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ABSTRACT

As a result of studying possible requirements for high-speed rotorcraft and studying many high-speed concepts, a new high-speed rotorcraft concept, designated as M-85, has been derived. The M-85 is a helicopter that is reconfigured to a fixed-wing aircraft for high-speed cruise. The concept was derived as an approach to enable smooth, stable conversion between fixed-wing and rotary-wing while retaining hover and low-speed flight characteristics of a low disk loading helicopter. The name, M-85, reflects the high-speed goal of 0.85 Mach Number at high altitude. For a high-speed rotorcraft, it is expected that a viable concept must be a cruise-efficient, fixed-wing aircraft so it may be attractive for a multiplicity of missions. It is also expected that a viable high-speed rotorcraft concept must be cruise efficient first and secondly, efficient in hover.

What makes the M-85 unique is the large circular hub fairing that is large enough to support the aircraft during conversion between rotary-wing and fixed-wing modes. With the aircraft supported by this hub fairing, the rotor blades can be unloaded during the 100% change in rotor rpm. With the blades unloaded, the potential for vibratory loads would be lessened. In cruise, the large circular hub fairing would be part of the lifting system with additional lifting panels deployed for better cruise efficiency. In hover, the circular hub fairing would slightly reduce lift potential and/or decrease hover efficiency of the rotor system.

This report describes the M-85 concept and presents estimated forward flight performance characteristics in terms of thrust requirements and L/D with airspeed. The forward flight performance characteristics reflect recent completed wind tunnel tests of the winged concept. Also presented is a control system technique that is critical to achieving low oscillatory loads in rotary-wing mode.

Hover characteristics, C_P versus C_T from test data, is discussed. The report discusses other technologies pertinent to the M-85 concept such as passively controlling inplane vibration during starting and stopping of the rotor system, aircraft control system, and rotor drive technologies.

INTRODUCTION

The helicopter, with its efficient hover capability and low-speed maneuver capability, has well served the contemporary military and civil communities. The user communities have long sought higher speed capabilities that have piqued the interest and innovativeness of designers for many years. This interest has driven designers to study a number of concepts that have promised much higher speeds than the helicopter of today. Recently, concepts such as the stowed rotor, the X-wing, and the folded tilt rotor have appeared and offer good potential for high speed with near-helicopter hover characteristics. These concepts have been studied analytically and experimentally to reveal both their advantages and disadvantages. The open literature presents the results of a number of studies.

User requirements for a high-speed rotorcraft concept are expected to be as follows:

1. hover efficiency and low-speed maneuver capability approaching that of the helicopter
2. high-speed maneuver capability and handling qualities of an airplane
3. a hover downwash field that is not injurious to either the ground surface or to a person
4. operational in turbulent atmosphere
5. efficient cruise speeds of 450 knots.
6. reliable and affordable aircraft with a low operating cost

As a result of integrating these requirements, a viable high-speed rotorcraft concept must be a cruise-efficient, fixed-wing aircraft if it is to be attractive for multiple uses. It is expected that a viable high-speed rotorcraft concept must be cruise-efficient, first, and efficient in hover, second.

By studying these requirements and many high-speed concepts, a new high-speed rotorcraft concept, designated as M-85, has been derived. The M-85 is a helicopter that is reconfigured as a fixed-wing aircraft for high-speed cruise.

The M-85 concept may make it possible to achieve a number of desirable performance goals such as

1. hover efficiency and low-speed maneuver capability approaching that of the helicopter
2. maneuver capability and handling qualities approaching that of an airplane while in fixed-wing mode
3. downwash field no worse than a CH-53
4. capability for conversion between rotary-wing and fixed-wing modes in turbulent atmosphere and during maneuvers
5. cruise speeds of 450 knots

In addition, the M-85 may exhibit the following characteristics: (a) minimum speeds of 160 knots in fixed-wing mode for a safe landing if conversion to rotary wing configuration is not possible, and (b) conversion from helicopter mode to fixed-wing mode that does not require a higher harmonic control system.

The M-85 is unique because it has the large circular hub fairing that is large enough to support the aircraft during conversion between rotary-wing and fixed-wing modes. With the aircraft supported by this hub fairing, the rotor blades can be unloaded during the 100% change in rotor rpm. With the blades unloaded, the potential for vibratory loads will be lessened. Also, the circular planform shape of the hub fairing eliminates N per rev vibratory loads characteristic of rotating noncircular hub shapes. Therefore, with the large circular hub fairing, conversion with the M-85 is expected to be smoother than with other edgewise-flying rotor systems such as the rotor/wing concepts described in reference 1. In cruise, the large circular hub fairing would be part of the lifting system with additional other lifting panels deployed for better cruise efficiency. In hover, the circular hub fairing would slightly reduce lift potential and/or decrease hover efficiency of the rotor system.

The purpose of this report is to introduce this new high-speed rotorcraft concept and to describe, on the generic conceptual design level, some examples of how this concept can be implemented. The aerodynamics of the basic concept will be discussed. Control concepts are presented for the rotor system and for the fixed-wing configuration. Some powerplant alternatives are presented. Also, limited basic hover and cruise performance are discussed.

NOMENCLATURE

A	aspect ratio, b^2/S
ac	aerodynamic center, %c 100
b	span, ft
c	wing or lift panel chord length, ft
C_D	overall drag coefficient, drag/qS
C_{Di}	induced drag coefficient or variational drag coefficient with angle of attack and/or with lift coefficient, drag/qS
cg	location of center of gravity, %c 100
C_L	lift coefficient, lift/qS
$C_{L_{max}}$	maximum lift coefficient
cp	location of center of pressure, %c 100
C_T	rotor thrust coefficient, thrust/$(\rho)\pi R^2(\Omega R)^2$
f	flat plate drag area, drag/q
GW	gross weight, lb
L/D	lift to drag ratio

M	Mach number, V/speed of sound
q	dynamic pressure, lb/ft^2
R	radius, ft
r	radial distance from center of rotor, ft
S	area, ft^2
V	freestream or flight velocity, knots
ρ	local air density, slugs/ft^3
Ω	rotor rotational speed, rad/sec

DESCRIPTION OF THE M-85 CONCEPT

The M-85 incorporates a rotating wing system for generating lift during hover and up to a reasonable speed for conversion from a rotary-wing to a fixed-wing configuration used for high-speed flight. A schematic three-view drawing appears in figure 1. The description of the concept is presented in very generic terms so as to not allow any particular implementation to become the concept itself.

For lift, the M-85 incorporates a rotor that may have two, three, or four blades. These rotor blades extend from a large diameter circular hub fairing that is about 50 to 60% of rotor diameter. The blades may use blown or unblown airfoils for producing lift. The airfoils may be symmetrical about their 50% chord position or the airfoils may be standard types. Both the circular hub fairing and the blades are rotating at the same rotational speed. The rotor may be shaft-driven or driven by reaction jets.

The pitch of each blade is separately controlled by rotary actuators mounted on each blade. There is no helicopter-type swashplate to mechanically vary blade pitch. The blades incorporate hingeless-rotor technology for blade restraint and a control system that minimizes oscillatory loads.

In hover and very low speeds, the blades provide the required lift. Lift modulation is through blade pitch control. Aircraft yaw control is by an anti-torque device or reaction jets. Aircraft acceleration in the longitudinal and lateral directions is accomplished by vectoring rotor thrust using blade cyclic pitch control for tip path plane tilt.

Acceleration from hover to conversion flight speed is accomplished using thrust from the fan-jet engines that are used for propulsion in cruise. The rotor would normally not be propelling because that would require a negative fuselage attitude. A positive attitude is required to enable lift to be produced by the rotor blades, the hub fairing, and fixed airframe components. Aircraft control is by the rotor controls and/or horizontal and vertical tail surfaces when they become effective with increasing speed.

At conversion airspeed, the aircraft increases angle of attack so that total aircraft lift is carried by the fixed airframe components and the rotating hub fairing. With total aircraft lift carried by these components, the rotor blades are then retracted into the hub fairing. While the blades are being retracted, rotor rpm may be adjusted to help smooth any oscillatory airloads. When the blades are fully retracted into the hub fairing, hub fairing rotation is stopped. During conversion, pitch and yaw control is by standard operation of horizontal and vertical tail surfaces, respectively. Roll control is achieved by differential deflection of left and right horizontal tail surfaces.

For cruise, two or four blades may be redeployed from the stopped hub fairing to become wings to generate lift, in conjunction with the hub fairing, for more efficient cruise. Aircraft pitch and yaw control is achieved with standard operation of horizontal and vertical tail surface. Aircraft roll is by differential horizontal tail deflection or differential blade pitch on the wing panels extending from the hub fairing.

The hover-to-fixed wing configuration sequence for two-, three-, and four-blade rotor configurations is shown in figures 2 through 4. These illustrations show the wings extended from the hub fairing to form a number of different configurations:

1. Extended from the 90° and 270° azimuth stations enable maximum effective aspect ratio with zero wing sweep. With the wings extended from the 90° and 270° azimuth stations, the hub fairing may be rotated to form the oblique-wing configuration of any sweep angle.

2. The wings can be extended to form other swept-wing configurations depending upon the number of blades. For three or six blades, sweep can be 30°. For four blades, sweep of 45° is possible in addition to the zero swept case.

To convert from fixed-wing mode back to helicopter mode, the process is reversed. First the aircraft slows down to conversion speed and any extended wings are retracted into the hub fairing. Then the hub fairing is brought up to full rotation speed using jet flux from the fairing or blade tip which may be slightly extended to uncover jet nozzles at the tip. Next, the blades are extended and blade pitch is used to modulate aircraft lift and provide low-speed control. The aircraft slows and maneuvers to the landing site where it comes to a hover and lands.

Although this process or technique for transforming a rotorcraft into fixed-wing configuration appears simple and relatively easy to execute, for the concept to be attractive, the performance and flight-control aspects of the concept must be satisfactory, if not outstanding.

Key aspects of the concept addressed in this report are as follows:

1. application of the disk-wing which includes the disk as a wing in conversion, the effect of adding lifting panels to the stopped disk, the case of the left wing's airfoil pointing trailing edge forward, and estimated performance characteristics for a hypothesized design

2. hover capability and performance
3. structural weight consideration for design of four-blade rotor systems
4. blade control technique
5. aircraft roll control
6. rotor drive system options
7. vibration control during 100% rpm change

First to be addressed is the aerodynamics of the application of the disk-wing to this concept.

APPLICATION OF THE DISK-WING TO M-85 CONCEPT

The disk-wing consists of two parts, one part is a large circular disk and the other part is a pair of lifting panels or wings. The wings are also considered as blades when they are rotating as a helicopter rotor.

For the M-85 concept, an important consideration regarding the application of the disk-wing involves the lift and drag characteristics in the cruise mode. Cruise mode is very important because cruise capability is the objective of the aircraft. Secondly, hover performance should be considered because the capability to hover is an important operational role for the aircraft and hover efficiency is the main reason for needing a rotorcraft. A third important consideration is the conversion flight mode between rotary-wing and fixed-wing configurations when the the blades are retracted into the hub fairing and the hub fairing is supporting the aircraft at relatively low flight speeds. The conversion mode is considered the flight mode that is the greatest technical challenge and the most critical with respect to the capability of the disk-wing to support the aircraft while disk rpm is varied over 100% of its operating range.

For discussion of the performance of the disk-wing to the M-85 concept, the hover mode will be discussed first, followed by a discussion of the conversion mode, and then the cruise mode will be discussed.

Hover

Considering that this concept eliminates about half of the inboard portion of the blades, it becomes a serious question as to the ability of the remaining blade to lift the vehicle. To evaluate the loss in lift with large blade cutout, the basic blade lift equation can be used:

$$d(\text{blade lift}) = \rho C_L c(\Omega r)^2 d(r)/2$$

With C_L representing the maximum local coefficient and integrating from $r = 0$ to $r = 1.0\,R$ yields for the conventional rotor

$$\text{Blade lift} = \rho C_L c(\Omega\,)^2 R^3[1.0\,]/6$$

For the M-85 rotor, integrating from

$$r = 0.5\,R \text{ to } r = 1.0\,R \text{ yields}$$

$$\text{Blade lift} = \rho C_L c(\Omega\,)^2 R^3[(1.0 - 0.125)]/6$$

$$= \rho C_L c(\Omega\,)^2 R^3[0.875\,]/6$$

Thus, by eliminating the inboard 50% of the blade, only 0.125 or one-eighth of the lift potential is lost. To get back that lift potential, the radius has to be increased by only 4% at the same rotational speed, Ω. Therefore, the lift potential of the M-85 rotor is not appreciably compromised by the large blade cutout that is filled in by a large diameter hub fairing.

Although the lift potential of the M-85 rotor is not compromised by the large hub fairing, there is a question regarding its efficiency in performing hover and low-speed ($V < 60$ knots) maneuvers compared to conventional helicopter rotors. Efficiency is expected to degrade because there are a number of interactions and basic flow distortions caused by the hub fairing. These potential interactions are

1. spanwise lift distribution caused by the lower aspect ratio of the blade
2. the influence of the downflow from the top of the hub fairing into the rotor blade
3. lift carryover onto the hub fairing by the vortex shed from the inboard junction of the blade
4. the effect of blade downwash on the pressure distribution on the underside of the hub fairing
5. the effect of the large decrease in effective blade pitch at inboard junction of the blade
6. the skin friction drag on the upper and lower surface of the hub fairing

The effects listed above need to be evaluated in focused experimental programs which can provide basic information and data for validating theoretical approaches.

A configuration similar to the disk-wing approach of the M-85 concept was experimentally tested at Langley Research Center (LaRC) and reported in a 1969 NASA TN (ref. 1) and in a Hughes Tool Company report (ref. 2). The NASA data showed the peak figure of merit (FM) to be 0.45 which was uncorrected for penalties associated with model scale and occurring at $C_T = 0.012$. The low level of hover FM exhibited by this rotor configuration can be attributed to the following sources:

1. the effect of the large decrease in effective blade pitch at inboard junction of the blade and extending inboard to 0.43 R from 0.55 R

2. the low Reynolds number due to scale and low tip speed (225 fps)

3. the lift-drag characteristics of the 15% elliptical airfoil

From another, but unreferenceable, Hughes report, a circular disk with a radius of 57% of the blade radius, resulted in a power penalty of 25% compared to a conventional rotor at $C_T = 0.012$. Of the total power penalty, approximately 40% was profile power and 60% was induced power. Although the 25% power penalty is significant, it will not size the engines because hover power may be about half the power required for high-speed cruise of 450 knots. It has been shown that a disk 50% of the rotor diameter will reduce the lift potential of the rotor by only 12%, but can increase rotor power requirements up to 25% based upon limited, model scale hover test stand data at low tip speed.

Thrust augmentation in ground effect was found to be exceptional with the large centerbody disk. Test stand data at low rpm, in figure 5 from reference 2, showed a thrust augmentation 10% greater than that achievable with conventional rotor configurations. The enhanced thrust augmentation is speculated to be a "fountain effect" from the downwash, at the periphery of the disk, which splits upon reaching the ground and a portion of which flows from the periphery toward the center of the rotor. At the center, it reacts with other inwardly moving air from the periphery and turns up, forming a fountain flowing toward the bottom surface of the centerbody and pushing up on the centerbody, thereby increasing thrust augmentation.

The Disk as a Wing for Conversion

In conversion, one vital issue is whether or not the disk, acting as a wing, has sufficient lifting capability to support the aircraft at relatively low flight speeds for a fixed-wing configuration, but at speeds that are considered high-speed for the rotorcraft. To evaluate the disk's lifting capability, published experimental aerodynamic data will now be reviewed.

The disk as a wing has been experimentally investigated in two forms: the thin flat plate disk and the 12% thick disk with various cross-sectional shapes. Although these disk configurations are not exactly like those envisioned for the M-85, they provide some insight of the aerodynamic characteristics that are to be expected from this type of configuration. The thin disk aerodynamic characteristics were reported in reference 3. The thin disk has a lift curve slope of 0.027 per degree of angle of attack and a $C_{L_{max}}$ of 1.2 at an alpha of about 40°. The large $C_{L_{max}}$ potential of the disk indicates the excellent possibility of the disk being able to produce sufficient lift in the conversion mode and at a speed low enough for the *rotating rotor* to be functional for generating sufficient lift for at least 1-g flight and at a speed high enough for the *stopped disk* to generate sufficient lift for 1-g flight. Of course, the angle of attack must be high to produce that C_L. Note, in the absence of aerodynamic data for a rotating disk, we will presume for now that rotating disk $C_{L_{max}}$ is equivalent to nonrotating $C_{L_{max}}$.

For demonstration purposes, we will estimate the size of a disk-wing that would lift 10,000 lb at a reasonable helicopter-type forward flight speed of 160 knots at a density altitude of 5,000 ft.

Using

Disk lift = C_LqS,

$C_L = C_{L_{max}} = 1.2$, and

dynamic pressure = 74.8 psf

then,

disk area, $S = 10{,}000/(1.2)(74.8) = 111.4\ \text{ft}^2$ and

disk diameter = 12 ft

Thus, the disk-wing can lift and be of reasonable small size depending upon the C_L, the speed, and air density.

Considering that a 10,000-lb helicopter may have a diameter of about 44 ft (the S-76 for example), it is encouraging that a 22-ft diameter disk at a $C_L = 0.35$ (only 29% of $C_{L_{max}}$) would supply sufficient lift for sustained level flight at 160 knots and still have lift capability for maneuvers. Therefore, it is reasonable to perceive that the disk can sustain lift during conversion from rotary-wing to fixed-wing mode and vice versa, and is therefore viable as part of the M-85 concept.

Although the lift characteristics of the disk are reasonable for conversion, the disk can produce large drag at the angles of attack for conversion. The experimental results indicate the drag-due-to-lift is quite high, with $C_{Di} = C_N$ sin alpha. The large drag-due-to-lift characteristic is largely due to the low aspect ratio (AR = 1.27) of the disk and the lack of nose suction associated with very thin "airfoils." Although you cannot do much about the drag generated because of the low aspect ratio wing, the penalties associated with lack of leading-edge suction can be alleviated by adding leading-edge curvature or roundness. Doing just this was reported in NACA TN 539 (ref. 4) wherein a Clark Y airfoil was used as the disk's streamwise cross-sectional shape. Figure 6 presents the reported test data for both the case of the disk with a sharp leading-edge flat plate and the disk with a rounded leading edge. Also shown are the drag characteristics using the induced drag calculation of $C_{Di} = C_N$ sin alpha. Figure 6 amply shows that the rounded nose is substantially better for minimizing drag of the disk-wing. Other benefits of nose roundness are illustrated in figure 7 where the lift characteristics are shown. Increased $C_{L_{max}}$ and greater alpha for $C_{L_{max}}$ are evident. Also seen in figure 7 is that airfoil camber is effective in generating lift at 0° angle of attack.

With the high C_L and the attendant high angle of attack, drag will be large even with the rounded leading edge. Therefore, engine thrust to overcome the high induced drag and the parasite drag will also be a major factor in determining conversion speed along with the disk's lifting capability.

From the study of aerodynamic characteristics of the disk as a wing, it was found that (1) the induced drag from the disk is very high, even with leading edge rounding, and (2) a disk with a diameter about 50% of the rotor radius, can easily provide sufficient lift to sustain an aircraft flying at speeds of contemporary helicopters. Therefore, the disk as a wing is viable for lifting the aircraft, but the attendant drag penalty will be large.

Although the high drag state does exist, the conversion flight time would be short, therefore, minimizing high engine thrust operation and fuel consumption. With the M-85, drag is reduced and economy is improved as speed is increased to reduce the angle of attack, and with decreased span loading by adding lifting panels to the stopped disk.

Adding Lifting Panels to the Stopped Disk

Adding lifting panels to the disk adds not only lift capability, but also improves cruise efficiency. Recent wind tunnel tests show that adding lifting panels increases lift system L/D to varying degrees based on the sweep of the panels. Figure 8 shows L/D versus C_L of the lift generating system (disk + wings + mutual interference) for 0, 30, and 45° swept lifting panels and for the wingless disk configuration. The drag characteristics also include the drag from the pylon between the disk and the fuselage and the interference drag from the junction of the fuselage and pylon. Also, the "mutual interference" drag includes the separated flow over the cowling that is aft of the pylon at zero angle of attack and low lift coefficient. This interference drag would be eliminated by straightening the cowl lines to go straight aft from the pylon.

Figures 9, 10, and 11 are photographs of the test configuration with the unswept wing. Figure 11 particularly shows the cowling shape that exhibited flow separation aft of the pylon. Adding lifting panels is shown to increase L/D_{max} from 11 for the wingless disk to nearly 20 for the 0° swept lifting panel configuration. Certainly two factors come into play for the improved L/D from the added panels:

1. the added panels increase the effective span

2. panel location on the edge of the disk affects the interaction of the vortex shed from lateral edge of the disk with the panels

The high L/D with the unswept lifting panels is the result of improved span loading and favorable interaction as a reaction to an up-flow induced at the wing by the disk. This induced up-flow increases panel lift and reduces panel-induced drag as the disk-wing angle of attack increases. The 30 and 45° swept panels, on the other hand, are located on the disk where the interaction is more neutral, where the up-flow and the downflow induced by the shed vortex is somewhat balanced. Therefore, they may only have the improved span loading factor working for them to enhance L/D.

Adding lift panels has been shown to greatly improve the L/D of the disk with the highest L/D produced by the unswept wing configuration. The high L/D of the unswept wing configuration will enable efficient cruise at speeds and altitude combinations that cause wing lift coefficient to be greater than 0.1. When wing lift coefficient is less than 0.1, induced drag is very low, and the unswept wing could be retracted to lessen compressibility drag or azimuthally indexed to form a swept oblique wing to lessen compressibility drag.

An Airfoil Pointing Backward

If the wing airfoil has a distinctive leading and trailing edge, and if the leading edge is forward into the wind during hover, then the left wing will have its trailing edge pointing forward during fixed-wing flight. This would result in a drag penalty for standard type airfoils. In addition, a cg-ac offset would result and be dependent upon the chordwise mass distribution. The probable resulting cg-ac offset and relative drag values are summarized in the following table.

Airfoil	cg, %c	cg-ac offset, %c Subsonic	 Transonic	Relative C_D
Standard RC10	25	0	–20	1.0
TE forward RC10	75	50	40	1.1-1.2
TE forward RC10	50	25	15	1.1-1.2

The table above shows the advantages of having the cg at mid-chord rather than at the c/4 for the leading-edge forward case when compressibility effects cause the ac to shift downstream. With the cg at 0.25 c, compressibility effects drive the center of pressure aft and away from the cg. With the cg at 0.50 c, compressibility effects drive the center of pressure toward the cg. Thus, in effect, with increased compressibility effects and attendant dynamic pressure, the cg-ac offset problem diminishes with the cg at 0.5 c. Similarly, as angle of attack increases at a set transonic speed, the center of pressure shift downstream with angle of attack would also favor the cg at the 0.50 c position. Thus, the cg at 0.50 c may be the best overall position.

There are several approaches to resolving the situation of the left wing trailing edge being forward in fixed-wing mode:

1. Left wing flies trailing edge forward in rotary-wing mode and leading edge forward in fixed-wing mode. Airfoil, cg location, and control system are optimized for cruise while enabling a stable rotary-wing mode.

2. Left wing and right wing use biconvex, blown, or unblown airfoil that is symmetrical about the 0.5 chord plane. Control system and location of cg are optimized for cruise while enabling a stable rotary-wing mode.

3. Left wing airfoil and cg are optimized for cruise and control system enables wing to change its pitch angle 180° to align itself into the aerodynamic environment associated with the fixed- and rotary-wing modes.

4. Left wing and right wing use an airfoil that is blown from leading edge and trailing edge with the cg at 0.5 c as was used for the X-wing concept.

Because cg-ac and cg-cp offsets can greatly affect structural requirements, dynamic characteristics, and control system requirements, they are important considerations and evaluation of the above approaches and others require additional study that integrates concept utilization, aerodynamic characteristics, structural and dynamic characteristics, and control system design. The additional study is well beyond the scope of this report.

CRUISE PERFORMANCE ESTIMATE OF THE M-85 CONCEPTUAL DESIGN

To obtain an order-of-magnitude view of the performance of this concept, an M-85 configuration will be hypothesized, technology assumptions will be advanced, and the performance subsequently will be estimated.

The example M-85 configuration is a small rotorcraft vehicle of 10,200 lb gross weight. Hover will be at 4,000-ft altitude with a temperature of 95°F and with a mean blade lift coefficient of 0.6, 650 ft/sec tip speed, and a blade annulus loading of 14 lb/ft^2. These hover requirements and the download, estimated at 9% of the gross weight, determine the rotor size to be

Rotor diameter = 37.7 ft

Disk diameter = 20.75 ft

Blade chord = 2.14 ft

The disk-wing or hub fairing is configured with a circular arc top surface and a flat lower surface. This cross section has been selected because it will minimize the interference drag of the fairing-pylon-fuselage combination. The low interference drag has been documented in NASA wind tunnel tests reported in reference 5.

The parasite drag for the fixed airframe is estimated (from wind tunnel tests of similar fuselage shown in fig. 11) to be 4.0 ft^2 of equivalent flat plate area as the fuselage and tail surfaces are low drag shapes and careful attention has been directed toward shaping and minimizing excrescence drags. The low drag reflects more typically high performance fixed-wing technology rather than helicopter technology. As a consequence of the low drag fuselage, the lift from the fuselage is quite small and insensitive to angle-of-attack change, hence fuselage lift is assumed to be zero.

Drag of the disk-wing is calculated as the sum of induced drag and profile drag. The induced drag is calculated from the induced drag characteristics and interference drag obtained in the NASA wind tunnel test of the unswept configuration in figures 9 through 11. The profile drag or minimum drag is determined by the basic flat plate skin friction drag for Reynolds number at the particular flight speed. Adding the wings and the disk will raise the parasite drag level to about 5.9 ft^2 in fixed-wing mode. Compressibility effects are omitted because the configuration has not been evaluated or designed under those conditions. Forward flight characteristics are determined from 110 knots to 550 knots at altitudes of 4,000 ft on a 95°F day and 35,000 ft on a standard day.

Figure 12 shows drag versus velocity for the fixed-wing configuration in cruise at 4,000 ft, 95°. The wing configuration is the disk with two panels extended laterally with zero sweep. Also shown is the profile drag of the wing and the parasite drag for the fuselage and empennage. From the minimum drag speed, total drag rises sharply as speed *decreases* toward 100 knots, a result of increasing induced drag while profile and parasite drags decline with decreasing dynamic pressure. As speed *increases* from minimum drag speed, fuselage drag is seen to totally dominate the drag picture and to overshadow the wing drag even at the low level of 4.0 ft^2. While wing profile drag is large, it is only about half the fuselage drag. Also, the wing-induced drag is small and inconsequential beyond 250 knots. It is obvious from this figure that low drag fuselages are essential for good cruise efficiency at high-speed and low-altitude operations. It can also be observed that the low aspect ratio disk-wing may not prevent efficient cruise performance at speeds above 350 knots.

Figure 12 also shows that conversion may be appropriate at speeds near 180 knots where the rotors can easily auto-rotate and aircraft control is assured. At this speed, disk C_L is 0.34 and angle of attack is only 12.6°, well within bounds of passenger acceptance.

Figure 13 shows L/D versus velocity for the same fixed-wing configuration and includes the alternate configuration of the disk itself being the "wing," that is, there are no lifting panels extended from the disk. This figure shows a maximum L/D to be almost 11 for the disk-wing configuration and only 5.5 for the disk-only configuration. L/D decreases with forward speed for both configuration as the lift coefficient decreases below the CL for L/D_{max} for the wing and as fuselage drag builds up. At high-speed cruise, drag is dominated by parasite drag with over 66% being attributed to the fuselage and the empennage drag. If only the fuselage drag is included in L/D calculations. GW/D or L/D is only 4.5 at 450 knots. Adding drag of the disk and wing, reduces the L/D to 3.1. Since the M-85 disk wing is much lower aspect ratio than the wings for other high-speed rotorcraft concepts, there is a natural tendency to think the M-85 would have much poorer cruise L/D compared to a more common high aspect ratio wing configuration for folded tilt-rotor concepts. This does not appear to be the case, however.

Consider a wing for a folded tilt-rotor concept that is sized by a wing loading parameter GW/S = 60 lb/ft^2. At the 10,200-lb gross weight, the wing area is 170 ft^2. The rotors are sized for a disk loading of 20 psf, a download of 9% of rotor thrust and a solidity of 0.12 with three blades. The 9.4-ft blades are folded back with its trailing edges against the sides of a pod housing the transmission and rotor pitch mechanism. The pod has a 2-ft diameter, a length from nose cone to tail cone of 15.22 ft with a constant diameter length of 7.22 ft for the blade trailing edge to butt against the pod. Using skin friction drag with an interference factor of 2.0 for the blade skin friction drag coefficient, the drag of the pod and exposed blades is $\Delta f = 0.45\ ft^2$ per nacelle and $\Delta f = 0.9\ ft^2$ for the aircraft. For the wing itself, the profile drag $\Delta f = 1.48\ ft^2$ based upon a thickness ratio of 0.22. Wing lift coefficient at 450 knots is 0.098 which leads to an induced drag of 0.1 ft^2 based upon an aspect ratio of 6 and an Oswald efficiency factor of 0.85. Summing the parasite drags and the induced drag results in a wing drag of $\Delta f = 0.9 + 1.48 + 0.1 = 2.48\ ft^2$. On the other hand, the M-85 disk wing has a total drag of 2.56 ft^2 which includes the drag of the pylon under the disk. Thus, the M-85 disk wing is very competitive with the wing-pod configuration of the folded tilt-rotor configuration even though the M-85 disk-wing is a much lower effective aspect ratio. It is, of course, the drag of the pods and the folded blades on the tip of the wing which cause the nearly equal drag of these two dissimilar lifting surface configurations.

For speed beyond 400 knots, the disk-only configuration can be just as attractive as the disk-wing, since the disk lift coefficients are extremely small.

The magnitude of parasite drag and profile drag at low altitude has long been a problem that has thwarted economical cruise for all types of aircraft, not just the M-85. For more economical cruise the common options are (1) reduce drag coefficient, (2) fly slower, (3) cruise at higher altitude, or (4) make the wing smaller. Cruising at higher altitude, even short ranges of 400 n.mi., has been the preferred option for economical cruise. This is also true for the M-85.

High-altitude cruise is the most attractive for range performance. However, high altitude may be a disadvantage for conversion if auto-rotation and the need for aircraft control is difficult to achieve with lower air density.

Figures 14 and 15 show respectively, the character of the high-altitude drag versus velocity and L/D versus velocity. High altitude of 35,000 ft is shown to reduce the drag and improve high-speed L/D compared to the low-altitude case. The lower drag results from the reduced density that greatly reduces the parasite and profile drag. Although, induced drag must increase with higher altitude, the large reduction in parasite and profile drag enable large net benefits from high-altitude cruise. The lessened air density aids high-speed cruise, but it penalizes conversion. For conversion at high altitude and at speeds less than 200 knots, the required lift coefficient is very high which in turn increases drag, predominantly induced drag, to very high levels. To circumvent these problems, conversion would have to occur at higher speeds than that needed at lower altitudes.

To summarize, this limited forward flight performance study has shown the parasite drag to be the major cause of low L/D at 450 knots and, at low altitude, adding the drag from a wing will drive the L/D considerably lower. The unusual M-85 disk-wing has a larger wetted area than a conventional wing and this results in greater profile drag and slightly reduced L/D when compared with a conventional wing. High altitude enables much better cruise efficiency because low air density greatly diminishes parasite drag. Although high altitude is most attractive for cruise and range performance, high altitude is not good for conversion if auto-rotation and aircraft control is difficult to achieve with the low air density.

BLADE CONTROL TECHNIQUE

During rotor rotation mode, the technique to control blade pitch should enable the rotor to produce hub moments that are adequate for sharp stable maneuvering, will minimize blade lift and hub moment sensitivity to horizontal and vertical gusts and result in smooth flight in smooth air.

One way to achieve this is with (a) a stiff-effective flapping hinge coupled with (b) a blade that can stably align itself, i.e., weathervane into the local relative wind and be controlled by (c) a moment-producing device that is controllable by the pilot. The stiff-effective flapping hinge would be good for efficient structural characteristics and enable production of sufficient hub moments for crisp control in helicopter mode. However, the stiff-effective flapping hinge will also cause considerable sensitivity to gusts and will produce very large unstable pitch moments about the vehicle center of gravity. These undesirable characteristics can be greatly alleviated by enabling the blades to weathervane into the relative wind. With nearly perfect weathervaning capability, the blades would produce nearly zero lift variations as it encounters gusts and when the angle of attack changes. Since weathervaning capability is the ability to produce a moment balance about a pitch axis with the aerodynamic center offset from the pitch axis, blade "steady state" lift can be controlled by controlling an input pitching moment to the blade. This concept of blade control is extremely different from the lift control technique used for contemporary rotor systems.

In the usual rotor system, the pilot changes lift by directly changing the pitch of the blades so the blades see an attendant change in angle of attack. In this M-85 control system, lift is controlled only by modulation of the moment about the blade pitch axis by the M-85 pilot, the same method used by the pilot in any fixed-wing aircraft. The pilot of a fixed-wing aircraft pulls back on the stick to deflect the horizontal tail surface and to cause a download on the tail. With a download on the horizontal tail, a positive pitching moment is produced about the aircraft's cg. The positive pitching moment causes the aircraft to pitch nose up to reestablish a pitching moment balance at the new aircraft pitch angle with an attendant increase in lift. For the M-85, the pilot causes a positive pitching moment change to occur about the wing or blade cg (and pitch axis), the blade pitches nose up to reestablish the pitching moment balance with a lift increase. Thus, lift control for the M-85 in hover is very much like the lift control of fixed-wing aircraft.

The M-85 blade self-aligning action that reduces effects of airflow perturbation is also very similar to response of statically stable ($-Cm_{\alpha}$) fixed-wing aircraft to airflow perturbation. For the fixed-wing case, when an upward vertical gust strikes the aircraft, wing lift increases and horizontal tail lift increases. Because tail lift increases, a negative pitching moment unbalance is created about the aircraft cg and the aircraft pitches nose down to alleviate the tail lift increase and restore the pitching moment balance for trim. Thus, the aircraft has weathervaned into the new relative wind to reestablish pitching moment balance, just like the M-85 blade. Thus, the M-85 blade, with its pitch axis ahead of the aerodynamic center (therefore $-Cm_{\alpha}$), weathervanes into the relative wind to correct for flow perturbation and flies like a fixed-wing airplane.

There are many ways of controlling the pitching moment input which involve mechanical, pneumatic, electromechanical, or aerodynamic systems. The ideal controller is probably a modern technology electromechanical actuator rather than any mechanical or pneumatic systems. An aerodynamic system offers the advantage of being able to leverage the input electrical power brought up through slip ring to the actuator to obtain much larger moment output. An example of this type of system is the servoflap control on H-2 rotors. It should be noted that the H-2 blade also flies like an airplane because it is effectively free of pitch restraint at the root of the blade and uses the pitching moment from the servoflap to change blade pitch and control lift.

Although, there is no actual implementation of the M-85 blade control technique, there is one that is a close relative—the free-tip rotor (FTR). The FTR had a 10% R tip that had self-aligning capability and was controlled by ground-adjustable pitching moment applied to the tip itself. The tips pitch axis and cg was forward of the tip aerodynamic center by abut 0.13 c. This offset enabled the tip to be highly responsive to airflow perturbations and resulted in considerable reduction (40 + %) in oscillatory blade loads, which is terrific for a tip only 10% of the blade radius. These results were reported in reference 6. The FTR implementation has experimentally proven the ability of a self-aligning tip to desensitize a rotor to flow perturbation (and probably gusts also). Although the pitching moment applied to the tip was ground adjustable, the pitching moment could be variable by the pilot as would be desirable for the M-85 concept.

A blade control technique has been presented that should enable pilot-directed moment generation about the cg that would be sufficient for crisp stable maneuvering. This technique is expected to produce the desired control moment while suppressing vertical vibration and gust response that is characteristic of large hinge offset rotor systems.

AIRCRAFT ROLL CONTROL

Obtaining roll control is most difficult during low-speed flight in the conversion mode with the blades retracted into the disk. It is most difficult because no surfaces are located a long distance from the cg as on a fixed-wing aircraft. The only surfaces available to produce rolling moment are the horizontal stabilizers and the vertical fin and these are rather close-coupled to the cg. Although there may be several other methods for achieving roll control, the best is probably differential lift on the horizontal tail.

ROTOR DRIVE SYSTEM

Rotor drive can be accomplished by either (1) cold or warm pressurized air jets emitted from the blades or from the disk itself, or by (2) shaft drive.

Between the two methods, pressurized air jets for rotor drive offer some attractive potential advantages over the shaft-driven system, such as

1. Lower weight and possibly lower internal volume by replacing heavy transmissions and shafts with lighter weight ducts.

2. Eliminating the need for an anti-torque system. Needed however, is a yaw control system, but it would be much lighter than an anti-torque system.

3. Easy diversion of the potential energy for other functions in the rotating system such as providing circulation control on the blade, or aerodynamic braking of disk rotation speed.

4. Increased reliability and lessened maintenance requirements by eliminating the transmission oil cooling system with its numerous parts and health monitoring hardware.

5. Lower cost to purchase and lower life-cycle cost.

Although the reduction in efficiency will have a major impact on required installed power for hover and an attendant large fuel consumption rate, many studies have concluded that a short utilization time of under an hour can enable a considerable aircraft weight saving. The key is short utilization time. Short utilization time is highly probable for the M-85 high-speed rotorcraft concept as the concept enables disengagement of the rotor drive power source soon after hover when the craft accelerates to forward flight as an autogyro.

A STRUCTURAL WEIGHT CONSIDERATION

There is at least one way to minimize structural weight of the lifting panels for a four-blade rotor system. Assuming "rotor blades" are lighter than "wings" because of the load relief from centrifugal force, then two opposing panels can be built as "wings" and two opposing panels can be built as "blades." Since two opposing panels are never extended as wings, they can be built as blades and take advantage of the reduced weight. Furthermore, they might be designed to carry a large percentage (80 to 90%) of the minimum flying weight with nonvariable lift and cyclic controls if they incorporated a blade control system technique discussed later. These special blades would be deployed during hover and low-speed flight below 60 to 80 knots and which would probably be the power bucket in speed-power polar.

POTENTIAL VIBRATION DURING 100% RPM CHANGE

Stopping and starting the rotor is a 100% rotor rpm change that causes encounters with a number of resonant frequencies and subsequent inplane vibration. To minimize this inplane vibration, a self-actuating vibration suppression system would be developed based upon the UREKA balance system reported in reference 7. The M-85 is a configuration, with the large diameter disk, that is very amenable to incorporating this self-actuating system. Therefore if incorporated, the inplane vibration may not be a significant concern.

CONCLUSION

The M-85 has been shown to be a potentially feasible concept for consideration as a high-speed rotorcraft with indications of performance capabilities that are equivalent to or may be better than other concepts such as the folded tilt rotor and X-wing.

New features of this concept are

1. a large-diameter hub fairing out of which protrude rotor blades to generate lift in helicopter flight mode for hover and vertical take-off

2. retraction of the rotor blades into the hub fairing to minimize oscillatory loads during conversion between rotary-wing and fixed-wing flight configurations

3. stopping of hub fairing rotation for fixed-wing flight configuration

4. option to deploy the blades to be wings jutting from the hub fairing and to orient the wings to produce different sweepback angles for more efficient cruise

5. ability to index the hub fairing in flight to change the sweep angle of the wings for optimizing cruise efficiency

6. ability to reverse the conversion process to change from fixed-wing to rotary-wing configuration for very low-speed flight and for hover and vertical landing

An M-85 high-speed rotorcraft concept may include a blade control system that enables the blade to weathervane into the airstream to lesson oscillatory loads while it produces desired lift for cruise and maneuvering flight. The concept would probably incorporate a pneumatic rotor tip drive system when helicopter-mode flight time is small. This would result in lower weight for the propulsion-rotor system due to greater simplicity and likely reduced costs.

The objective of an aircraft having quiet, efficient hover capability and a efficient high-speed cruise capability may be achievable with the M-85 high-speed rotorcraft concept. Hover power is expected to be no greater than 25% more than hover power for a conventional rotor with low disk loading. This 25% power increment was determined from small-scale model hover tests which are probably pessimistic compared to full-scale rotor. A free-pitching blade control technique is presented as a method of producing sufficient pitch and roll moments about the aircraft cg for aircraft control while inherently suppressing wake- and gust-induced oscillatory vertical loads. Cruise L/D at 450 knots and 35,000 ft altitude was found to be reasonably attractive and certainly much better than cruise at a low altitude of 4,000 ft. The improvement in L/D at high altitude is seen to be primarily from reduced parasite drag associated with low air density at high altitude.

The circular disk, acting as a wing during conversion flight mode, can easily support the aircraft. With low altitude and with flight speed of 160 knots, the lift coefficient of the disk is about 30% of the maximum lift coefficient. This would leave sufficient lift margin for maneuvers during conversion. Also, the simplicity of the conversion technique with the possibility of little or no requirement for higher harmonic control and with the ability to easily handle turbulent air during conversion would all combine to make the M-85 a potentially attractive high-speed rotorcraft concept.

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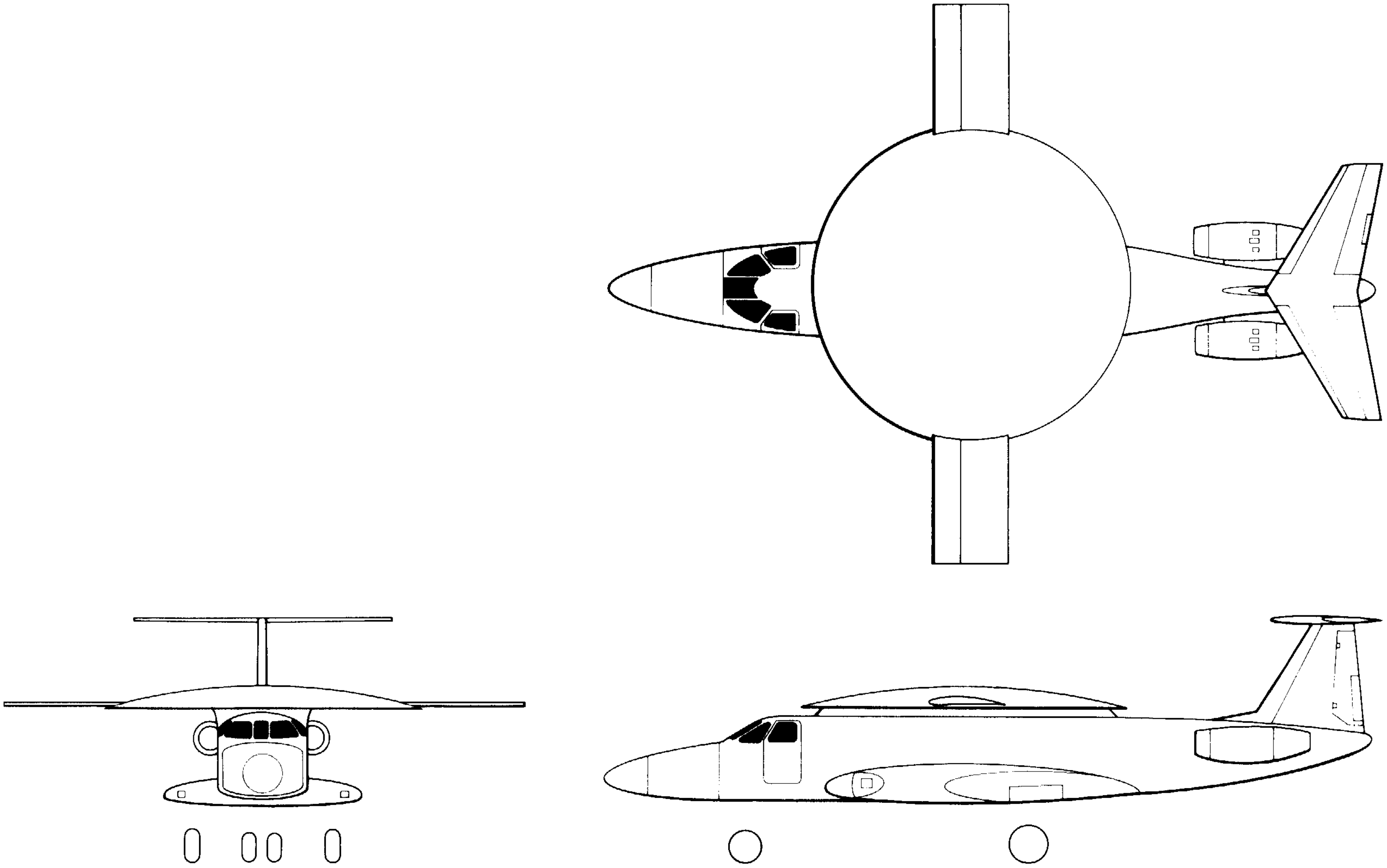
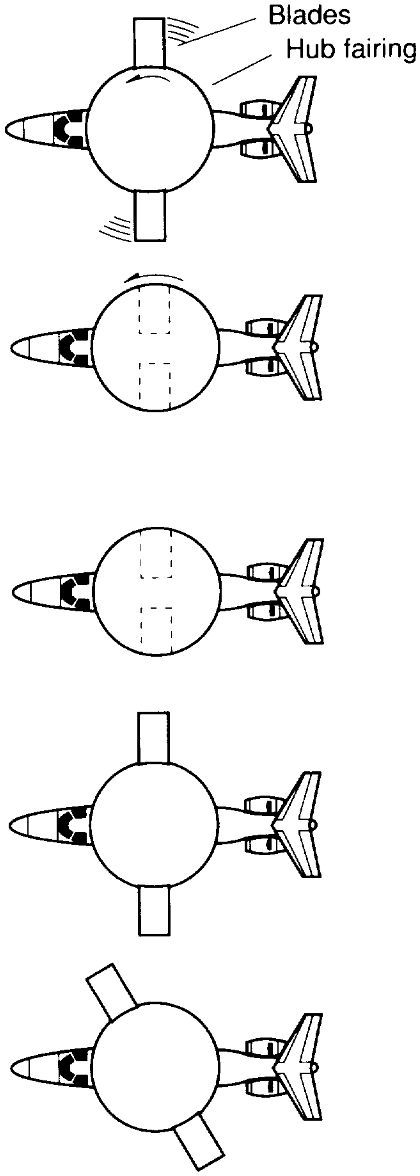


Figure 1. M-85 schematic.



Hub fairing and blades rotate at the same rotational speed.

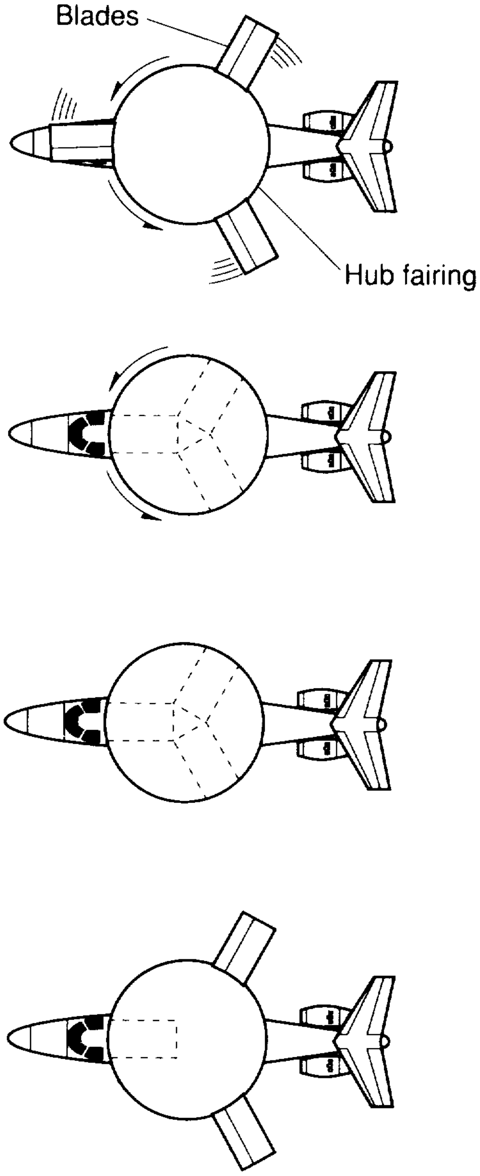
M-85 hovers, takes off and accelerates to conversion speed.

At conversion speed, blades are drawn into the rotating hub faring.

After blades are retracted into the hub fairing, disk rotation is stopped.

With disk rotation ended, selected blades are deployed and possibly disk is indexed to form various swept-wing configurations.

Figure 2. Two-blade M-85 configuration conversion sequence.



Hub fairing and blades rotate at the same rotational speed.

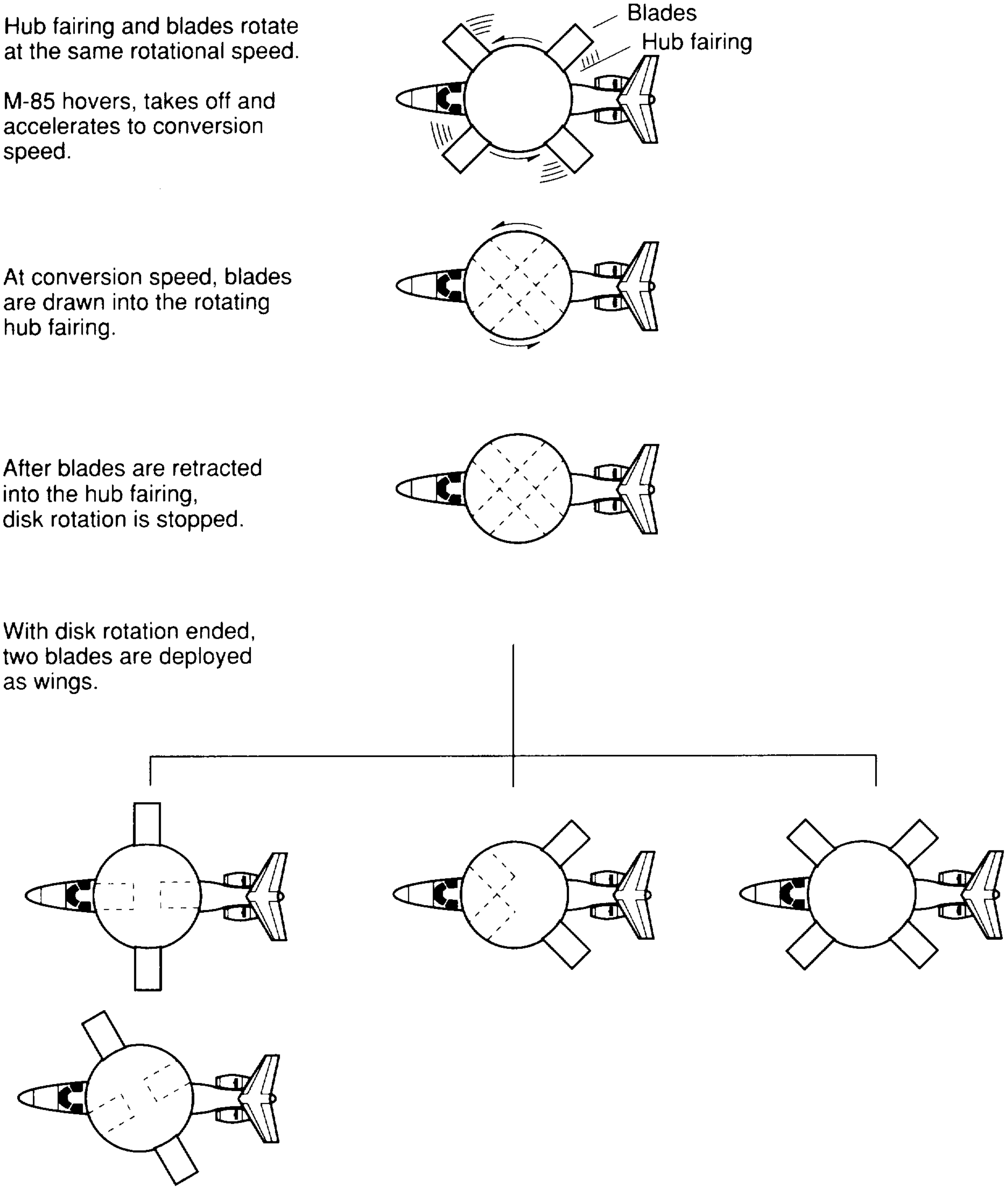
M-85 hovers, takes off and accelerates to conversion speed.

At conversion speed, blades are drawn into the rotating hub faring.

After blades are retracted into the hub fairing, disk rotation is stopped.

With disk rotation ended, two blades are deployed as wings.

Figure 3. Three-blade M-85 configuration conversion sequence.



Hub fairing and blades rotate at the same rotational speed.

M-85 hovers, takes off and accelerates to conversion speed.

At conversion speed, blades are drawn into the rotating hub fairing.

After blades are retracted into the hub fairing, disk rotation is stopped.

With disk rotation ended, two blades are deployed as wings.

Figure 4. Four-blade M-85 configuration conversion sequence.

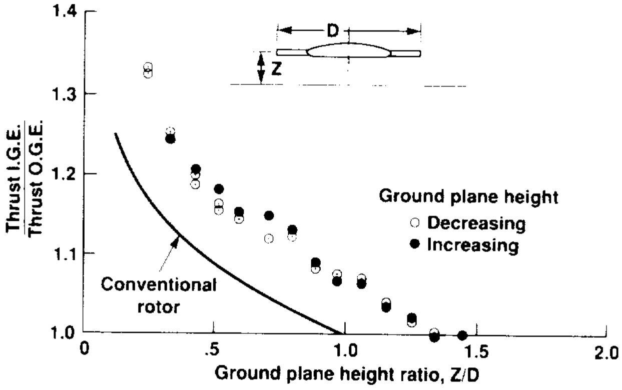


Figure 5. Ground effect with rotor/wing configuration.

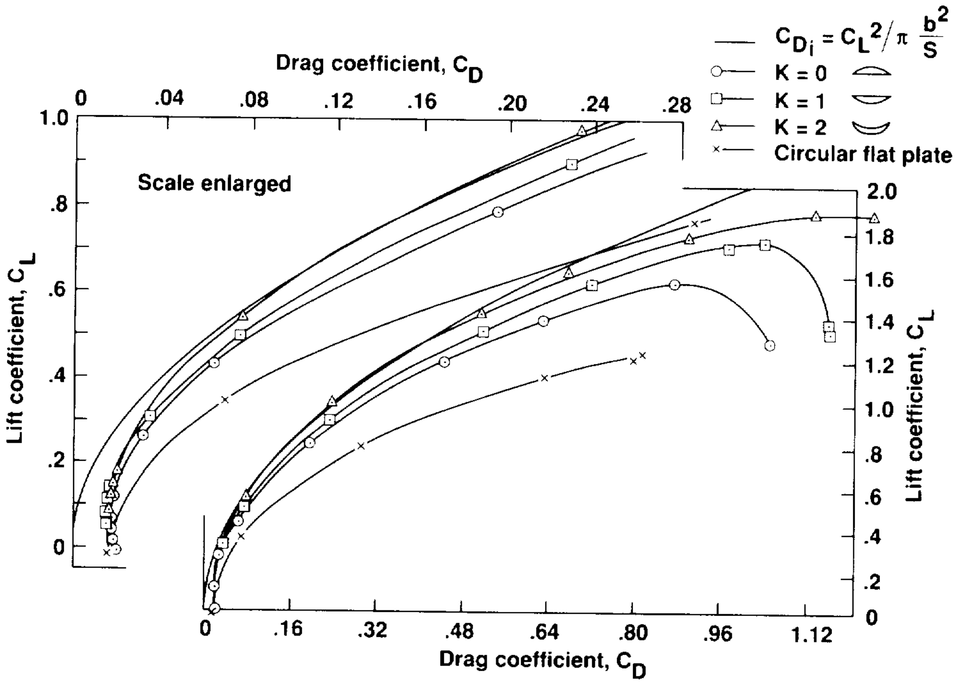


Figure 6. Drag polars for disks with and without Clark Y airfoil cross section from NACA TN-539.

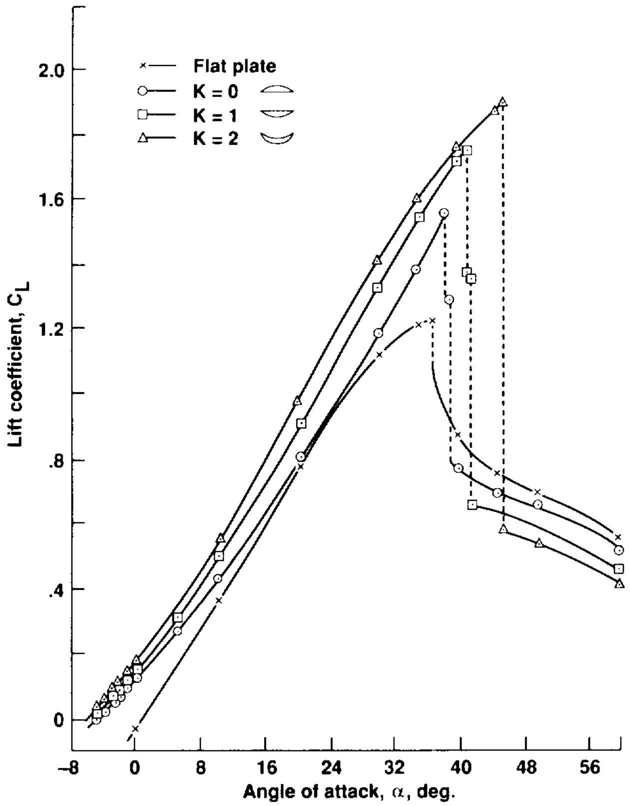


Figure 7. C_L versus alpha for disks with and without Clark Y airfoil cross section from NACA TN-539.

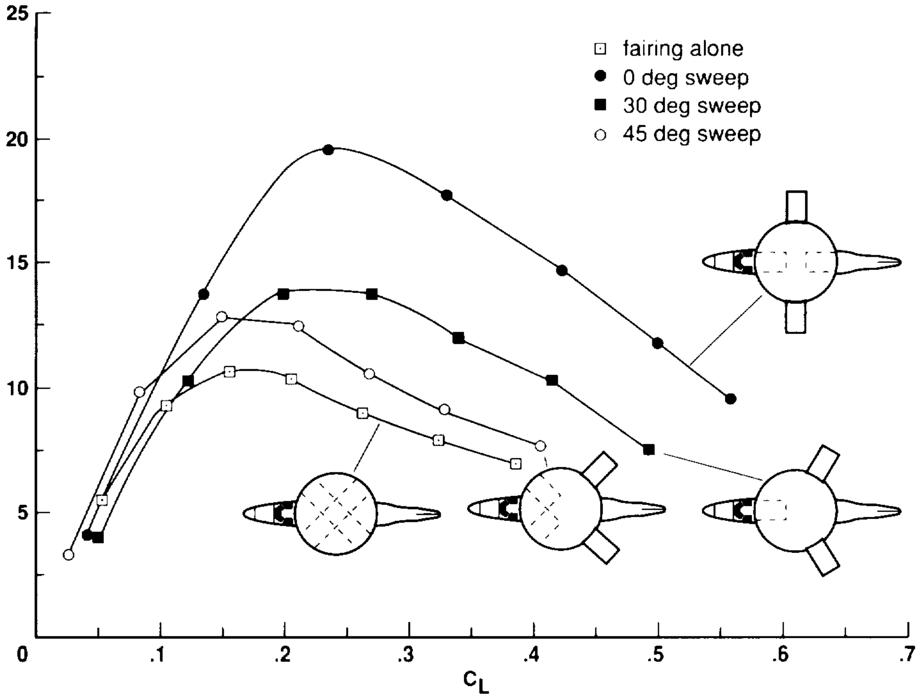


Figure 8. L/D for lifting surfaces versus C_L for disk and various wing combinations.

Figure 9. Zero sweep disk-wing configuration for NASA Langley Research Center 14- × 22-foot wind tunnel test (underside view).

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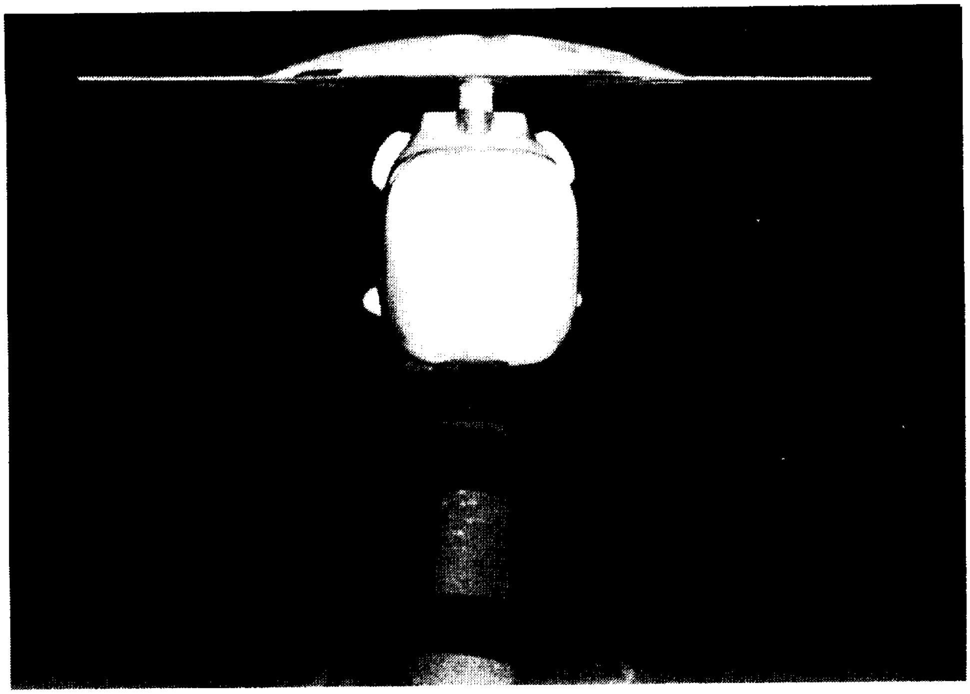

Figure 10. Zero sweep disk-wing configuration for NASA Langley Research Center 14- × 22-foot wind tunnel test (front view).

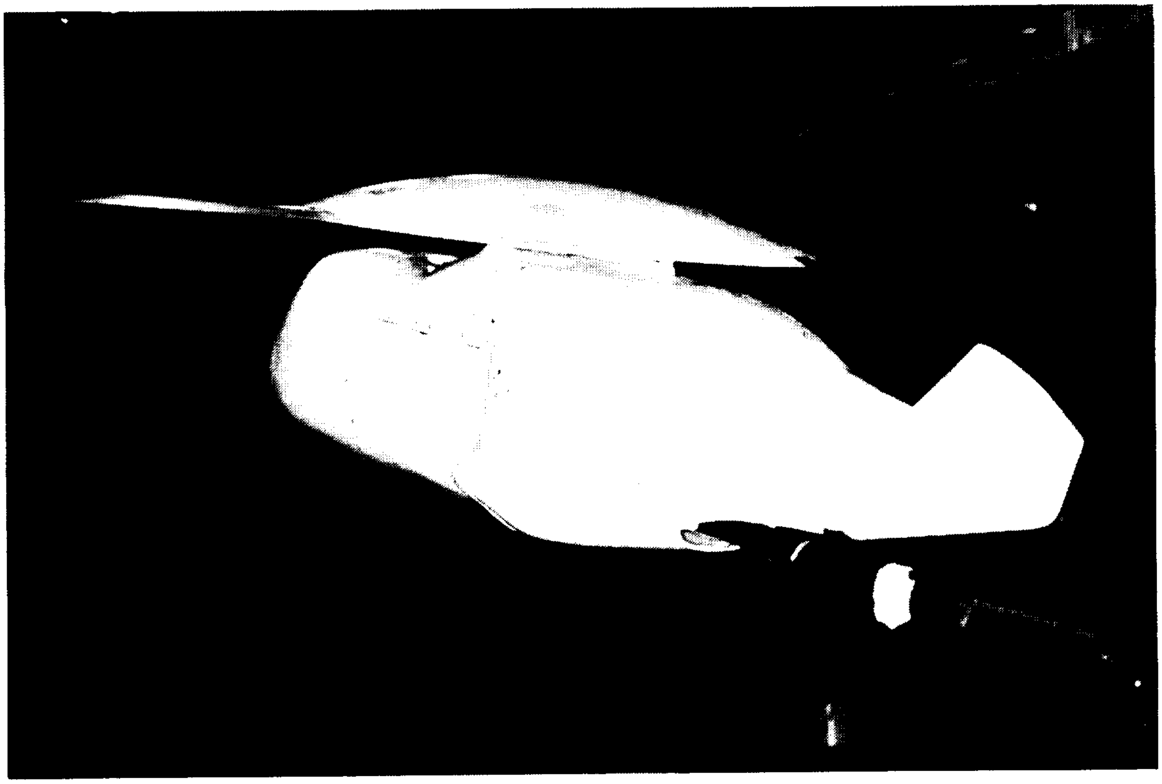

Figure 11. Zero sweep disk-wing configuration for NASA Langley Research Center 14- × 22-foot wind tunnel test (side view).

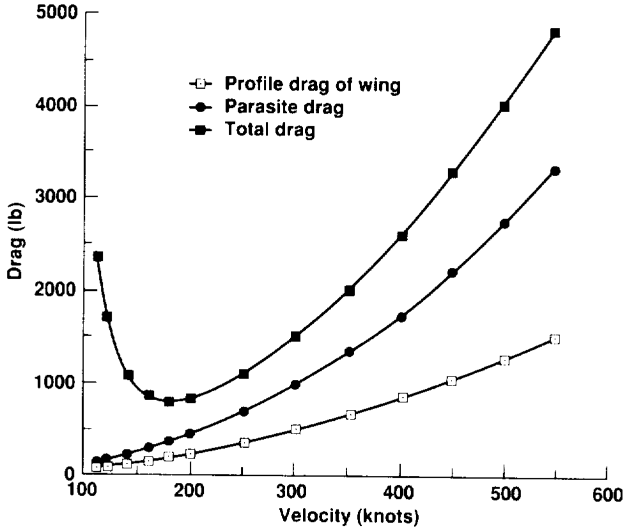

Figure 12. Drag of M-85 conceptual design; GW = 10,200 lb, $f_e = 4.0\ ft^2$, altitude = 4,000 ft.

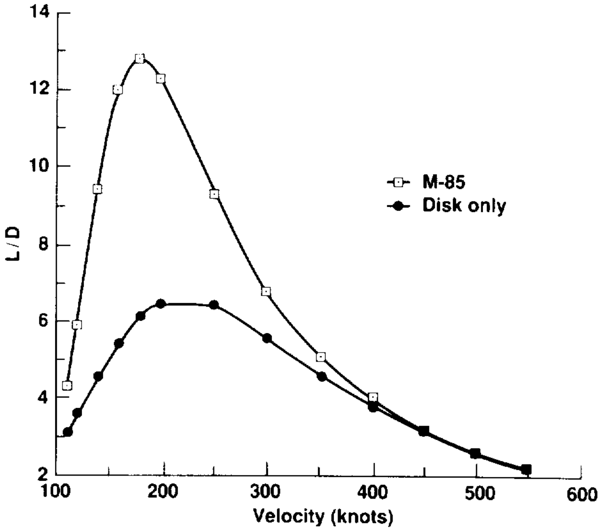

Figure 13. L/D of M-85 conceptual design; GW = 10,200 lb, $f_e = 4.0\ ft^2$, altitude = 4,000 ft.

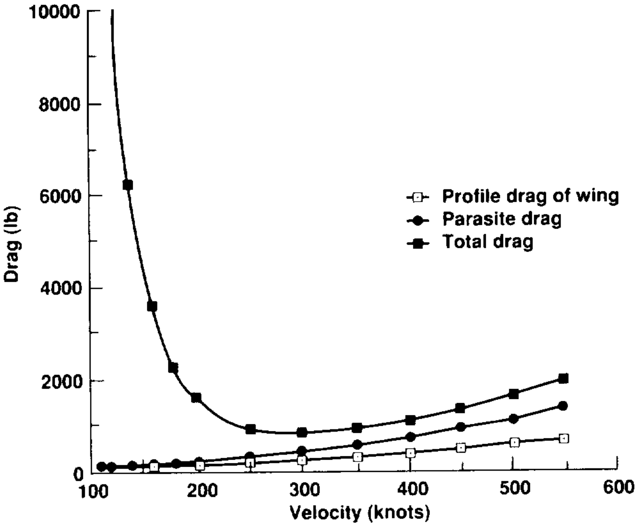

Figure 14. Drag of M-85 conceptual design; GW = 10,200 lb, f_e = 4.0 ft^2, altitude = 35,000 ft.

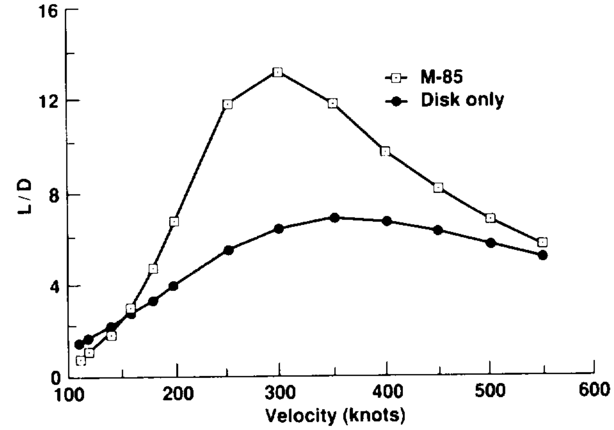

Figure 15. L/D of M-85 conceptual design; GW = 10,200 lb, f_e = 4.0 ft^2, altitude = 35,000 ft.

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16. Abstract

As a result of studying possible requirements for high-speed rotorcraft and studying many high-speed concepts, a new high-speed rotorcraft concept, designated as M-85, has been derived. The M 85 is a helicopter that is reconfigured to a fixed-wing aircraft for high-speed cruise. The concept was derived as an approach to enable smooth, stable conversion between fixed-wing and rotary-wing while retaining hover and low-speed flight characteristics of a low disk loading helicopter. The name, M-85, reflects the high-speed goal of 0.85 Mach Number at high altitude. For a high-speed rotorcraft, it is expected that a viable concept must be a cruise-efficient, fixed-wing aircraft so it may be attractive for a multiplicity of missions. It is also expected that a viable high-speed rotorcraft concept must be cruise efficient first and secondly, efficient in hover. What makes the M-85 unique is the large circular hub fairing that is large enough to support the aircraft during conversion between rotary-wing and fixed-wing modes. With the aircraft supported by this hub fairing, the rotor blades can be unloaded during the 100% change in rotor rpm. With the blades unloaded, the potential for vibratory loads would be lessened. In cruise, the large circular hub fairing would be part of the lifting system with additional lifting panels deployed for better cruise efficiency. In hover, the circular hub fairing would slightly reduce lift potential and/or decrease hover efficiency of the rotor system. This report describes the M-85 concept and presents estimated forward flight performance characteristics in terms of thrust requirements and L/D with airspeed. The forward flight performance characteristics reflect recent completed wind tunnel tests of the winged concept. Also presented is a control system technique that is critical to achieving low oscillatory loads in rotary-wing mode. Hover characteristics, CP versus CT from test data, is discussed. The report discusses other technologies pertinent to the M-85 concept such as passively controlling inplane vibration during starting and stopping of the rotor system, aircraft control system, and rotor drive technologies.

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