\theta_x = f[x]$) becomes

$$\theta^\circ_x = 38.5\,\frac{\bar{C}_{L_h}}{a\,x} + \tan^{-1}\left(\frac{\sqrt{w_{R_h}/2\rho_h}}{V_{t_h}\,x}\right) \qquad (10)$$

As an example, blade pitch distribution calculated by the above formula for an assumed $\bar{C}_L = 0\ 6$, $V_{t_h} = 750$ fps, hovering altitude of 4,000 ft and a disc loading of $w_R = 45$ lb /sq ft (corresponding to the four propellered aircraft of Æ = 8 and wing loading of $w_w = 70$ lb /sq ft) is shown in Fig 5

Radial twist distribution ($\theta_t = f[x]$) as required for a uniform downwash in hovering is shown separately between blade station x = 0 3 and the tip at the bottom of Fig 5 As to the general blade setting in hovering it may be noted from the upper graph of Fig 5 that the pitch angle at the 3/4 blade radius is $\theta_{75R} \approx 16°$

Optimum Blade Pitch Distribution for Cruise

As to the twist distribution advantageous in forward flight, it will be chiefly governed by the ratio of flight velocity to tip speed (μ_f) The average induced velocity, being small in comparison with the flying speed will have only a secondary influence on the power required by the propeller

In analogy to hovering, the average propeller lift coefficient in forward flight can be expressed as follows

$$\bar{C}_{L_f} = \frac{6\,w_{R_f}}{\sigma\,\rho_f\,V_{t_f}^2\left[\sqrt{(1+\mu_f^2)^3} - \mu_f^3\right]} \qquad (11)$$

This equation can be rewritten in terms of the average lift coefficient in hovering, hovering density, hovering tip speed, and lift to drag ratio in forward flight

$$\bar{C}_{L_f} = \bar{C}_{L_h}\,\frac{\rho_h}{\rho_f}\left(\frac{V_{t_h}}{V_{t_f}}\right)^2 \frac{1}{\varepsilon_f}\,\frac{1}{A} \qquad (11a)$$

where $A = \sqrt{(1 + \mu_f^2)^3} - \mu_f^3$ and whose values can be found in Fig 6

In Fig 7 (bottom) the average propeller lift coefficient at 1 2 V_{opt} and 20,000 ft are shown for tip speeds of 750 and 500 fps assuming that $\bar{C}_{L_h} = 0\ 6$ and hovering altitude is 4,000 ft

It can be seen from Fig 8 that even at the reduced tip speed, the

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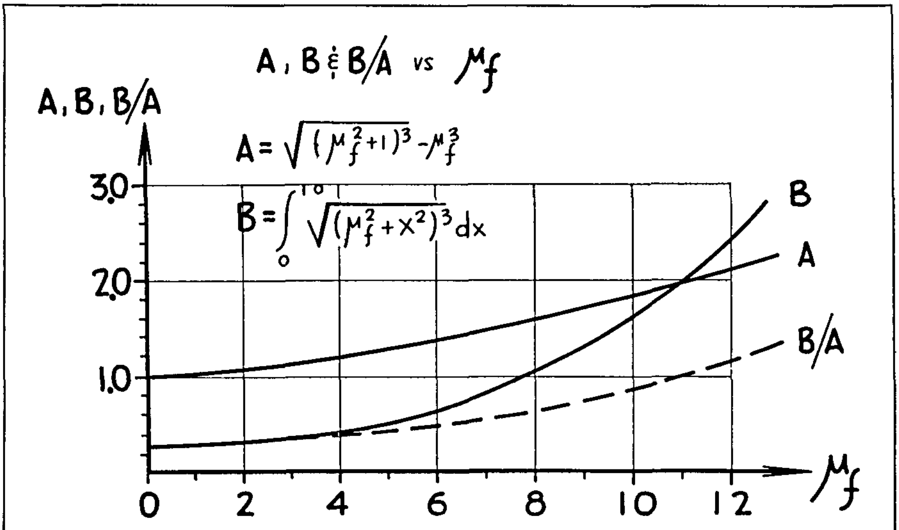

Fig 6 Graph for A, B and B/A values

average lift coefficients in forward flight are quite low These low $\bar{C}_{L_f}$ values indicate that in general blade section lift coefficients will also be low and, hence, their angle of attack small This means that even small deviations from the required angles of attack resulting from an improper pitch angle (twist) distribution may produce a negative lift at some blade stations with a loss in propulsive efficiency By contrast, in hovering, where induced velocities are high, deviations from the ideal twist distribution will also result in some increase in the induced power but these losses will be relatively minor Consequently, should any conflict exist between the twist distribution required in forward flight and that in hovering, the twist distribution advantageous for cruising should be adopted

Pitch distribution in cruise can be established from the requirement that the induced velocity is uniform In analogy with hovering an expression for a distribution of the section lift coefficient along the blade ($c_{lx_f} = f[x]$) can be established

$$c_{lx_f} = 8\frac{\mu_f^2}{\sigma}\,\frac{1 + v_{idf}/V}{\sqrt{\mu_f^2 + x^2}}\,\frac{v_{idf}}{V} \qquad (12)$$

But, $v_{idf}/V_f << 1\ 0$ (see Fig 7) and eq (12) can be simplified as follows

$$c_{lx_f} = 8\frac{\mu_f^2}{\sigma}\,\frac{v_{idf}/V}{\sqrt{\mu_f^2 + x^2}} \qquad (12a)$$

As an example the c_{lx_f} distribution for the previously considered case

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of the four propellered, $\mathcal{R} = 8$, $w_w = 70$ lb /sq ft aircraft is shown in Fig 5 (bottom) It can be seen from that figure that even for a lower tip speed of 500 fps, section lift coefficients of the blade in forward flight are very low indeed

Pitch distribution ($\theta_x = f[x]$) required to produce the necessary section lift coefficient distribution can easily be obtained from eq (12a)

$$\theta^{\circ}_{x_f} = 80 \frac{\mu_f^2}{\sigma} \frac{v_{id_f}/V}{\sqrt{\mu_f^2 + x^2}} + \tan^{-1} \frac{\mu_f}{x} \qquad (13)$$

In Fig 5 pitch angle distribution assuring a constant induced velocity at 1 2 V_{opt} is shown for $V_{t_f} = 750$ and 500 fps for the above considered example of the rotor-propeller It should be noted that a large general pitch increase is required from that in hovering for $V_{t_f} = 750$ fps $\theta_{75R} \approx 41°$, while for $V_{t_f} = 500$ fps $\theta_{75R} = 53°$ (in hovering it was 16°)

The twist distribution required in cruise is shown between x = 0 3 x = 1 0 at the bottom of Fig 5 It can be seen that differences in the optimum twist distribution for hovering and cruise are not significant However, as it has been mentioned previously an optimum twist for cruise should be favoured

Propeller Efficiency

Propeller efficiency in forward flight at a speed V can be defined as

$$\eta_{pr} = \frac{TV}{TV + k_f T v_{id_f} + P_{pr_f}} \qquad (14)$$

where T is thrust, k_f is the ratio of actual induced power to the ideal one, and P_{pr_f} is the profile power (in ft lb /sec) which can be expressed as follows

$$P_{pr_f} = \frac{1}{2} \rho \sigma \pi R^2 \bar{c}_{do_f} V_{t_f}^3 B \qquad (15)$$

where $\bar{c}_{do_f}$ is the average profile drag coefficient in forward flight and

$$B = \int_0^{1\,0} \sqrt{(\mu_f^2 + x^2)^3}\, dx \qquad (16)$$

Values of B can be obtained for various μ_f's from Fig 6

Dividing the numerator and denominator of eq (14) by T and remembering that from eq (11)

$$T/\sigma \pi R^2 \rho V_{t_h}^2 = \frac{1}{6} \bar{C}_{L_f} A \qquad (16a)$$

eq (14) can be rewritten as follows

$$\eta_{pr} = \frac{1}{1 + K_f\left(\frac{v_{id_f}}{V}\right) + 3\left(\frac{\bar{c}_{do_f}}{\bar{C}_{L_f}}\right) \frac{B}{A} \frac{1}{\mu_f}} \qquad (17)$$

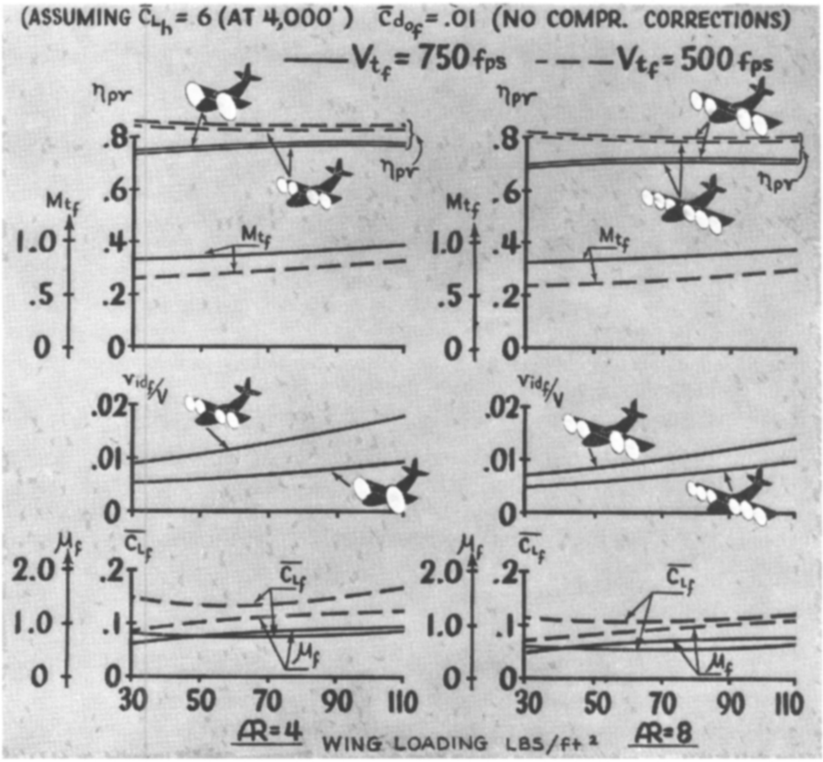

Fig 7 Propeller efficiencies in cruise at 1 2 V_{opt} and 25,000 ft , also V_{id_f}/V , and $\bar{C}_{L_f}$

Assuming that the average profile drag coefficient in forward flight is $\bar{c}_{do_f} =$ 01, while average propeller lift coefficients are as shown at the bottom of Fig 7 and v_{id_f}/V as in the middle of that figure, the propeller efficiency can be calculated from eq (17) The results are shown (Fig 7, top) against wing loading, for $V_{t_f} =$ 750 and 500 fps for aircraft having Æ = 4, n = 2 and 4 and Æ = 8, n = 4 and 6 In the above calculations compressibility effects were neglected (resultant tip Mach numbers are shown in the middle of Fig 7) but especially for $V_{t_f} =$ 500 they should be of no significance

It can be seen from Fig 7 (top) that reasonably good efficiencies in cruise can be obtained if the propeller rpm can be appreciably reduced in forward flight from that in hovering

In general the following conclusions can be made regarding the rotor-propeller of the tilt wing aircraft

(*a*) Solidities will be rather high and in order to reduce them, efforts should be made to develop airfoils that will enable operating at high average rotor lift coefficients and high tip speeds in hovering (*b*) Large pitch changes between hovering and forward flight may be expected and those aspects should be reflected in the design of pitch controls

(*c*) Twist distribution optimum for cruise should be adopted, and

(*d*) In order to improve propulsive efficiency in forward flight the propeller rpm should be considerably reduced from that in hovering

Transition

Basic Relationships

Transition from hovering to airplane flight and especially back to hovering represents one of the most important problems of the tilt wing configuration In this manoeuvre the wing may be at a high angle of attack with reference to the airflow resulting from the propeller downwash and aircraft translational velocity At low flying speeds when hovering controls —basically independent of aircraft flying speed—are in operation, wing angles of attack in excess of stalling can be tolerated But stall should be avoided at higher speeds, especially if the airplane-type lateral controls are the only ones active at that time

Furthermore, in transition considerable pitching moments of aerodynamic nature, originated by the wing and rotor-propeller (especially of the rigid type), may be present as well as those resulting from the centre of gravity shift associated with the wing tilt

In spite of continuous efforts of NACA and especially its representatives such as C H Zimmerman and his group, R E Kuhn, M O McKinney and many others (Ref 5-8), there is still a considerable lack of theoretical

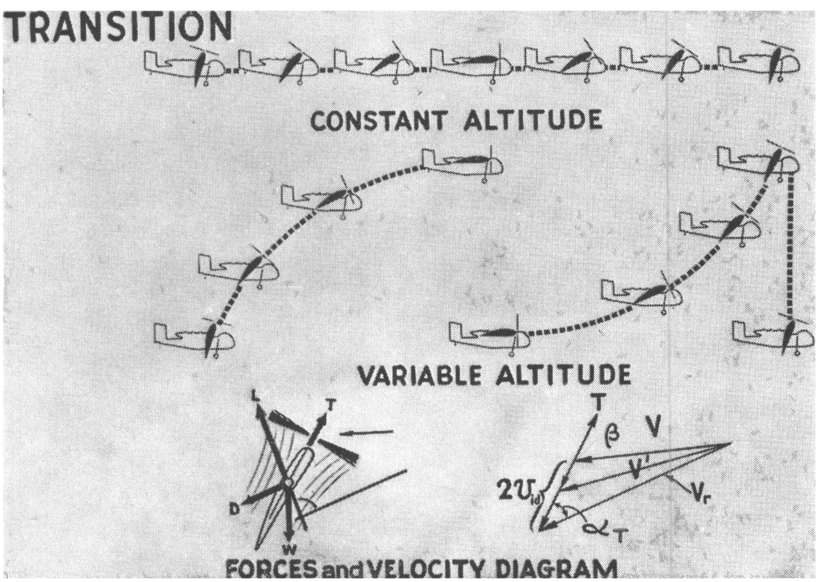

Fig 8 Types of transition Force and velocity diagram

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and experimental data regarding the behaviour of wings and rotor-propellers of different types (rigid, articulated) in this regime of flight Many problems associated with the prediction of forces and moments acting on the wing-propeller assembly in transition still wait to be solved One of those un-

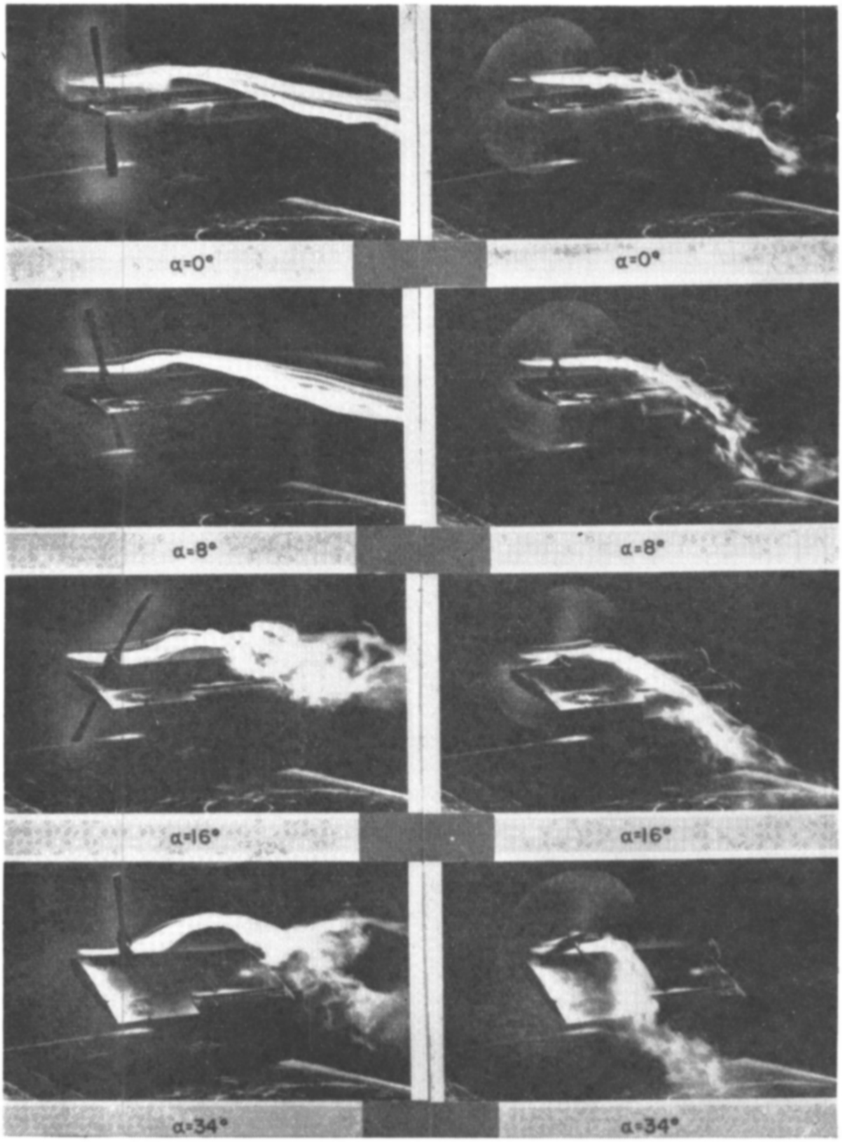

Fig 9 Smoke tunnel tests, at Princeton University, showing flow over the wing with and without the propeller downwash

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certain areas is represented by the interaction of the rotor-propeller slipstream with the flow created by the wing itself Even with a wing completely submerged in the rotor-propeller slipstream a question may be asked whether the ratio of the combined cross sectional area of the propellers slipstream to that of the stream tube affected by the wing (circle inscribed on the span) is significant as far as wing forces and moments are concerned In other words, whether six or four propellers completely submerging the wing in their slipstream and creating a given induced velocity will have the same effect on the wing as two propellers submerging the wing in a slipstream of the same velocity

Since this problem at present cannot be answered with certainty, it is assumed for simplicity that aerodynamic forces and moments acting on the wing depend in all cases on the following factors only (*a*) velocity V_r being a resultant of the doubled ideal induced velocity (v_{id}) of the rotor-propeller, and the velocity of flight (V) of the aircraft , (*b*) angle of attack of the wing (α_w) with respect to this resultant , (*c*) aerodynamic characteristics (C_L , C_D , C_M) of the wing itself, and obviously, (*d*) air density

It is assumed (as was done by Glauert) that in any regime of flight the thrust of the rotor-propeller will be equal to the mass flow passing through a sphere circumscribed over the rotor disc, times doubled ideal induced velocity The latter value can be expressed as follows

$$v_{id} = \frac{w_R}{2\rho V'} \tag{18}$$

where V^1 is the resultant flow through the sphere (Fig 8, bottom)

Denoting by β an angle between the rotor-propeller thrust and aircraft flight path the resultant flow velocity V' becomes

$$V' = \sqrt{(V + v_{id}\cos\beta)^2 + v_{id}^2 \sin^2\beta} \tag{19}$$

and eq (18) can be rewritten as

$$v_{id}^4 + 2V\cos\beta \, v_{id}^3 + V^2 v_{id}^2 - \left(\frac{w_R}{2\rho}\right)^2 = 0 \tag{20}$$

when V, β, w_R and ρ are given this equation can be solved for v_{id} and the resultant flow velocity in the fully developed slipstream can be obtained as

$$V_r = \sqrt{(V + 2v_{id}\cos\beta)^2 + (2v_{id}\sin\beta)^2} \tag{21}$$

while angle of attack of the wing (α_w) becomes

$$\alpha_w = \alpha_T + \alpha_i = \tan^{-1}\frac{\sin\beta}{2v_{id}/V + \cos\beta} + \alpha_i \tag{22}$$

In the above equation α_T is an angle between rotor-propeller axis and the resultant flow, V_r, while α_i is the wing incidence with respect to the rotor-propeller axis Eq (22) indicates how, due to the 2 v_{id}/V ratio, the actual

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wing angle of attack is reduced from its geometric incidence with respect to the flight path Fig 9 reproduced from smoke flow studies performed on the Vertol 76 wing at Princeton University illustrates that point by showing how at high wing attitudes stall is removed in the presence of a strong propeller slipstream

Shaft horsepower required during transition per pound of thrust (SHP/T) can be readily expressed in terms of the aircraft speed along the flight path and ideal induced velocity (Ref 3, p 50)

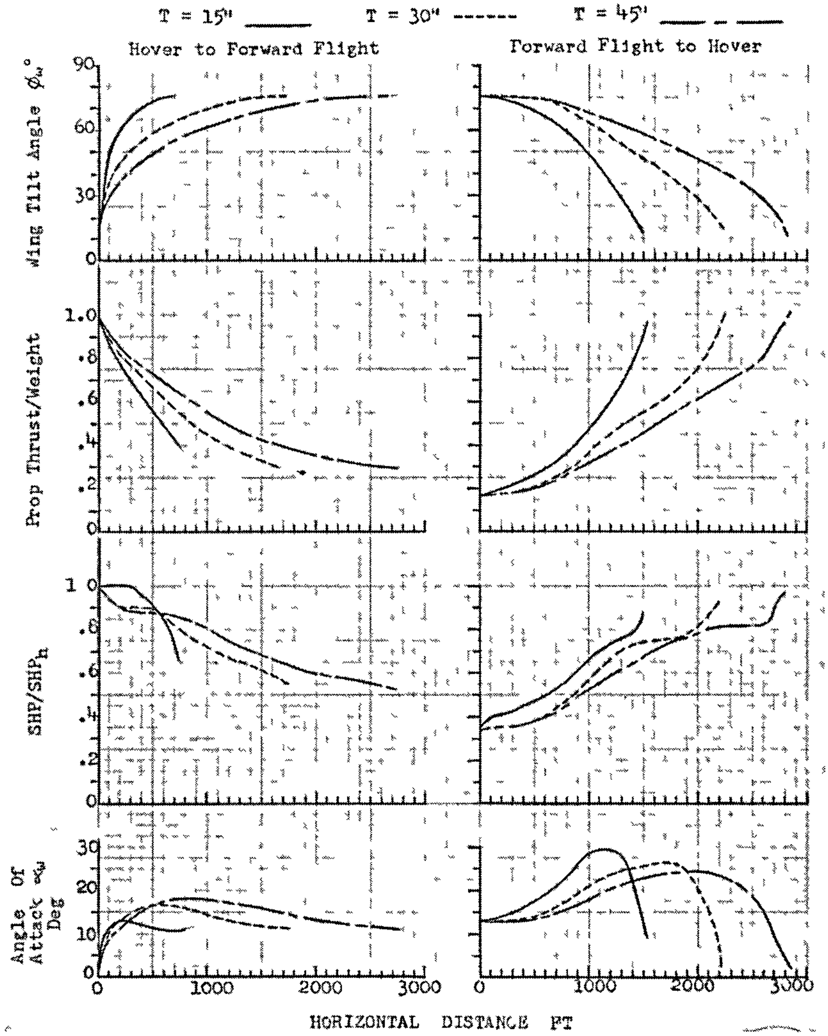

Fig 10 Results of an analytical study of a constant altitude transition

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$$\frac{SHP}{T} = \frac{1}{\eta_{tr}}\left[\frac{1}{550}\left(V\cos\beta + k\,v_{id}\right) + P_{pr}\right] \qquad (23)$$

Having all those basic relationships established actual transition can be investigated

Types of Transition

Two basic types of transition can be visualized one in a level flight, and another with variable altitude (Fig 8)

Experience gained with models in the level transition from hovering to forward flight is discussed in Refs 8 and 9 and some theoretical aspects of this manoeuvre are considered in Refs 9 and 10 Furthermore, in conjunction with the development of the Vertol 76 flight research aircraft, more detailed studies of the level flight transition both departing from and returning to hovering were performed by F R Mazzitelli*, using the following procedure Equations of motion in the horizontal (x) and vertical (z) directions as well as about pitching axis were established and programmed on a 650 IBM digital computer Taking 0 1 sec time intervals equations of motion were solved simultaneously (setting z = 0) for several assumed rates of the wing tilt (15, 30, 45 secs , etc)

The results are shown in Fig 10 and indicate that rate of wing tilt is one of the most important parameters in the whole constant altitude transition manoeuvre It indicates that as far as the wing angle of attack is concerned fast rates of wing tilt may be beneficial in a transition from hovering while in the opposite manoeuvre the slower the wing tilt the better However, even at wing tilt in 45 seconds, high wing angle of attack may be encountered (in a transition to hovering) which may require either some stall delaying devices (slats, etc), or still slower rates of the wing tilt For this reason, constant altitude transition to hover may be undesirable

The main advantage of the transition with variable altitude lies in that through the whole manoeuvre angles of attack of the wing can be maintained at a low (below stalling) value

The analysis of this type of transition can be somewhat simplified as the small angle assumption can be made with respect to β, which will simplify eq (19) and yield a v_{id} value as in forward flight

$$v_{id} = -\frac{V}{2} + \sqrt{\frac{V^2}{4} + \frac{w_R}{2\rho}} \qquad (23a)$$

In performing numerical calculations it may be more convenient to resolve all forces into those acting along the flight path and those perpendicular to it Forces along the path will give at every instant an acceleration along the path, while those perpendicular to it will give an instantaneous radius of the flight path Establishing maximum values for power and thrust as well as selecting tangential and centrifugal accelerations, a satisfactory flight path with a low wing angle of attack can be worked out

* Chief of Aerodynamics, Research and Development, Vertol Aircraft Corp

Controls and Stability

Controls

Tilt wing aircraft should be fully controllable in hovering and near hovering as well as forward flight In this latter regime control problems are no different from any fixed wing aircraft and thus will not be considered here In hovering and near hovering the tilt wing should possess controls capable of producing pitching, rolling and yawing moments basically independent of the aircraft translational speed In addition, as in helicopters, altitude control is required

Pitching and yawing control can be obtained in many different ways, such as

(*a*) Utilization of the exhaust of a special jet engine or engines mounted in the tail

(*b*) Deflection by vanes or other arrangements of the air flow produced by a special ducted fan located in the aft portion of the fuselage

(*c*) Fans submerged in vertical and horizontal stabilizers

(*d*) Application of cyclically controlled flapping rotor-propellers with a horizontal hinge offset sufficient to produce large enough hub moments*

(*e*) Utilization of wing flaps or ailerons submerged in the rotor downwash

As to the pitching control response requirements, it is difficult at present to set up any definite standards as there is no actual experience with this type of aircraft It may be stated, only, that in general control pitching moments should be large enough to compensate for (*a*) aircraft c g travel resulting from operational loading of the aircraft , (*b*) c g shift due to the tilt wing , (*c*) to balance aerodynamic moments which may develop in transition On top of providing the necessary trim, pitching controls should produce angular accelerations comparable with those required for helicopters of similar weight category

Definite yawing control response requirements cannot be established as yet either Some guidance, however, can be found in the specifications for helicopters of similar gross weights

Rolling control of the tilt wing in hovering can be provided most readily through differential variation of the collective pitch of rotor-propellers on the opposite side of the aircraft plane of symmetry It should be noted, however, that in this solution yawing moments (especially at lower than hovering tilt angles) can be introduced This is due to the yawing component of the moment produced by the differential rotor-propeller thrusts on one hand, and to the asymmetry of the wing lift forces resulting from different slipstream velocity and/or aileron deflection on the other While differential thrust components produce yawing moments, in the direction of co-ordinated turns, differential lift components act in the opposite way Both effects should be studied, therefore, in the design of rolling controls based on the differential propeller thrust principle

Because of the fact that the effectiveness of rolling control through differential collective pitch varies with the wing tilt, it is necessary during

* This may be necessary as deflection of the thrust vector itself in the presence of the wing acting as a straightening vane will probably be of little effectiveness

transition to gradually eliminate it and introduce the airplane-type roll control

Since, however, during transition in general and especially from forward flight to hovering, wing stall may be experienced, it may be desirable to provide roll controls independent of the wing angle of attack, its tilt and air flow velocity around it. Air jets located at the wing tips and producing forces perpendicular to the aircraft roll axis regardless of the wing tilt may be given as one of the many possible solutions

As to the desirable lateral control response, helicopter requirements may serve as a guide for hovering and near hovering flights, while for the final stages of transition fixed wing aircraft may provide the necessary standards

Altitude control in or near hovering can be most logically provided (as in helicopters) through the variation of the rotor-propeller collective pitch while turbines at the selected rpm will produce power necessary for a given pitch. It should be noted, however, that although in hovering collective pitch values at 75R are similar to those of helicopters (see Fig 5) they must be increased three to four times in cruise. Furthermore, in transition thrust variations and associated collective pitch changes may also be required. All this should be considered in the design of the rotor-propeller collective control system for the whole range of operation from hovering to V_{max}

Stability

Similar to the above considered control problems, those of stability in an established forward flight are no different than in fixed wing aircraft. Attention will be concentrated on hovering only. In this latter regime of flight stability problems in pitch and roll are of prime interest. As indicated in Ref 11 these two types of motion can be considered separately

Neglecting vertical motion of the aircraft, motion along the horizontal axis (x) and pitching attitude of the aircraft can be described by the following simplified linearized equations

$$\frac{W}{g} x = \frac{\partial F_x}{\partial x} x + \frac{\partial F_x}{\partial \theta}\theta + \frac{\partial F_x}{\partial \theta}\theta$$

$$I_y \theta = \frac{\partial M}{\partial x} x + \frac{\partial M}{\partial \theta}\theta + M_y \qquad (24)$$

where F_x is a general notation for the resultant of forces in the x direction

Knowing numerical values of the derivatives indicated in eqs (24), step-by-step solution of those equations can be programmed on a digital computer, so that the time history of the aircraft motion can be obtained. However a more convenient approach is obtained when the whole problem is set up on an analogue computer, as in this way the importance of various derivatives may be immediately ascertained simply by turning the potentiometer dials

This latter approach was chosen by P F Sheridan* in studying longitudinal stability of tilt wing aircraft in hovering

* Special Projects Engineer, in charge of Stability and Control of the Vertol 76

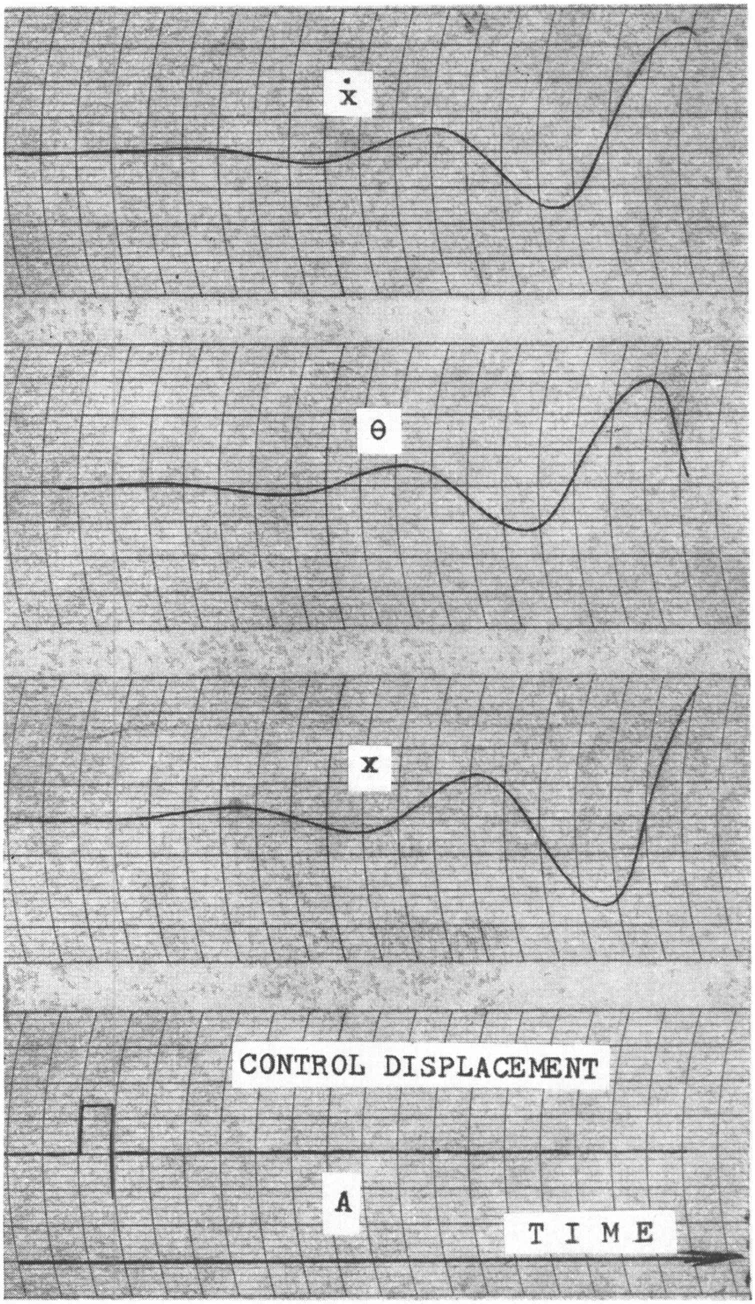

Fig 11 Analogue study of longitudinal dynamic stability in hovering Aircraft reaction to control impulse

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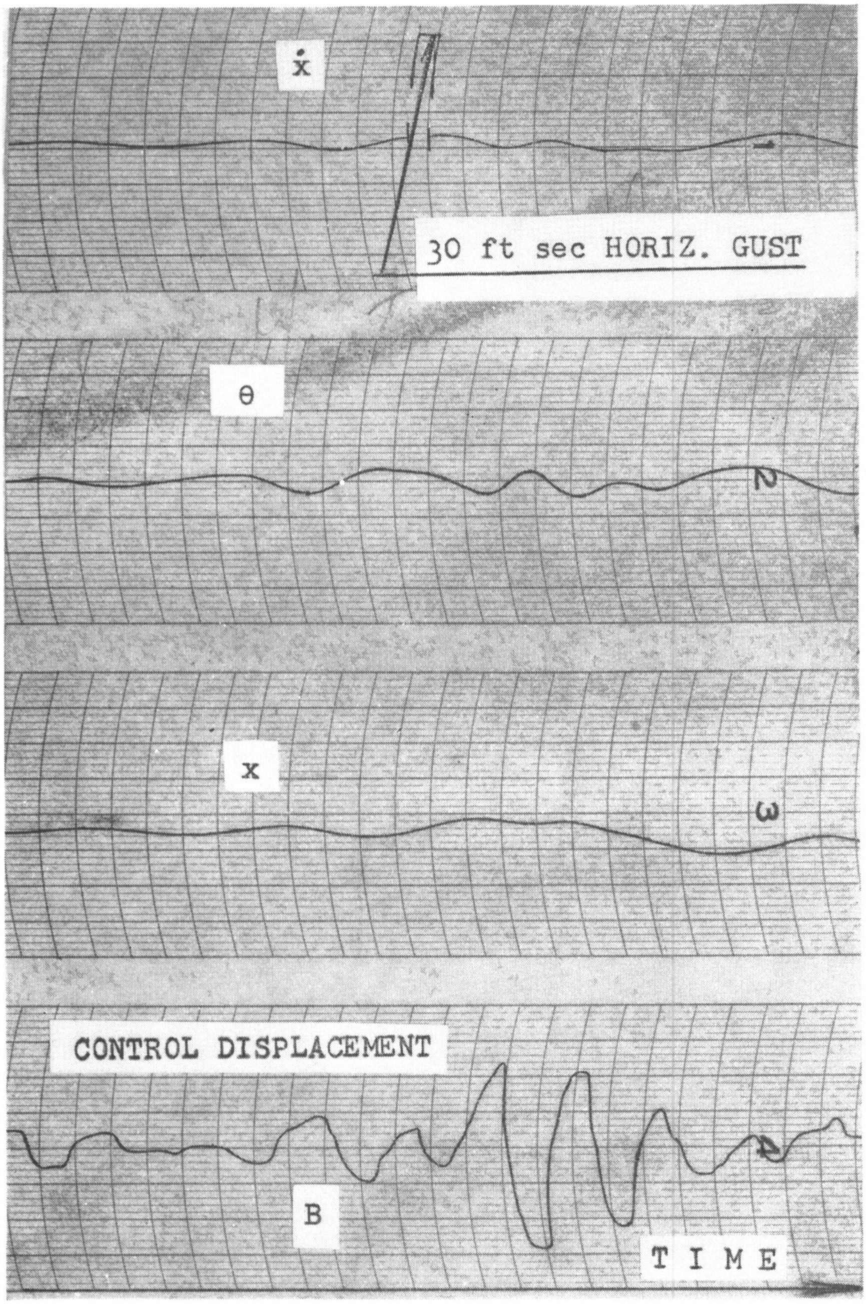

Fig 12 Analogue study of longitudinal dynamic stability in hovering Controlled hovering and reaction to 30 fps horizontal gust

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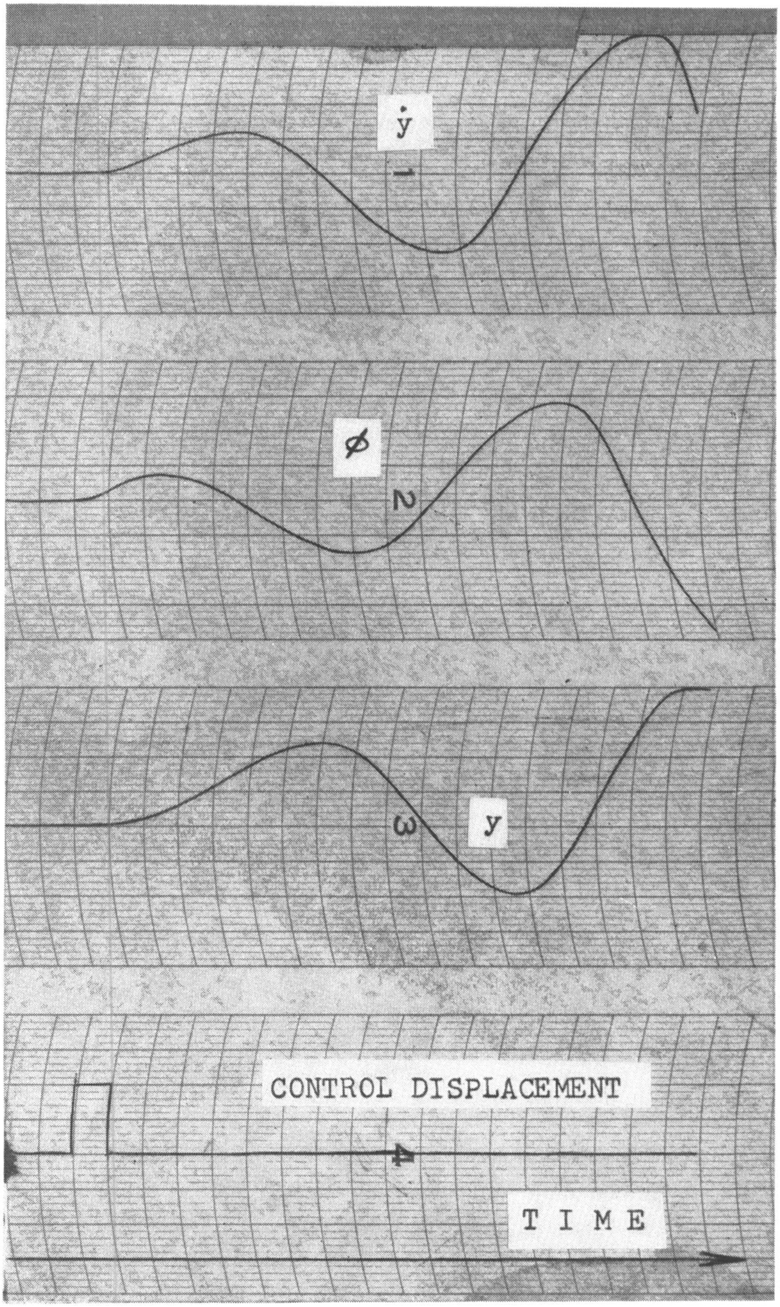

Fig 13 Analogue study of lateral dynamic stability in hovering showing aircraft reaction to control impulse

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Behaviour of the tilt wing aircraft in hovering is somewhat similar to that of a helicopter In both cases, the main source of instability lies in the nose-up pitching moments associated with the horizontal translation of the aircraft However, in the tilt wing aircraft pitch-up moments of the rotor-propellers (both rigid and articulated) may be increased by the aerodynamic forces acting on the wing, should they produce a positive moment about the aircraft c g

Typical analogue computer traces of aircraft motion following a pulse disturbance are shown in Fig 11

Analogue setups, so convenient for the solution of stability problems, may also be quite useful for pilot's familiarization with control responses of aircraft he is going to fly (Ref 12)

Fig 12 illustrates the time history of a steady hover maintained on the analogue by the pilot It can be seen from this figure that a continuous effort on the part of the pilot is required in hovering of a tilt wing aircraft However, installation of a pitch rate damper would render the pilot's task much easier

Lateral stability of the tilt wing aircraft should be more favourable than the longitudinal This is due to the absence of the de-stabilizing wing effect and to the presence of additional damping resulting from the side-by-side disposition of the rotors The linearized simplified equations of motion are as follows

$$M\dot{Y} = \frac{\partial F_Y}{\partial Y}\dot{Y} + \frac{\partial F_Y}{\partial \phi}\phi + \frac{\partial F_Y}{\partial \phi}\phi$$

$$I_x\phi = \frac{\partial L}{\partial Y}\dot{Y} + \frac{\partial L}{\partial \phi}\dot{\phi} \tag{25}$$

Fig 13 depicts the lateral motion (sideward translation and rolling) due to a pulse disturbance The period and amplification with respect to time is seen to be considerably better than those of the longitudinal case In this latter case, pilots found it much easier to " fly " the analogue than in the longitudinal

Conclusions of General Considerations

It may be concluded from the considerations of the design problems of the tilt wing type VTOL aircraft that

(*a*) This type may find an application in performing several military and civilian missions

(*b*) In order to achieve better zero range payload characteristics at normal (hovering) gross weight design should be optimized for VTOL performance, disregarding STOL aspects

(*c*) Means of achieving good fuel consumption in forward flight are the same as in the fixed wing aircraft (high Æ, aerodynamic cleanliness, high cruise altitude, etc) However, in order to maintain acceptable propeller efficiency in cruise, power plants should permit considerable reduction of rpm Switching off of some power plants may also be desirable (*d*) Control and stability in hovering and transition have their particular problems, but a solution for all of them appears to be technically feasible

(*e*) Many problems and especially those regarding flying qualities in hovering and transition should be intensively studied in the actual flight before final requirements for operational aircraft are established This flight programme can probably be achieved fastest and cheapest through special flight research aircraft such as the Vertol 76, which is financed by the U S Army and built under technical cognizance of the Office of Naval Research

Vertol 76 VTOL Tilt-Wing-Type Research Aircraft

Introduction

The Vertol 76 is a two place aircraft designed and manufactured to explore the tilt wing principle within a short period of time and at low cost On April 15, 1956, Vertol Aircraft Corporation received a contract to design, manufacture and test the Vertol 76 Eleven and one-half months from the receipt of the contract, it was designed and shop completed (Fig 15) with P J Dancik acting as Project Engineer and under technical supervision of L L Douglas, Vice President of Engineering , D A Richardson, Chief Project Engineer in Preliminary Design , and this author

Design Philosophy

Since the prime purpose of the flight research vehicle is to get flight test results in the shortest possible time and at the lowest possible cost, a small light aircraft is essential (Ref 1) and originally a much smaller aircraft (G W about 1900 lb , horsepower about 400) was considered However, due to a better availability of the T-53 turbine, the actual design work of the 76 model started around that engine Introduction of a more powerful engine (even when restricted to 600 H P) resulted in a growth of the whole aircraft Provisions were made for a co-pilot, the size was increased, and the gross weight grew to about 3,000 pounds

In order to obtain uncoupled pitch and yaw control moments as well as to use a known control system, it was decided that two separate propeller-type controls will be used, one for pitch and one for yaw In this way the present configuration was obtained

Since the Vertol 76 was conceived from the very beginning as a single engine aircraft, the problem of the engine out condition acquired a special importance Engine failure becomes most critical in hovering and early part of conversion, as at the disc loading of about 30 lb /sq ft and blade twist of —20° an autorotative descent becomes rather doubtful In view of this fact, an engine-out safety can be achieved in two ways

(*a*) Perform the whole conversion from hovering and back to hovering at an altitude sufficiently high to bring the wing to the airplane position through an emergency arrangement and make a recovery through a pull out

(*b*) Perform the whole conversion manoeuvre at such a low altitude that descent in the case of engine failure will not be catastrophic

Fig 14 (prepared by F R Mazzitelli) indicates that from a hovering altitude of 1,500 ft a recovery is possible However, the key to the success

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of this manoeuvre lies in a quick reaction of the pilot at the moment of engine failure (one second delay) followed by a proper displacement of the controls (controlled recovery in Fig 14) and obviously a quick tilt of the wing from hovering to the airplane position is essential When recovery from an engine failure is made through airplane flight it is not too important

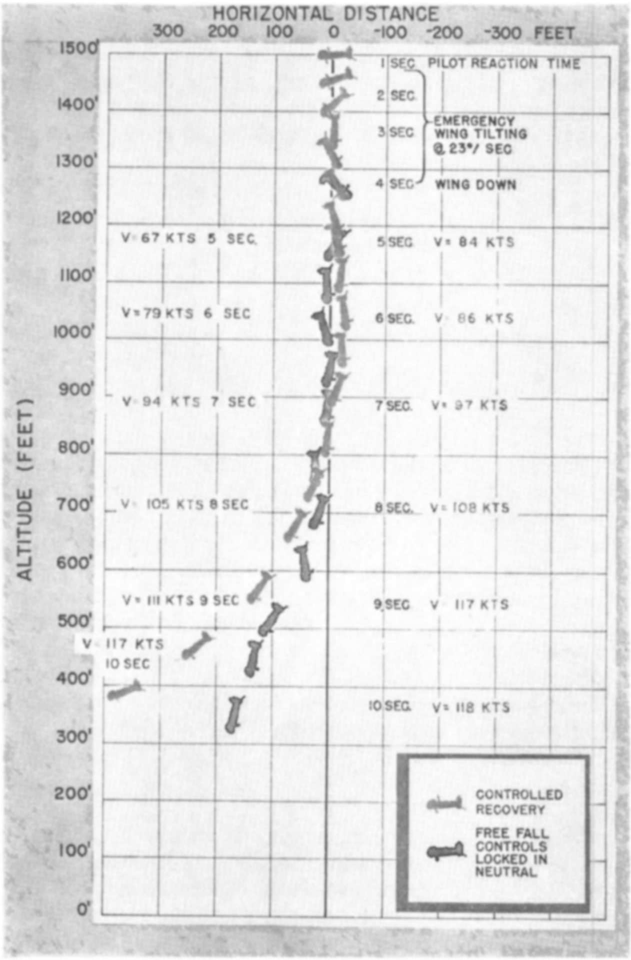

Fig 14 Vertol model 76 power failure from hovering at 1,500 ft

whether hovering controls can operate after engine failure or not However, at low altitude engine failure, it is important that the hovering controls remain in operation all the time and contact with the ground is made by the aircraft in an attitude decided by the pilot

The requirement of aircraft controllability even at 0 forward speed at the engine out condition leads to a solution where tail control fans are directly connected to the rotors drive system and not to the engine In this way, the accumulated kinetic energy of the rotor propellers, perhaps aided by some autorotational effects, will sustain the whole transmission system turning and thus provide the necessary control

At a high altitude conversion, to and from forward flight, there is a freedom of selecting the flight path (with varying altitude) in order to assure the best working conditions for both slipstream covered and exposed parts of the wing By contrast, in the close-to-the-ground conversion, altitude of flight must be kept practically constant and rate of the wing tilt remains the only important parameter (propeller thrust and power required result from the selected rate) in determining working conditions of the wing inside and outside of the propeller slipstream

An opportunity to examine more closely all problems associated with the conversion is given by tests conducted at the NACA tunnel at Langley Field with a 1/4 scale free-flight model of the Vertol 76 Force measurements on this model were performed in the full scale wind tunnel for the airplane configuration This was followed by hovering force measurements and free-hovering flights Finally, completely satisfactory free-flight transitions were made

An important decision regarding basic philosophy of design referred to the type of rotor-propeller to be used Because of simplicity, the rigid type was most attractive although some weight penalty was expected in that solution However, the main reason for eliminating rigid propellers (at least for the time being) was that during transition large hub moments may be introduced by them whose trimming might create an additional demand on the tail control forces In order to provide the largest possible margin for control, it has been decided to incorporate flapping hinges Although flapping hinges introduce Coriolis loads which are usually alleviated through the incorporation of vertical hinge, this latter solution was excluded because of the mechanical instability problems on the ground as well as in flight and additional complexity As to the Coriolis effects it is estimated that elastic properties of the shafting will permit to maintain the in-plane loads on the rotor-propeller blades at an acceptable level

Description

A Lycoming T-53 free turbine engine is mounted externally atop the fuselage for ease in maintenance and inspection Power from the engine is distributed by mechanical shafting to two 3-bladed rotor-propellers and two 4-bladed tail fans Both the rotor-propellers and tail fans are interconnected by shafting and in the event of power failure, override the engine through a sprag clutch installed in the upper central transmission box

The two main rotor-propellers are of wood construction with stainless steel protective leading and trailing edge strips Both steel strips connect to the pitch bearing housing and help to carry centrifugal forces

The cockpit controls are conventional and consist of pedals, cyclic stick and collective pitch lever Since an extra function of tilting the wing was required, a wing tilt switch was mounted on top of the pilot's cyclic stick

During the conversion cycle from hover to airplane flight the control

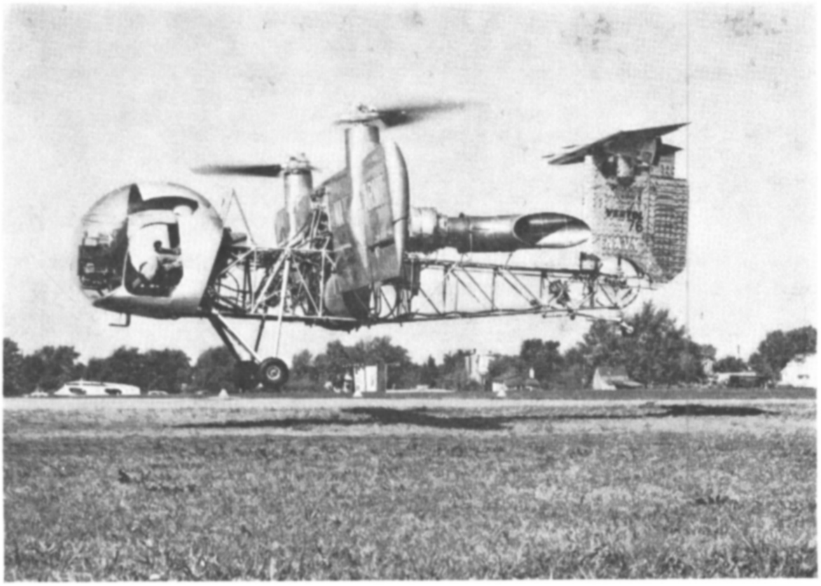

Fig 15 The Vertol 76 on its first hovering flight

system converts automatically to airplane controls The differential collective pitch system washes out while the aileron system, which acts in reverse in hover, reorientates itself and washes in Thus, with the wing in the full down position, roll control is achieved through the ailerons only

The collective pitch lever which is used for vertical ascent and descent in the hover regime is not effected by the wing tilt positions but merely acts as a propeller pitch change lever in forward flight

The body group and wing are conventional and to maintain low costs of this project and keep the development time and technical unknowns to a minimum, standard and existing designs have been utilized where possible

Preflight Ground Tests

To obtain specific data on the Vertol 76 ducted fan prior to flight, the aircraft tail assembly was mounted beneath a Vertol helicopter blade whirl tower so as to simulate forward flight

To determine whether the Vertol 76 research aircraft can be operated without danger of encountering mechanical instability, special tests on the actual aircraft were performed No mechanical instability was detected

ACKNOWLEDGEMENT

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SYMBOLS

AR	aspect ratio
C_L	wing lift coefficient
$C_{L_{opt}}$	wing lift coefficient at $(L/D)_{max}$
C_D	wing drag coefficient
$\bar{C}_L$	average rotor-propeller lift coefficient
c_l	section lift coefficient
c_{do}	section profile drag coefficient
$\bar{c}_{do}$	average section profile drag coefficient
c'_{do}	equivalent profile drag coefficient of wing plus empennage, $c'_{do} = (c_{do_w} S_w + c_{do_e} S_e)/S_w$
b	wing span, ft
D	drag, lb, or rotor-propeller diameter, ft
e	span effectiveness coefficient
F	force, lb
f	equivalent flat plate area, sq ft
g	acceleration of gravity, 32 2 ft/sec ^{2}
K_T	ratio of sea level SHP to altitude SHP
K	ratio of actual to ideal induced power
I_y	aircraft pitching moment of inertia, slug ft ^{2}
I_x	aircraft rolling moment of inertia, slug ft ^{2}
L	lift (lb), or aircraft rolling moments, ft lb
M	aircraft pitching moment
n	number of rotor-propellers per aircraft
PL/W	payload to gross weight ratio
$(PL/W)_o$	payload to gross weight ratio at zero range
P_{pr}	rotor-propeller profile power, h p
R	rotor-propeller radius, ft
SHP	shaft horsepower, h p
SHP/W	shaft horsepower per lb of gross weight, h p/lb
$(SHP/W)_{ins}$	shaft horsepower per lb of gross weight installed
T	thrust, lb
V	velocity along flight path, fps, or kn
V_{opt}	flying speed at $(L/D)_{max}$, kn, or fps
V	resultant flow velocity through rotor, fps
V_r	resultant flow velocity from rotor-propeller slipstream and V, fps
V_t	rotor-propeller tip speed, fps
v_{id}	ideal induced velocity of rotor-propeller, fps
W	gross weight, lb
$(W_F/W)_{f_{100}} = \gamma$	fuel to gross weight ratio for 100 n miles, %
w_R	rotor propeller disc loading, lb/sq ft
w_W	wing loading, lb/sq ft
w_t	equivalent flat plate area loading (W/f), lb/sq ft
x	non-dimensional blade station, or longitudinal displacement, ft
y	lateral displacement, ft
α_w	wing angle of attack, deg
α_i	wing incidence with respect to rotor-prop axis, deg
β	rotor-prop tilt with respect to flight path, deg
ϵ	lift to drag ratio
φ	rolling angle, rad or deg
φ_w	wing tilt from hovering position, deg
η_{pr}	propulsive efficiency
η_{tr}	ratio of rotor-propeller to engine shaft power
μ_f	ratio of aircraft flying speed to rotor-propellor tip speed
ρ	air density, slug/cu ft
σ	rotor-propeller solidity (total blades area/πR^2)
θ	rotor-propeller blade pitch angle, or aircraft pitching attitude
θ_x	rotor-propeller blade pitch angle at station x
θ_t	rotor-propeller blade twist

Subscripts

f	forward flight
h	hovering

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11 Zimmerman, C H "Some Stability Problems of Vertically Rising Aircraft," *Proceedings of the Second Annual Western Forum, American Helicopter Society*, 1955

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Discussion

After the showing of a film, the **Chairman** called on Mr SHAPIRO to open the Discussion

Mr J S Shapiro (*Consulting Engineer*) (*Founder Member*), expressed great pleasure at having the first opportunity of thanking the Author, saying that he had listened with interest and joy because the Author was a man who really lived his subject and was taking such a close part in something now being created, to which everyone looked forward with great interest and hope

The Author had been so self-critical and sober in his assertions, not exceeding the bounds of fairly well proved physics and aerodynamics, that it was extremely difficult to be critical, and he would, therefore, follow the implication of Dr Bennett's invitation to him, and offer a few philosophical remarks

As the Author had said, the convertible was not in itself a substitute for or successor to the helicopter, but another form of aircraft In fact, the helicopter was valuable because it was itself a convertible to fail to realise that would be to forget what the helicopter really was Whatever the mission, the value of the helicopter was that it had speed and range in addition to hovering power From that premise, the argument for the convertible could be developed , but his feeling had always