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STUDIES ON ROTOR AND FLIGHT DYNAMICS OF A HORIZONTALLY STOPPABLE HINGELESS ROTOR AIRCRAFT

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Summary

At the MBB Company a research aircraft has been defined within the category of V/STOL-aircraft combining the vertical flight capability of helicopters with the efficient high speed potential of fixed-wing aircraft. This stowed rotor aircraft concept, called Rotorjet, is supplied with thrust during hover and low-speed flight by two horizontally stoppable rotors and is provided with propulsion in high speed flight by fan-engines.

To begin with, a short description of the main features of this research aircraft concept is given. The paper then discusses fundamental investigations concerning the rotor characteristics and the control and flight dynamic behaviour of the aircraft during the transition flight and during the rotor stopping manoeuver. Analytical and model test results are presented.

Various aspects of the trim requirements and of the aircraft stability derivatives are described. Flight conditions with highly nonlinear characteristics during low-speed transition are examined. The paper shows that control and stability of the hingeless stiff flapwise rotor during the stopping phase pose no great problems. It is proved by dynamic simulations that both the transition from hover to forward speed and the rotor stopping manoeuver (including response due to gusts) can be performed with normal stability augmentation.

1. Introduction

Since the beginning of helicopter activities at MBB, a variety of rotary-wing V/STOL- projects have been started in the fields of pure helicopters, compound helicopters, tilt-rotor and tilt-wing aircraft. As has been recognized for many years, one way of combining the vertical flight capability of helicopters with the efficient high speed flight of fixed-wing aircraft is to apply the stowed rotor concept. A conceptual design study was conducted at MBB to define a stowed rotor research aircraft. The approach used in this study was based on a wide field of experience with hingeless rotor helicopters (BO 105) and with VTOL-fighters (VJ - 101). This work includes a significant amount of analytical, experimental, wind tunnel and flight test experience.

The stowed rotor concept, called Rotorjet, shows two horizontally stoppable rotors in a side-by-side arrangement. The purpose of the research aircraft was to prove the technical feasibility of the horizontally stoppable twin-rotor concept and to investigate the problems associated with the transition and conversion (start/stop) process. These aspects are as follows:

(1) Control and stability of rotors and aircraft during the transition and conversion phase
(2) Dynamic and aeroelastic characteristics of the coupled rotor-wing-fuselage system during the start-stop sequence
(3) Rotor vibratory loads during the transition/conversion modes

Analytical and wind tunnel studies were conducted in order to get an understanding of these complex problems.

The paper cannot deal with the whole scope of investigations conducted, but will concentrate on the problems associated with the control and stability characteristics of a stoppable rotor aircraft during the critical phases. The understanding of these aircraft characteristics is essential for a critical examination of this type of composite aircraft.

2. General Configuration

2.1 Concept Description:

The concept studies conducted by MBB resulted in the stowed rotor aircraft concept, shown in Figure 1. The aircraft, called "Rotorjet," is a twin rotor configuration with the two rotors mounted in a side-by-side position on the outer wings. The rotors are capable of being stopped and folded in a horizontal position and stowed into nacelles on the wing. After the conversion phase the aircraft is flying as a conventional fixed-wing airplane with forward thrust being provided by fan-engines. The research vehicle is designed for a gross weight of 5 tons (11,000 pounds) and a cruising speed of more than 700 km/h (380 knots). A description of the Rotorjet concept is given in Reference 1.

In general, the studies have revealed that this twin side-by-side horizontally stoppable rotor configuration has unique features. The most important ones can be said to be the following:

(1) Presence of only one conversion phase with a wide transition and conversion corridor
(2) Simplification of start-stop process due to small and stiff rotors
(3) Freedom from roll-pitch couplings due to side-by-side rotor arrangement
(4) No need for anti-torque devices
(5) High sub(super)sonic speed potential with reasonable L/D values

For the understanding of the results discussed, the following sections contain a rough description of essential components, for example, wing, rotor and control system.

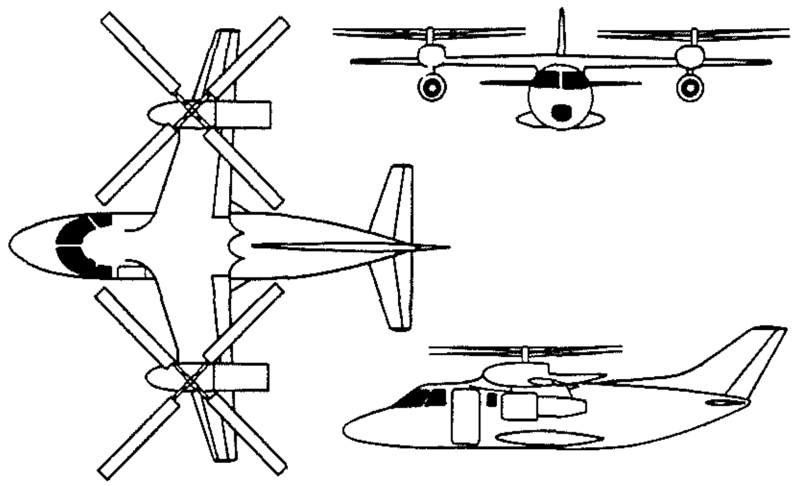

Figure 1 General Arrangement of Rotorjet Stowed Rotor Aircraft

2.2 Rotor Description

The horizontally stoppable rotor must be operated under a wide field of aerodynamic conditions. It must perform as a conventional helicopter rotor during hover and low speed, as a deloaded compound rotor during higher speeds, and as a slowed rotor during the stopping procedure. This change of operating conditions is of decisive importance for the design of the rotor system.

During the conceptual design study, the primary goal was not to optimize the rotor characteristics with respect to all technical problem areas. The purpose was much more to get a rotor system which made possible the study of the particular problems of the start-stop phase and of the technical feasibility of the horizontally stoppable rotor concept, in general.

Therefore, the rotor layout was governed by the following three design goals:

(1) Small rotor size with respect to the stopping problems
(2) Hingeless rotor with high blade stiffness to overcome the destabilizing effects during the stopping sequence
(3) Low or zero blade twist to minimize the rotor hub moment and to simplify rotor deloading and stopping

The basic rotorsystem of the Rotorjet concept is a four-bladed hingeless rotor having a diameter of 21 feet, a 12.7% solidity ratio and a tip speed of 820 fps. The rotor type can be classified as a stiff flapwise, stiff in-plane hingeless rotor, having fundamental frequency ratios of $\omega_\beta/\Omega \simeq 1.50$ (flapping) and $\omega_\zeta/\Omega \simeq 1.40$ (in-plane) at nominal rotor speed.

The rotor dynamic characteristics with respect to control and stability are determined by the rotor flapwise stiffness, or fundamental frequency ratio. Figure 2 illustrates the general influence of flap frequency on flapping response, on moments and phases, shown for 100% RPM. It should be noted

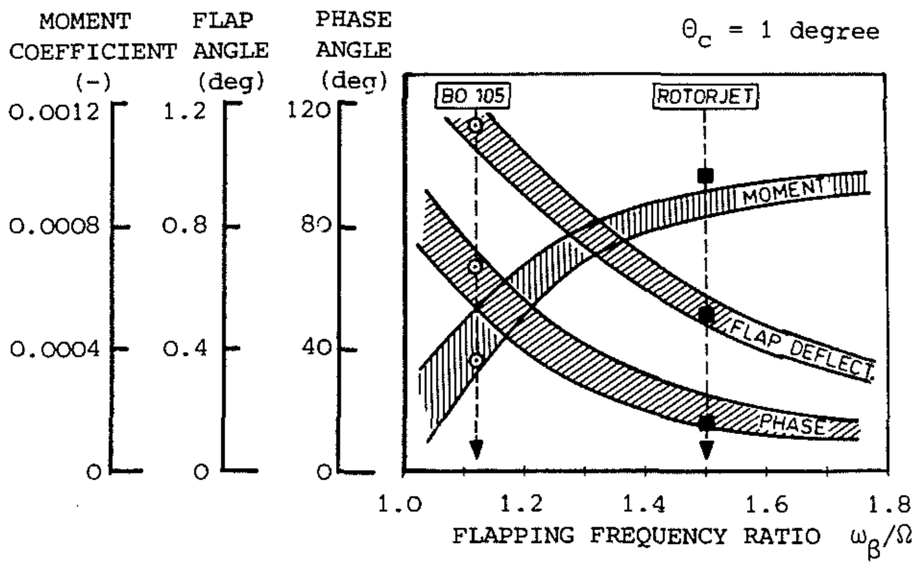

Figure 2 Control Behaviour as a Function of Rotor Stiffness

that, while the flapping amplitudes due to cyclic control decrease, the control moments increase with flap frequency. The comparison of a stiff flapwise rotor (Rotorjet) with a typical soft flapwise rotor (BO 105) shows that the nondimensional moment capacity for the stiffer rotor is about three times higher and the flapping amplitudes are reduced 60 percent in comparison to the softer rotor. The control phase angle has a magnitude of 10 - 15 degrees.

During the stopping-starting process the rotor RPM is reduced and, therefore, the dynamic characteristics of the blade over speed range are of interest. The blade frequency plot for the flapwise and inplane bending modes is shown in Figure 3. During the phase of stopping the rotor the blades are passing through a number of harmonics of rotor speed and are, therefore, subject to higher harmonic airload excitation. This fact leads to the occurence of high blade moment response at the resonance frequencies. Resonance effects of this kind during the conversion phase have been investigated by analytical studies and model tests. However, these results are not included within the scope of this paper.

A factor of major importance is the relative stiffness behaviour over rotor speed. Due to loss of centrifugal force the flap frequency decreases, however, the elastic blade root restraint causes an increase of frequency ratio with decreasing rotor RPM. Figure 4 shows the variation of ω_β/Ω during the stopping procedure for the hingeless rotor. This relative stiffening is of paramount importance for the stability of the blade flapping motion during the start-stop manoeuver.

In the diagram of Figure 4, the change of equivalent system used in the analytical model is also indicated. The equivalent flapping hinge offset increases from 35 % to 45 % of radius as the rotor slows down. This amount of hinge offset in comparison to the 15% offset of a typical soft flapwise hingeless rotor (BO 105) indicates the stiffness of this rotor.

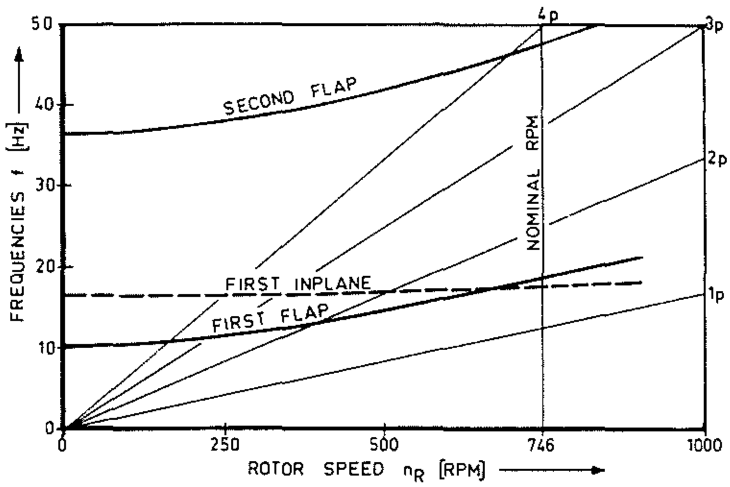

Figure 3 Main Rotor Blade Frequency Spectrum

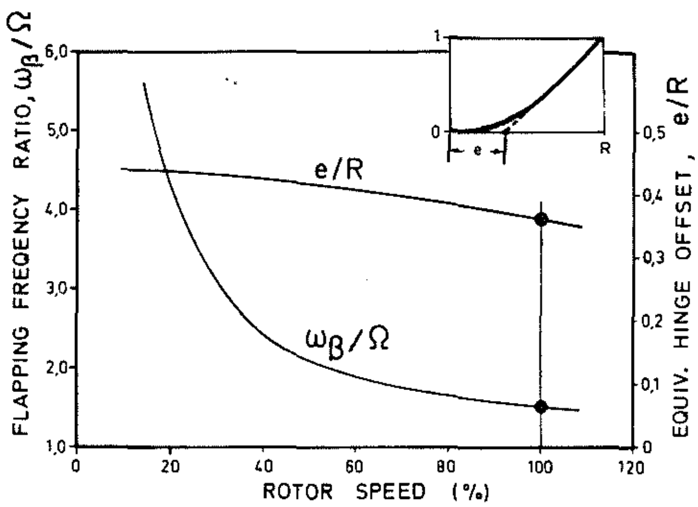

Figure 4 Effect of Rotor RPM Reduction on Flapping Frequency

2.3 Other Systems

Wing: The wing design is of critical importance for a stoppable rotor aircraft. It has to incorporate both high-lift technology to provide low conversion speed and high wing loading to give economic cruise flight performance. For a conversion speed of 140 knots a maximum lift coefficient of 2.3 is required, which is obtained by usual high lift devices.

Power Distribution: The power distribution is modulated according to the flight mode. In the helicopter flight during hover and low speed transition the fans produce zero-thrust, the total shaft power being available for producing rotor lift. With increase of transition speed the fans are used to provide increasing propulsive thrust, while the rotor is slowly deloaded.

Transition-Conversion Control: Conventional helicopter controls are connected to fixed wing surface controls. A rough description of this control system is given in Table I. During hover and low-speed flight the aircraft is controlled primarily by the rotor, i.e. collective pitch for vertical control, longitudinal cyclic for pitch control and differential collective pitch on the two rotors for roll control. Yaw control is provided by differential thrust of the fans.

CONTROL AXIS	HELICOPTER CONTROLS	FIXED WING A/C CONTROLS
VERTICAL	COLLECTIVE PITCH	FLAPS
ROLL	DIFF. COLL. PITCH	AILERONS
PITCH	CYCLIC PITCH	ELEVATOR
YAW	DIFF. FAN-THRUST	RUDDER

TABLE I CONTROL SYSTEM

With increasing airspeed the rotor controls are phased out with the fixed-wing surface controls becoming more effective. During the stopping process the helicopter controls are completely disengaged and the aircraft is controlled in the conventional airplane manner. The different controls are connected on the cockpit control devices by an automatic mechanism.

3. Wind Tunnel Model Tests

From 1968 to 1969, a program of model testing was conducted in the 5 by 7 meter wind tunnel of the Eidgenössische Flugzeugwerke at Emmen, Switzerland. Three phases of rotor operation, all unique to stowed rotor aircraft, were tested: The transition flight regime, the stopping and starting of the rotor and the blade folding sequence. The model permitted the determination of aeroelastic behaviour of the rotor, of control and trim characteristics, of stability derivatives and of airloads. The results of this model testing are reported in Reference 2.

3.1 Model Description

The model shown in Figure 5 consists of a 1/3-scale model rotor with original tip Mach-number. This model was completed with a semi-span wing-fuselage model. The rotor was 2 m (6.5 feet) in diameter and was of the hingeless stiff flapwise type. The blades were dynamically similar to full scale-design with respect to the first flapwise frequency. The powered rotor system and the wing model were separately mounted with no mechanical connection.

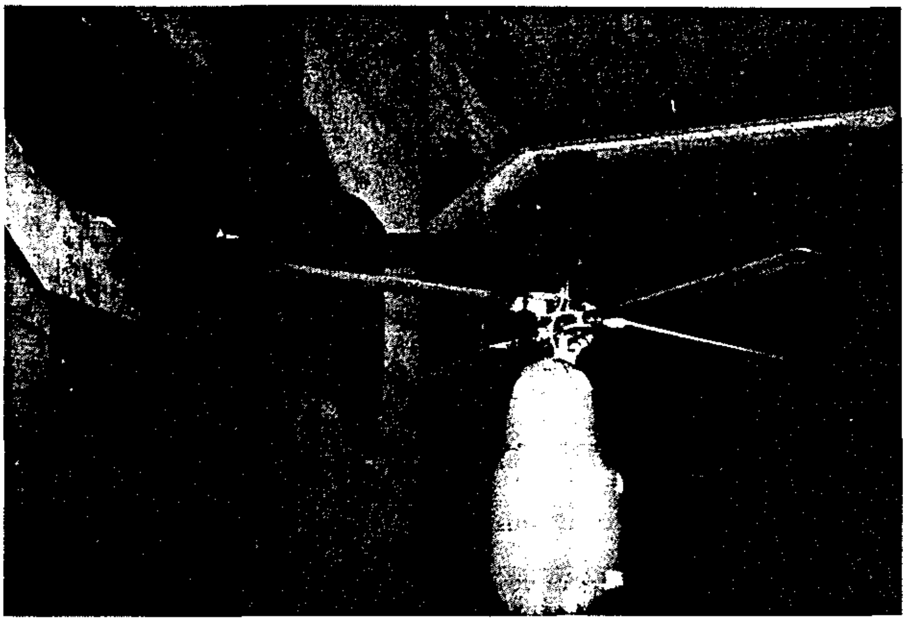

Figure 5 Semi-Span Aircraft Model with 6.5 foot Diameter Stoppable Rotor

Two types of rotors were tested. The majority of experiments concerning the rotating and stopping rotor phase was conducted with a three-bladed rotor. A four-bladed rotor, equipped with a blade folding mechanism, was used for the experiments dealing with the blade folding operation.

Inclination and distance between rotor and wing was varied in order to examine in more detail the influence of rotor-wing interference on the transition flight behaviour. The rotor had a conventional helicopter control system with collective and cyclic pitch. Shaft angle of attack could be varied. Power was provided by a 250 hp electric motor. The wing was equipped with double-slotted flaps.

For investigation of the individual forces and moments the rotor was mounted on a six-component balance system, and the wing-model on a separate four-component system.

3.2 Wind Tunnel Measurements

The separated model mounting and the separation of balance systems allowed for the determination of different influences, such as,

- isolated rotor characteristics
- complete model characteristics
- influence of rotor vertical position and shaft inclination relative to the wing.

Flight parameters that had an influence on the different flight modes were varied. At wind speeds of up to 250 km/h pitch attitude was measured between -6 and +12 degrees. At the conversion speed of about 23o to 250 km/h the rotor stopping phase was tested within the full range from 100% down to zero RPM, with collective pitch and shaft angle of attack kept close to zero.

Rotor forces and moments along with signals from the blade flap, chord and pitch link strain gauges were recorded. The test results are discussed in the following section in connection with the analytical studies.

4. Analytical Model

4.1 General Capability

The analytical model used for convertible rotor aircraft calculations is shown in Figure 6. The entire aircraft model allows for the representation of many different concepts with respect to the following features:

- General aircraft configuration, (i.e. rotor-wing arrangement, number of rotors)
- Type of transition/conversion (i.e. tilting and stowing concepts)
- Type of rotor start-stop process (i.e. horizontally or vertically stoppable rotors)

The computer program named SACRA (Stability Analysis of Convertible Rotor Aircraft) is a universal aerodynamic/flight dynamic program encompassing the following procedures:

- Steady state trim calculation
- Aerodynamic and load calculation for the rotors
- Aerodynamic calculation of fixed-wing surfaces
- Dynamic control and stability calculation of the entire aircraft
- Transient response calculation for transition and conversion phases

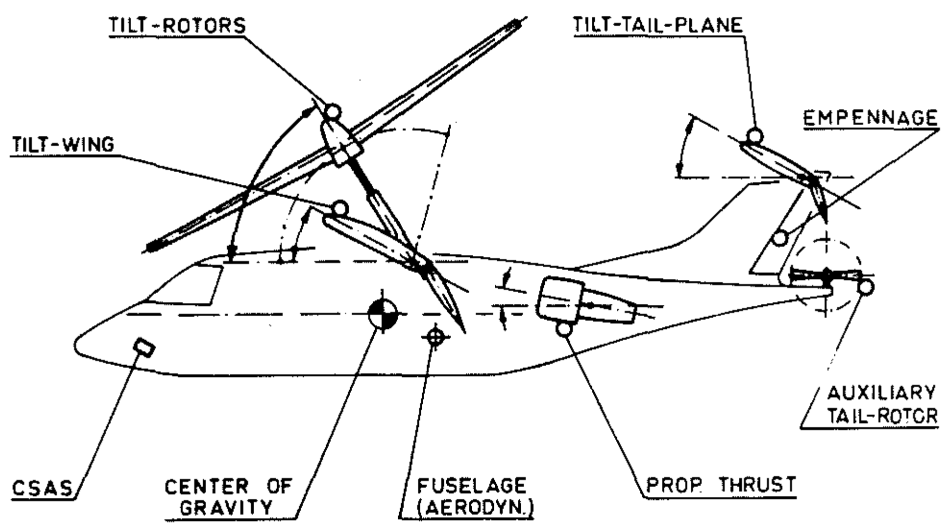

Figure 6 Analytical Model for Convertible Rotor Aircraft

4.2 Mathematical Model

Rigid Body Degrees of Freedom: The rigid-body modes in the three axes are required for accurate prediction of the flight dynamic characteristics of convertible rotor aircraft. Roll-, pitch and yaw together with longitudinal, lateral and vertical degrees of freedom are considered.

Blade Degrees of Freedom: In the case of hingeless rotors the elastic cantilevered blades are represented by an equivalent hinged, spring restrained rigid blade, simulating the first flapwise natural mode and frequency. This "equivalent system" representation has proved a valid instrument for all flight dynamic investigations of hingeless rotors (see Reference 3). In order to minimize the number of degrees of freedom, the first inplane mode (lead-lag) and the higher-frequency blade modes are neglected. The flapping degrees of freedom are calculated separately for all rotors, which is necessary for an exact representation of stability and control derivatives, especially with respect to nonsymmetric conditions. Variations of flap frequency during start-stop processes are accounted for in the flight dynamic calculations. Variable rotor RPM is included in order to simulate stop-manouevers as well as power failures.

Aerodynamics: The aerodynamic blade calculation is based on current blade element theory, with aerodynamic coefficients taken from two-dimensional airfoil data including stall, reverse flow and compressibility effects. Emphasis is placed on an appropriate description of the induced velocity in the rotor disc. The significant hub moments generated by hingeless rotors cause large azimuthal nonuniformities in downwash and, therefore, require additional longitudinal and lateral gradients over rotor disc. This is accomplished through a theory which applies momentum theory to azimuthal and radial rotor elements locally. Control power and stability derivatives proved to depend to a very great extent on nonuniform downwash effects.

Wing and tail-plane are computed by simple lifting-line theory using measured data of 2D-airfoil coefficients. A simple representation of interference effects between rotor-wing and wing-tailplanes is included.

Control Mechanism: A complex control system in the program provides for the simulation of the engagement and disengagement of the different controls during the transition and conversion modes. Pilot inputs on all controls and tilt procedures can be simulated dynamically. It is possible to include stability augmentation systems and the pilot's behaviour by using suitable pilot functions. In order to describe the aircraft's response to external disturbances, gusts can be simulated. The model is described in Reference 4.

5. Isolated Rotor Investigations

During the transition and conversion mode, the rotors are operated at quite different flow conditions. Before examining control and stability of the whole aircraft, some studies are conducted on an isolated rotor.

Influence of Rotor Thrust: Cyclic control moments are shown in Figure 7 as a function of rotor collective pitch for hovering flight. It can be seen from this diagram, that theoretical calculation of control moments of a high disc loading rotor depends substantially on the appropriate description of the induced downwash. A theory with a uniform downwash model would yield too large cyclic moment capacity and give erroneous phasing angles.

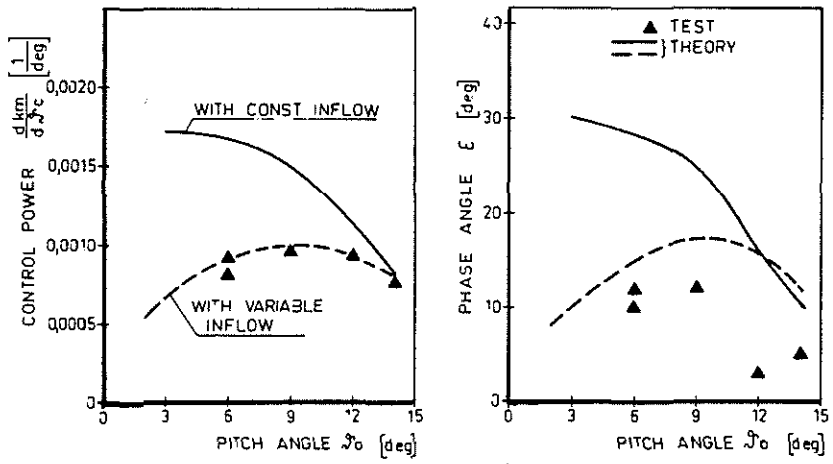

Figure 7 Control Power Versus Thrust (Hover)

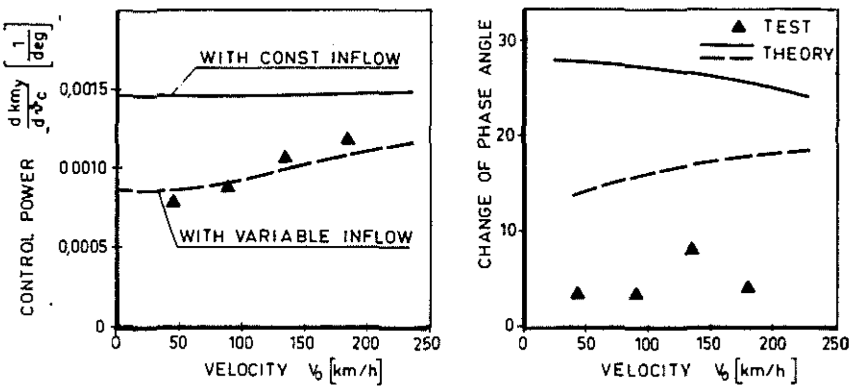

Figure 8 Control Power Versus Trim Speed (Isolated Rotor)

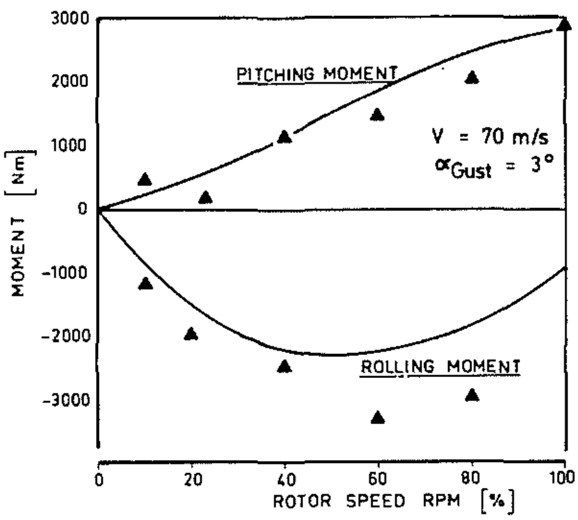

Figure 9 Rotor Hub Moments Due to Gust

Influence of Flight Speed: Longitudinal control sensitivity of the isolated rotor over airspeed is shown in Figure 8. The trim settings of collective pitch and rotor attitude are held constant at those values at which the transition process is performed. The variation in the sensitivity of the longitudinal cyclic moment is shown to increase by about 50 percent over the transition range.

Influence of Rotor Speed: In order to minimize the risks of the start-stop sequence it is necessary to unload the rotor from lift and from hub moments as far as possible.

During the investigations on the isolated rotor, shaft angle inclinations have been varied to simulate disturbances due to gusts over the whole RPM range. Typical results are presented in Figure 9, showing the sensitivity of rotor roll and pitch moments to gust angle during the slowing process.

A comparison between the cyclic moment capacity and the gust moments shows that the cyclic pitch requirements for compensating the gust moments are low.

6. Aircraft Trim during Transition and Conversion

6.1 Trim Parameters

In the following sections the trim characteristics of the whole aircraft will be explored, covering the level flight speed range from hover to 250 km/h and the full rotor speed range from 100% to zero RPM. Rotor collective and cyclic pitch together with tailplane deflections are shown in Figure 10. Collective pitch angle is reduced continuously from hover to forward flight, yielding the desired flat angle for deloading the rotor at conversion speed. Longitudinal control with airspeed is affected by the continuous disengagement of helicopter control and the engagement of lifting surface control. Because of the high tailplane incidence, the tail loading becomes an uploading at speeds around 30km/h, so that the rotor has to counteract this moment with a reduction of longitudinal cyclic. Aircraft pitch attitude is held constant at -5 degrees up to about 200 km/h and is then reduced to +1 degree, when approaching the conversion speed.

The stopping process is determined by zero collective setting and zero shaft angle. It should be noted that the cyclic feathering required to produce zero shaft moment becomes zero as RPM decreases. This ideal condition will be modified later; it will be shown that only small cyclic angles are needed to compensate for gust disturbances. It should further be noted that there is no lateral control requirement during the whole speed range. This inherent symmetry about the roll axis (no longitudinal to lateral coupling) is a unique feature of this aircraft concept.

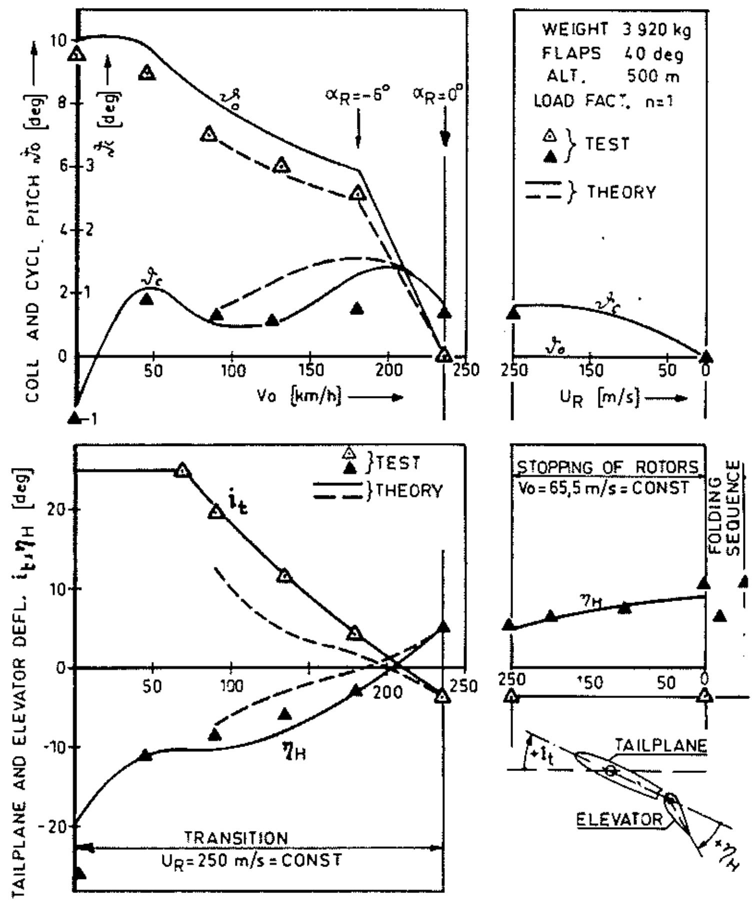

Figure 10 Control Settings During Transition and Conversion Flight

6.2 Forces and Moments

Level flight trim loads on rotor, wing and tailplane were obtained during the trim calculations, these same essential results being shown in Figure 10. The lift sharing diagram, Figure 11 , shows that the wing downloading becomes an uploading at speeds as low as 100 km/h, resulting in low power requirements during helicopter flight. The total aircraft weight is shifted to

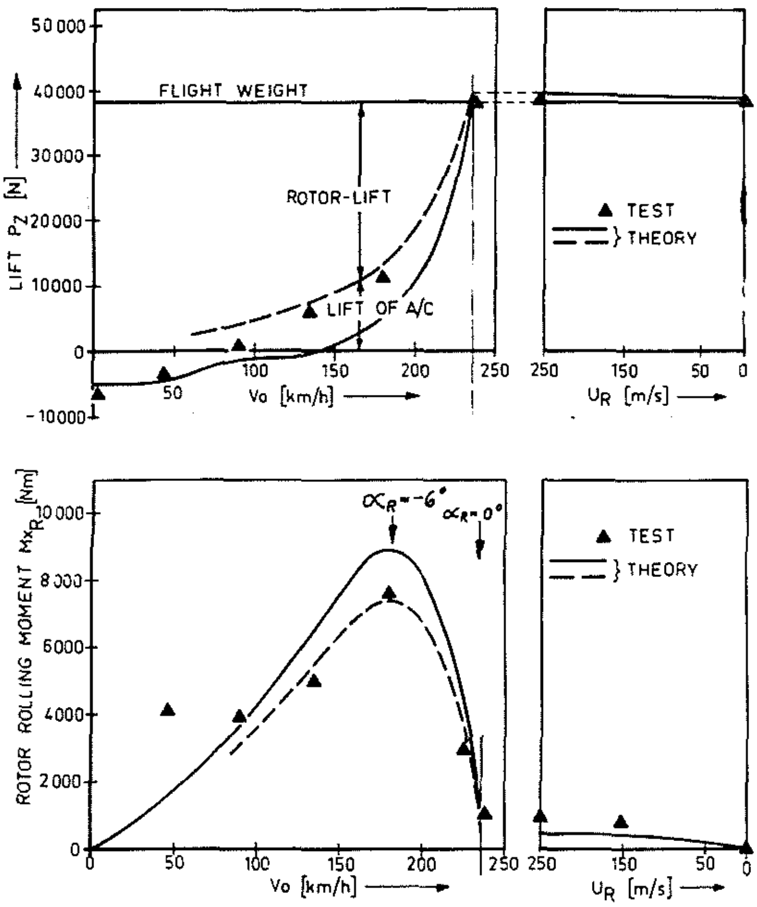

Figure 11 Forces and Moments During Trim Flight

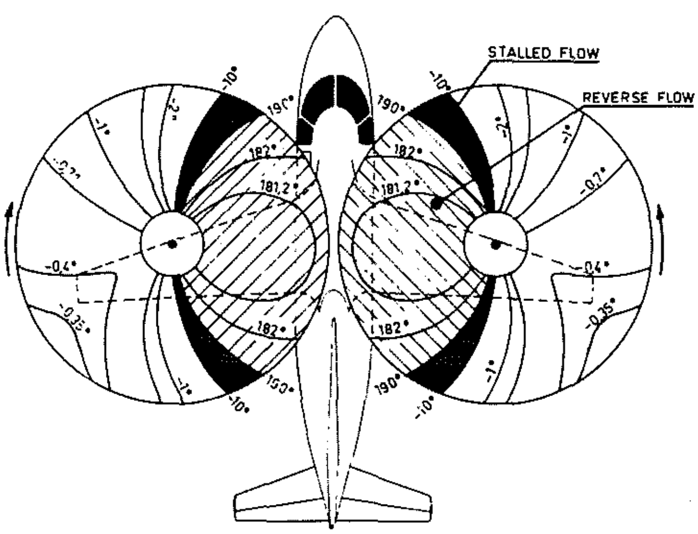

Figure 12 Angle of Attack Distribution at Unloaded Rotors at V = 235 km/h, 12.5% RPM

the wing at the conversion speed of 235 km/h. The two theoretical results shown are based on two different assumptions about rotor-wing downwash influence. One can see from the diagram, that the simple downwash theory with pure geometric calculation of the downwash angle (solid line) is only true near hover condition. The dotted line represents a largely reduced downwash effect and it can be seen that the real interference loading lies somewhere in between. It is obvious from these results, that improved downwash information is necessary for a complete understanding of the trim characteristics, especially within the medium flight range.

The rotor rolling moments, as shown in Figure 11, are not considered to be a problem, since the rotor has to be designed for a much higher amount of moment capacity. Furthermore, these moments can easily be brought down to a lower level by applying a slight, fixed lateral control. From the flight dynamic perspective, it is evident, that due to the symmetrical rotor arrangement the rolling moment on one rotor is counteracted by that of the other under all flight conditions.

Figure 12 is a picture showing this inherent symmetry (angle of attack distribution over a rotor disc). The case shown is for an unloaded rotor at 235 km/h speed, and slowed down to 12% RPM (advance ratio μ = 2.1).

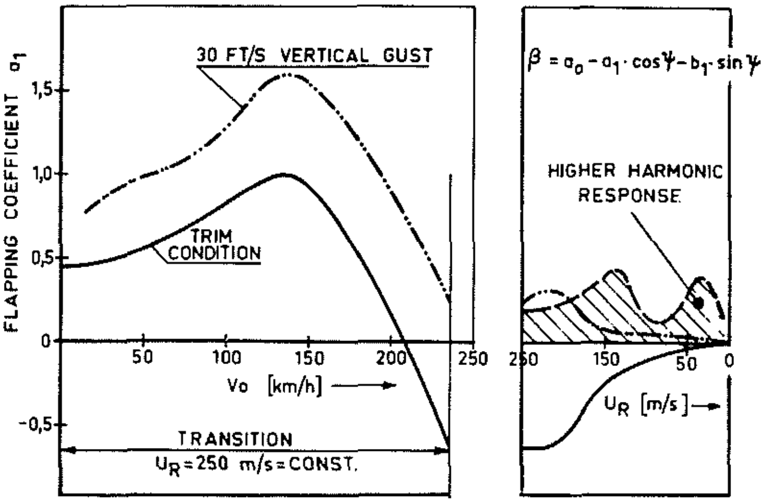

Figure 13 Blade Flapping Amplitudes in Trim Flight With and Without Gusts

6.3 Gust Sensitivity

Finally, attention must be given to gusts which are encountered during transition and start-stop manoeuvers. Typical calculation results are presented in Figure 13 which shows the effect of a 30 fps gust on the blade elastic deflections. The change of flapping angle due to a vertical gust in forward flight is primarily of first harmonic order (a_1), the maximum flap angles being about 1.5 degrees. Within the slowing phase there are higher harmonic contents, resulting from the blade resonance conditions. It is an important fact that flap deflections due to gusts during the stopping process remain below the normal forward flight deflections.

7. Stability and Control Characteristics

When examining the stability and control characteristics of a convertible rotor aircraft, two aspects must be considered. First of all, these flight conditions, for which the characteristics are determined, must represent real trim conditions. It lies in the nature of rotor powered VTOL-aircraft, that in the very low speed range several stability derivatives show highly nonlinear character and, therefore, are very sensitive to the manner in which the aircraft is trimmed. Second of all, proper attention must be given to the interference effects between rotors, wing and tailplane. The rotor downwash impact on the wing and the subsequent wing-tail interference change rapidly with increase of airspeed.

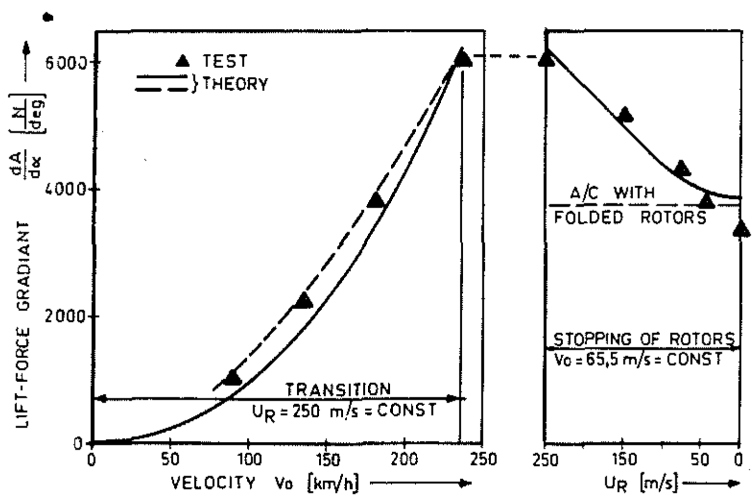

Figure 14 Aircraft Lift Slope Derivative During Transition and Conversion

7.1 Stability Derivatives

The following discussions concentrate on the longitudinal stability during the transition range and during the start-stop phase. The most interesting terms defining the dynamic longitudinal stability will be examined. Analytical and test results will be brought in.

Aircraft Lift Slope: A first derivative which is of importance in the vertical motion of the aircraft is the change of vertical force with variation in angle-of-attack. This aircraft lift curve slope is shown in Figure 14. The general trend versus speed is comparable to pure helicopters; at maximum transition speed about 40 percent of the lift gradient is provided by the two rotors.

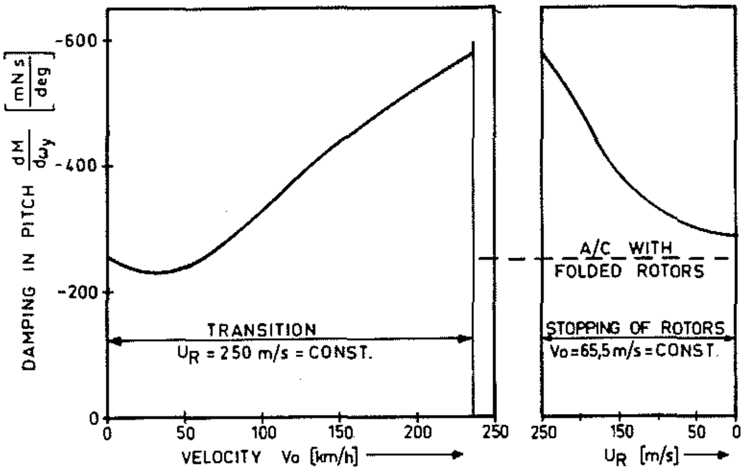

Figure 15 Pitch Rate Damping During Transition and Conversion

Pitch Rate Damping:

Pitch rate damping, of the aircraft, shown in Figure 15 is found to be low in comparison to hingeless rotor helicopters, especially when the high moment of inertia of the aircraft is taken into account. The only contribution in hover and low speed stems from the rotors. Their relatively low damping is a result of their counteracting effects of high flapwise stiffness and high blade Lock-number (low blade mass). With increase of airspeed the horizontal tail becomes active, providing sufficient aerodynamic damping in forward flight. Note that about 60 percent of total aircraft damping at conversion speed comes from the two rotors. Experimental data are not available from the wind tunnel tests.

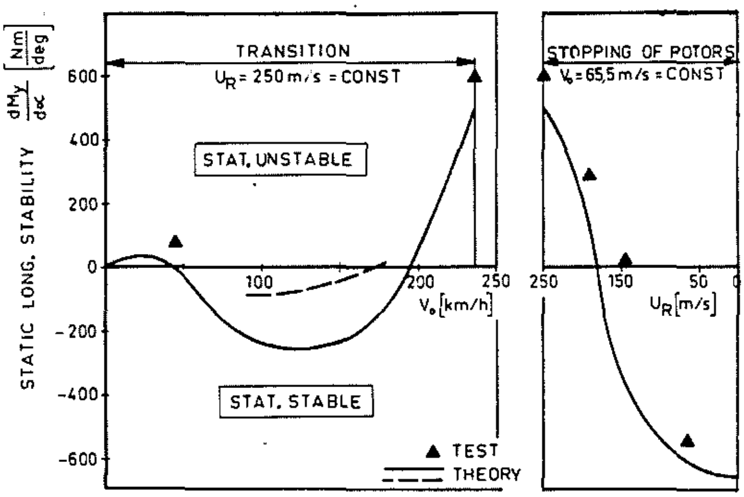

Figure 16 Angle-of-Attack Stability During Transition and Conversion

Static Longitudinal Stability: The change of pitching moment with respect to angle-of-attack, or vertical velocity (M_w), is one of the determining derivatives for the dynamic stability. The curve of M_α versus speed, shown in Figure 16, can be explained by the fact that highly unstable characteristics of stiff rotors are combined with inherently stable characteristics of a fixed-wing airplane. The diagram shows negative (stable) values at medium speeds and an unstable M_α-derivative at conversion entry speed. As the rotor slows down, its unstable M_α-contribution is reduced and is overcome by the fixed-wing aircraft properties, resulting in a statically stable aircraft, when the rotors are stopped.

The theoretical results show some uncertainty in the medium speed range, because of the lack of information about the downwash interference mechanism between the rotor, wing and tailplane. In contrast to this fact, the rotor instability can be predicted quite confidently, as has been proven from the comparison with isolated rotor test results.

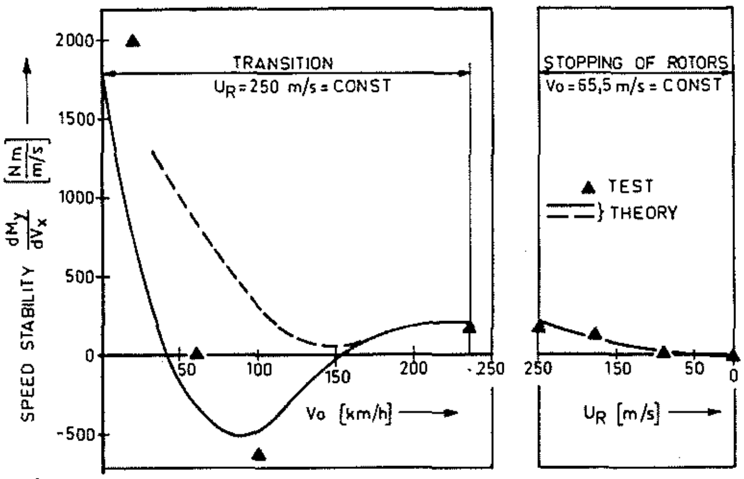

Figure 17 Speed Stability During Transition and Conversion

Speed Stability:
The speed stability (Figure 17) is high at hovering condition, and reduces rapidly with increase of airspeed. This shape is a result of the large positive value of the hingeless rotors and a negative contribution from the high incidence horizontal tail. This aerodynamic effect has already been described in connection with trim angles. It is important to note that the dip in the M_u -derivative within the medium transition range can be evened out by another tail incidence angle program, for example.

In general, the nonlinearity of the M_u-derivative over flight speed is predicted quite successfully by theory. The differences between the two assumptions for downwash-interference in the theory is an indication of the sensitivity of important derivatives to interference effects, and to aircraft trim conditions, as well.

7.2. Dynamic Stability

When discussing the dynamic stability characteristics, only a rough overview shall be given, instead of an exact description of the different *modes of motion*. Theoretical results of stability values in terms of time to double amplitude and time to half amplitude of the critical longitudinal motion are given in Figure 18. During hover and low speed, the aircraft's dynamic characteristics are determined by the large positive speed stability and the low pitch angular damping. This combination produces a relatively fast oscillatory instability, showing a time to double amplitude in the magnitude of three to four seconds and a period in the order of seven seconds.

As the forward speed is increased, the speed stability decreases and may even become negative, as discussed in Figure 17 . Due to the strong dependence of this derivative on rotor downwash interference effects and trim conditions, in general, a variety of dynamic characteristics are apparently possible at the intermediate flight conditions. This fact is indicated also by

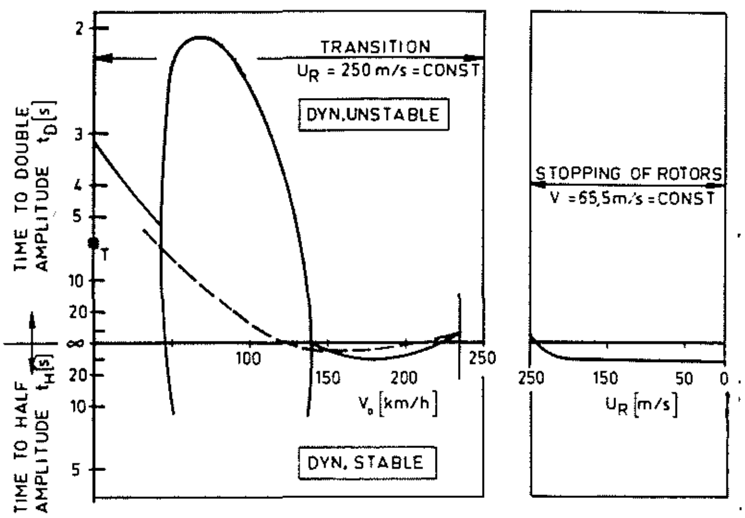

Figure 18 Dynamic Longitudinal Stability During Transition and Conversion

the two theoretical results, representing two different assumptions of downwash interference. At high transition speeds, the oscillatory motion tends to become stable, due to small values of speed stability and only moderate angle-of-attack instability.

The dynamic characteristics during the rotor stopping phase are influenced by the stabilizing trend in the angle-of-attack stability, (see Figure 16), while the aircraft pitch rate damping remains high. This results in a stable aircraft during the conversion phase.

A qualitative comparison of these stability characteristics to helicopters with hingeless rotors shows, that helicopters are more stable during hover and low speed conditions, because of much lower speed stability and higher damping. Stability characteristics in the medium speed range between these two types of aircraft can be quite similar if the tendency toward negative (unstable) speed stability of the convertible aircraft can be curbed. Means for doing this are well known. At the high transition speed range, the dynamic stability behaviour is superior to that of hingeless rotor helicopters which usually show greater dynamic instabilities at higher forward speeds.

7.3 Control Characteristics

The control system considered in these studies includes a connection between conventional helicopter controls and fixed wing surface controls, as previously described. The longitudinal control characteristics, Figure 19, show the lowest control power available in hovering flight, where control is provided only by rotor cyclic pitch. For the assumed moment of inertia of the aircraft, the pitch acceleration is of the order of 0.5 radians per seconds squared per inch stick input. Together with the damping moments, as shown in Figure 15, these control characteristics reach twice the value of MIL-H-8501A IFR-require-

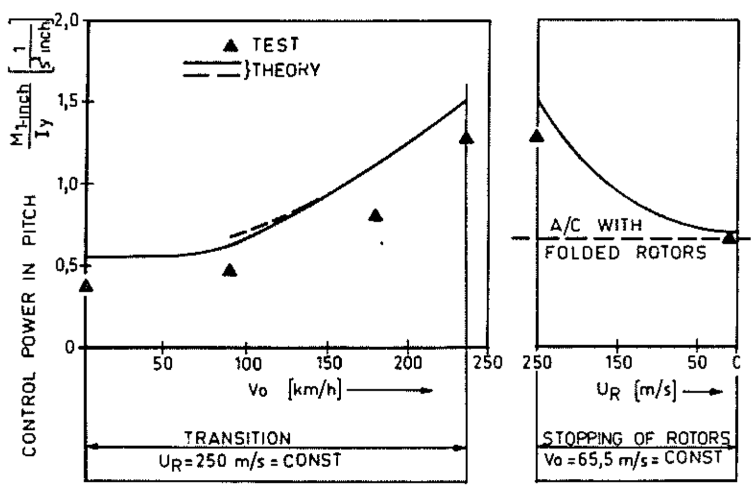

Figure 19 Pitch Control Power During Transition and Conversion

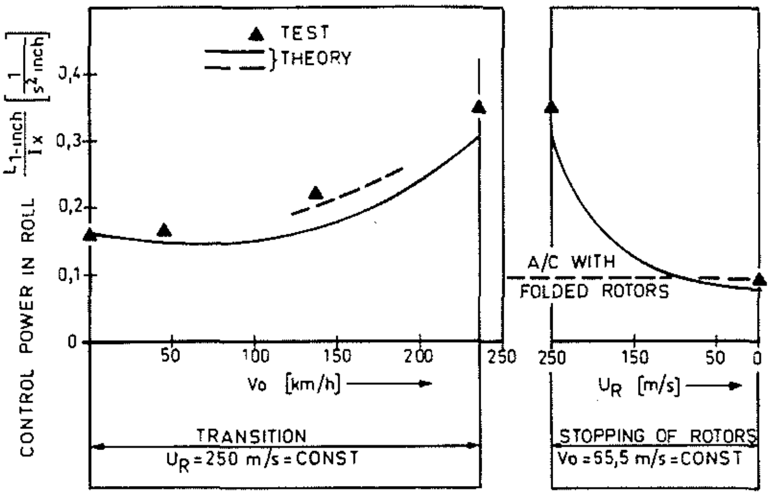

Figure 20 Roll Control Power During Transition and Conversion

ments for hovering flight.

Lateral control in hovering and low speed flight is supplied by differential collective pitch at the two rotors. The lateral control power, shown in Figure 20, is lower than in longitudinal direction, owing primarily to the much higher rolling amount of inertia of the aircraft. Control power and damping barely reach the IFR-requirement of MIL-H-8501A.

When comparing these hover control characteristics to hingeless rotor helicopters of equivalent size, it becomes apparent that longitudinal control characteristics are quite similar. In the lateral direction, due to the much higher moment of inertia of the side-by-side rotor configuration, the aircraft's control and damping are considerably lower. In forward flight, these characteristics improve substantially, owing to the fixed-wing aircraft surface contributions.

Yaw control considerations are excluded from the discussions in this paper, because definite statements depend on actual projects, and the application of yaw-axis specifications for these types of VTOL-aircraft is not clear.

8. Dynamic Simulation of Transition and Conversion

From the complex stability derivative behaviour, it becomes clear, that the transition and conversion phases can be treated realisticly only by a dynamic simulation. The SACRA computer program allows for the calculation of a transient response time history.

8.1 Starting Transition

Figure 21 depicts a typical time history of a transition flight from hover to conversion speed, as calculated by the program. All the important control and flight parameters are shown during a 30 second transition phase. The transition is initiated by a slight collective input, succeeded by the pilot's command to attain a -5 degree nose down attitude, which is held constant over the acceleration period. When reaching a certain forward speed, the collective is reduced, the weight being continuously shifted to the wing. The pilot then changes the aircraft attitude to +1 degree in order to approach the conversion phase. This pilot model included describes the normal human pilot behaviour. Static control travel over speed is stable during the whole transition phase, the control corrections for stabilization are small. The flight path parameters are shown on the right side of the diagram. After 30 seconds the horizontal distance is about 1000 meters, height about 180 m.

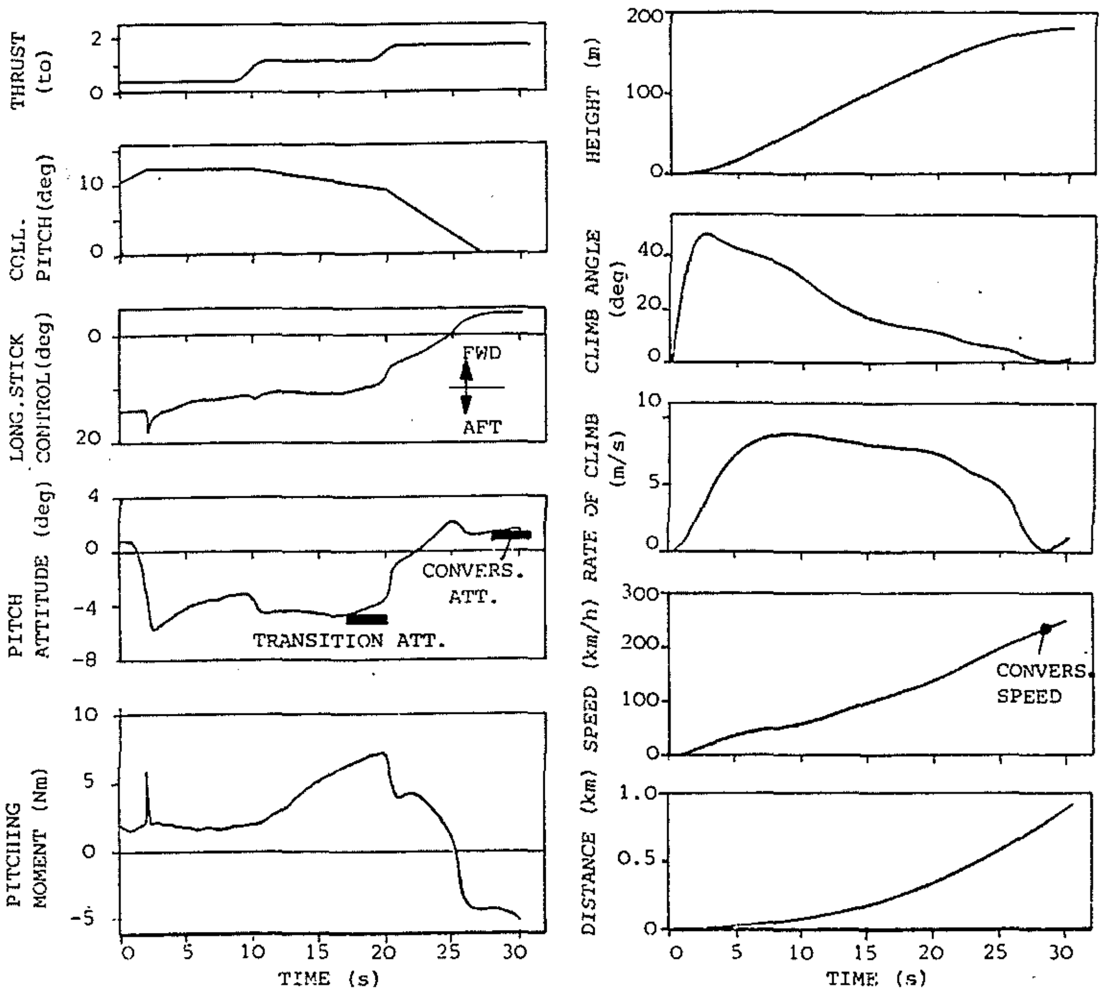

Figure 21 Calculated Time History of Transition Flight from Hover to Conversion Speed

8.2 Rotor Stopping Manoeuver

Because of the importance of the stopping process, intensive transient studies have been conducted. Figure 22 shows a computed time history of a stopping process initiated at a speed of 235 km/h. The rotor is stopped within a four second period. In order to demonstrate the response under rough air conditions also, a second case is shown with the aircraft subjected to a 30 fps sine-squared vertical gust. The diagram summarizes the response characteristics of the rotor and of the aircraft. The rotor is unloaded completely from thrust and moments during the stopping phase, the aircraft response is smooth under ideal flight conditions.

In the second case, the gust is encountered when the rotor has slowed down to the range of 90 to 50 percent RPM, with the maximum gust velocity occuring at 60 percent RPM. Control of the aircraft during this phase causes no difficulty. The gust imposes a vertical load factor increment of about

0.8g, while attitude disturbances remain small. Rotor hub moments during this phase are influenced by quite different inputs, for example, changes in rotor speed, gust inflow angle, and control movements. Both pitching and rolling moments remain within moderate values.

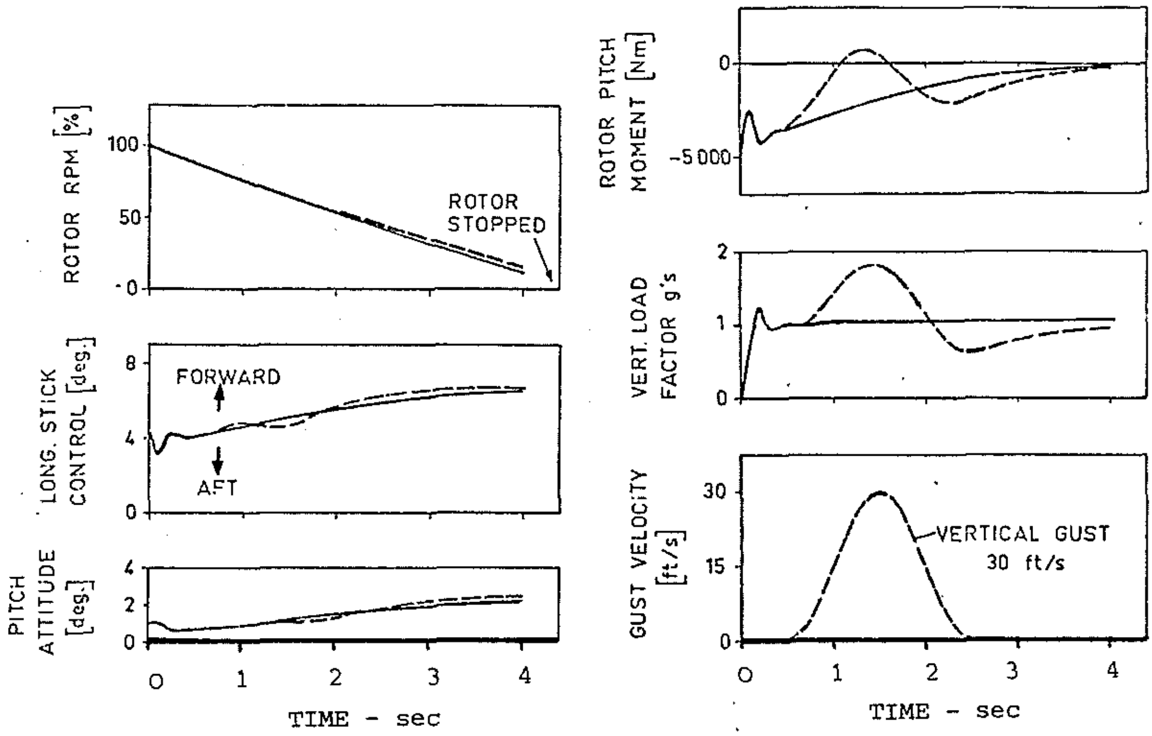

Figure 22 Calculated Time History of Rotor Stopping Manoeuver With and Without Gust Penetration

9. Conclusions

Some essential questions concerning flight dynamic behaviour of a horizontally stoppable rotor aircraft concept (Rotorjet) have been examined in this study. The critical phases of transition from hover to forward flight and of rotor stopping have been investigated. Based on theoretical and experimental results, the following conclusions can be made:

1. Aircraft trim within the range of pure helicopter flight and fixed wing airplane flight is possible without any discontinuities of trim parameters. During the rotor stopping phase only small amounts of cyclic pitch is required to compensate for gust disturbances. Elastic flapping deformations of the rotor blades remain below normal trim flight deflections. Load and stability problems are minimal due to the high stiffness, zero-twist rotor blade design.

2. Nonlinearities of some essential stability derivatives are encountered during the intermediate transition flight, owing primarily to rotor downwash interference effects on the wing and tailplane. Static and dynamic stability derivatives for the rotor stopping phase are a result of reduced rotor participation and increased fixed-wing surface contributions.

3. Longitudinal dynamic stability in hover and low speed flight is characterized by a relatively fast oscillatory instability. A variety of dynamic characteristics is possible at intermediate speed, owing to rotor downwash interference. At high transition speeds the longitudinal motion tends to become stable. The reduction of pitch-up instability during rotor stopping results in a stable aircraft during the conversion phase.

   The dual rotor aircraft demonstrates symmetry about the longitudinal axis, without any longitudinal to lateral couplings under all flight conditions.

4. Control sensitivity is moderate during hover and low speed flight. Longitudinal control characteristics are well within IFR-requirements, lateral control and damping are considerably lower because of the high moment of inertia of the side-by-side rotor concept.

5. It was shown by dynamic simulations that both the transition from hover to forward speed and the rotor stopping manoeuver can be performed with normal stability augmentation.

6. Theory was quite successful in predicting aircraft loads and trim, control and stability characteristics during hover, low and high speed, as well as for the rotor stopping phase. Improved downwash information is necessary for more exact predictions within the intermediate speed range.

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