Studies of a Gunship Escort concept for the MV-22

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ABSTRACT

The success of the MV-22 Osprey is that its unique combination of range and speed out-performs all existing helicopters, For the full scale Escort, the advantages sought would be reduced aircraft empty weight; simplified wing, fuselage, empennage design and manufacture; to achieve rolling take-offs and/or CTOL for higher payloads or higher altitudes; simpler deck handling; simpler wing fold; and simpler conversion and meshing systems, including gunship escorts. This success creates the opportunity for a new design, tailored to the formidable task of escorting the MV-22. It needs to be compact, agile, longer range and as fast as the MV-22. These studies propose the core physics of the MV-22, move the rotors from the wing tips to mount them on the aircraft centre-line, and lead to a concept of inter-meshing rotors tilting back one-at-a-time, to act as pusher props in the airplane mode. This concept was granted US patent no. 7584923 in 2009. The studies show that the concept has the potential to be an excellent gunship escort for the MV-22 and propose that the next steps should be feasibility studies as a precursor to proposals for full scale flight demonstration.

NOMENCLATURE

A	effective disk area of the rotor(s), ft2
cant(°)	angle of mast relative to XZ plane
Cd0	section zero-lift drag coefficient
Cl	wing lift coefficient
Ct	rotor thrust coefficient, $T/\rho A (\Omega R)^2$
Ct/ σ	blade loading coefficient
DE	differential equation
DL	disk loading, T/A
FCC	flight control computer
FM	figure of merit
fusDrag	fuselage drag, lbf
HOGE	hover out of ground effect
L/D	aircraft lift to drag ratio
MTOW	maximum TOW, lb
NDSolve	a numerical DE solver
P	power, hp
propEffic	propeller efficiency
R	rotor radius, ft
SFC	specific fuel consumption
T	rotor thrust, lbf
Tilt(°)	rotation about x-axis: 0° is full forward, 90° is hover, 180° is fully back for cruise
TCL	thrust control lever
TOW	take-off weight, lb
γ(°)	twice cant(°)
ζ	transmission efficiency
θ	mesh angle, or mesh error
κ	induced power factor
ρ	air density
σ	rotor solidity, ratio of total blade area to A
φ	mast angle of tilt

INTRODUCTION

The V-22 Osprey entered full scale production in 2005/6 and now is in service as the MV-22 with the US Marine Corps (USMC) and as the CV-22 with the USAF.

It has a unique combination of range and speed that out-performs all existing helicopters, including gunship escorts. This success creates the opportunity for a new design of gunship, tailored to the task of escorting the MV-22.

The use of gunship helicopters as escorts is well established (Ref. 1), and a tiltrotor gunship concept was proposed (Ref. 2), based on the successful XV-15 demonstrator programme. Reference 3 describes an insertion of expeditionary forces, which appears as a mission where MV-22s plus Escorts as studied here, would make a powerful capability.

The need for a gunship escort for the V-22 Osprey had been raised in 1996 (Ref. 4), and in 2004 when it was reported (Ref. 5) that "The Marine Corps' top aviation officer has asked Bell Helicopter Textron Inc. to study arming its executive jet-sized BA609 tilt-rotor aircraft as an escort for the V-22 Osprey tilt-rotor troop transport", and no

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doubt the need has been discussed many times since as the Osprey programme progressed.

The MV-22 Osprey fits the sea basing concept of projecting and sustaining naval power, which suggests that an armed escort for the MV-22 would be a valuable force multiplier. Starting from that premise, the studies proceed as follows:

- Review the MV-22 Osprey
- Choosing the physics
- Configuration down-select
- Specification and performance
- Meshing Aerodynamics and Mechanics
- Scale model tests
- Enabling technologies
- Next steps towards a Project
- Conclusions

MV-22 OSPREY

The main users of the Osprey are the USMC and so that is where this study is focussed, but not to exclude its findings from wider relevance or application.

The MV-22 Osprey extends the reach of the Marines, enabling them to carry payloads faster and further. It has seen service with the USMC in Iraq as a transport, in Haiti on humanitarian missions, and now is in Afghanistan with the USMC Marine Medium Tiltrotor Squadrons. It extends the reach of the USMC because of its speed and range advantage over existing helicopters. Fundamentally this advantage is down to the aerodynamics and physics engineered into its design.

Some of this can be seen in Figure 1 which shows the right wing and rotor of an MV-22 Osprey. Lance Cpl. Mark Moretz, a flight line mechanic with Marine Medium Tiltrotor Squadron 261, 3rd Marine Aircraft Wing (Forward), is making a pre-inspection of the MV-22, preparing for a full day of missions.

It is a good view of the how the proprotors look in hover or helicopter mode. The blades are twisted, more than on helicopters, less than on turboprops. Gone is the complex hub and blade attachment common on helicopters, the blade roots finish cleanly at a spinner that covers the hub. The hub includes blade attachment, full blade cyclic and collective pitch control, and vibration absorbers.

The nacelle/wing fairing is in the broken position, revealing the deep thickness to chord ratio of the wing. The wing has a 5.5 aspect ratio and, in cruise, the engine nacelles have an end plate effect, helping to give the Osprey an exceptional lift to drag by rotorcraft standards.

Figure 1. Pre-inspection prior to missions in Afghanistan, April 24 2010

Dominating this view of the wing, are the full width flaperons. In hover some of the rotor downwash hits the wing, wasting part of the rotor's lift. Deploying the flaperons halves the blocking effect of the wing, recovering a valuable lift increment (Ref. 6).

Away from the flaps, on the wing just inboard from the nacelle, is seen a wing fence that reduces tail vibration at low aircraft speed. It reduces the wing and nacelle vortices generated at intermediate tilt angles.

Obviously the proprotors and engine nacelle combine to make a large mass mounted at the wing tip. In level flight this spreads loads on the wing, which is good structurally. Dynamically, having a long moment arm at the wing tip, they present roll and yaw inertia. On ship, in a heaving deck situation, they load the wing stow system. Equally the moment arm gives the rotors good authority in roll and yaw.

An early development review on the Osprey's aerodynamics (Ref. 7) gives an insight into how the aircraft achieves its speed, range and performance.

CHOOSING THE PHYSICS FOR THE ESCORT

The purpose of the MV-22 Osprey is to extend the reach of the Marines, to carry payloads faster and deeper into hostile territory.

On an MV-22 mission, for example to insert or extract troops at a landing zone deep in hostile territory, the escorts must protect the MV-22s every step of the mission and especially at the landing zone. Landing zone duties would be scouting, suppressing hostile fire to clear a window for the troop insertion or extraction, acting as spotter for other providers of air cover, and providing communications or related support. The escort should have a contingency reserve, and speed in hand, so that if diverted it can catch up to rejoin the MV-22 mission. An escort that has the speed but not the range, or has the range but not the speed, will penalise MV-22 operations.

Once at the landing zone, the escort needs agility and endurance at very low speeds, especially when operating at hover. The physics of the rotary wing is particularly well adapted to this type of duty. Other schemes, successfully used in V/STOL aircraft, achieve hover at the expense of much higher fuel consumption. The reason for this is that fuel efficiency is directly proportional to the diameter of the column of air supporting the aircraft. The large diameter rotor of a helicopter gives it a major advantage in hover efficiency over the relatively small diameters of V/STOL nozzles.

It is concluded that the escort will have a rotary wing for hover and low speed flight.

For the cruise portion of the mission, the escort needs speed and range, so the next criterion for choosing the physics for the escort is cruise efficiency, the lowest drag design at MV-22 cruise speed.

There is a wide range of possible configurations, represented here by three generic concepts:

helicopter
compound helicopter
tiltrotor

The principal assumptions for their cruise modes are that for the helicopter, all vertical lift and horizontal thrust are provided by the main rotor(s); that for the compound helicopter, lift may be provided in part or wholly by fixed wings and thrust by propeller or other means; and for the tiltrotor that the wings provide all the lift and the tilted rotors all the horizontal thrust.

In hover, tiltrotors, helicopters and compound helicopters share the same lifting physics: the rotor. For the same aircraft weight and rotor effective areas, the power needed to hover is the same for each concept.

In cruise, the lifting physics are different. Tiltrotors use fixed wings, helicopters use rotors, and compound helicopters use a combination of rotor, separate propulsion and wings. The difference in the drag of rotors and wings at high forward speeds is a key issue.

For the same duty in cruise, rotors have much higher drag than wings. This is because the advancing blades face into the wind and so reach Mach number limits sooner. The retreating blades face away from the wind and have to operate closer to stall. Both situations require the blade airfoils to operate away from their optimum and are high drag compared with that of the wing whose airfoil can be designed to operate at the optimum cruise speed.

The subjective comparison in Table 1 immediately suggests that tiltrotors have a significant advantage over pure helicopters.

Compound helicopters also have a significant advantage over helicopters by reducing the work of the rotor in cruise, an effective way of reducing their drag.

Table 1. Sources of drag in Cruise for three escort concepts

	Helicopter	Compound	Tiltrotor
Fuselage drag	full	full	full
Rotor drag	full	reduced	0
Wing drag	0	full	full

At present there are advanced compound helicopters in test (Ref. 8, 9) each with a different mix of approaches to make significant performance improvements. In forward flight, the rotor of a helicopter provides lift and the propulsive thrust to maintain speed. Adding an efficient fixed wing to a helicopter allows the rotor lift to be off-loaded. Adding a separate propeller, jet or ducted fan can relieve the rotor of its propulsion duty. Reducing rotor rpm at high forward speed allows advancing blade losses to be reduced. Using two main rotors that contra-rotate achieves torque balance without the losses of a tail-rotor, and if side-by-side or co-axial, allows the use of opposing lateral cyclic to off-load retreating blades to reduce their losses.

From a subjective point of view, compound helicopters should be able to match the speed of the MV-22 at cruise. However it is difficult to believe that their rotor drag and its penalty on range can be removed entirely.

At MV-22 mission cruise speeds, all else being equal, the physics of a tiltrotor is assessed as having lower drag than the competing concepts, so that is the chosen physics for the gunship escort studied in this paper.

This was felt to be a good choice because it means that the basic physics of the MV-22 and its escort are the same. Where the MV-22 goes, so can its escort.

CONFIGURATION DOWN-SELECT

Having chosen to stay with the well proven physics of the XV-15, MV-22 and BA609 tiltrotors does not mean that a wing-tip rotor layout suits a gunship. So the study next considered the tiltrotor layout implications for an escort.

For a transport, having the tilting proprotors at the wing tips brings important advantages: efficient use of the proprotors and freedom in designing the fuselage for loading and for airdrop and similar priorities.

Equally, having the tilting nacelles and proprotors at the wing tips would meet the speed and range needed for escort duties. The downside is that the nacelles and proprotors are relatively bulky. Their presence on the wing tips mean the field of view and fire from the cockpit forward is less good than a helicopter gunship. The blades spread beyond the aircraft's wing tips so the spot deck area is high. The weight penalty for wing-slew for stowage remains. Also the wing design and its aerodynamics are constrained by carrying the nacelles, and the roll and yaw moments of inertia are high. The high rate of descent Vortex Ring State (VRS) should be the same, including the positive feedback causing un-commanded roll (Ref. 10). The robust strategy of applying forward tilt for recovery from VRS should also apply.

Moving the proprotors to the centre line of the aircraft

Assume that the rotors are brought to the centre line of the aircraft in a compact arrangement, as co-axial or as intermeshing rotors.

It is likely that the effective disk loading may need to be higher, but spot deck area and roll inertia are reduced. Simpler wing fold can be used for stowage, and there are different aerodynamic and structural options for the wing design. The vortex ring state will occur, as in all rotorcraft, but having the rotors compactly together on the aircraft centre-line should reduce or eliminate un-commanded roll.

These changes move the tilt rotor concept from transport towards an agile gunship.

Placing the tilting rotors on the fuselage is not new. In 1929 George Lehberger had very similar ideas, see Figure 2

Discussing a modern version of this approach with a manufacturer, the most telling comment was that tilting the coaxial rotors forwards placed a heavy transmission immediately above the cockpit and placed the rotors into the forward field of view.

This was seen as a distraction to the crew. It certainly reduces their field of view, denies safe egress in airplane mode, and denies some convenient locations for weapons and sensors.

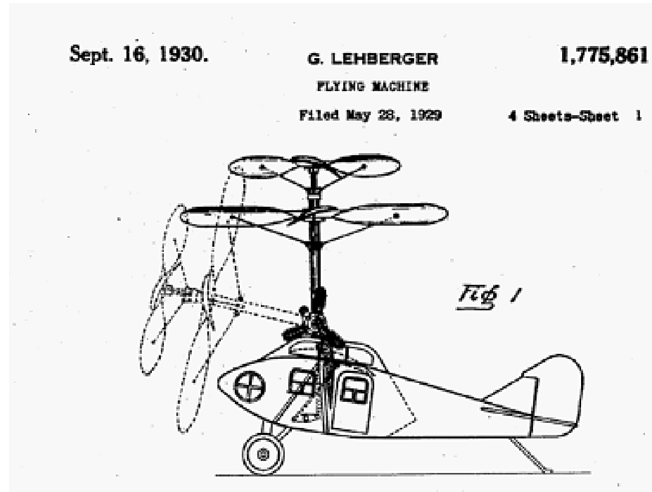

Figure 2. George Lehberger's patent for a Flying Machine, filed in 1929.

Taking these perceived pros and cons into account, it was decided to survey all "possible" centre-line tiltrotor configurations.

Survey and down-select of possible centre-line tiltrotor configurations

The survey and down-select were based on a light aircraft application, which meant that safety issues took a priority as well as having the common interest in range at cruise speed. Nine centre-line tiltrotor configurations were compared with five examples of other rotorcraft and fixed wing configurations. Figure 3 shows cartoon sketches of some of the 9 centre-line concepts.

One difference between the tiltrotors is the quadrant of tilt: the Osprey is 1st quadrant, 0° to 90°. Option 2 is also 1st quadrant. Options 4B, 6A, 6B and 7 are 2nd quadrant, 90° to 180°, and option 3 is 3rd quadrant, 180° to 270° which was proposed in the Focke-Angelis FA 269 concept. The 4th quadrant, 270° to 360°, was considered of no interest.

Descriptions, comments and estimates of cruise speed, range and some other parameters were built up as a spreadsheet, and then grouped by topic to be ranked in comparison tables.

The process was iterative. If a comparison table showed a problem and there were a credible fix, the comparison was updated. If the fix was effectively a new configuration then that was added separately, e.g. configuration 4 became 4A and 4B. In the next iteration 4B was eliminated because it relied on a pusher prop during rotorcraft conversion from helicopter mode to wing mode.

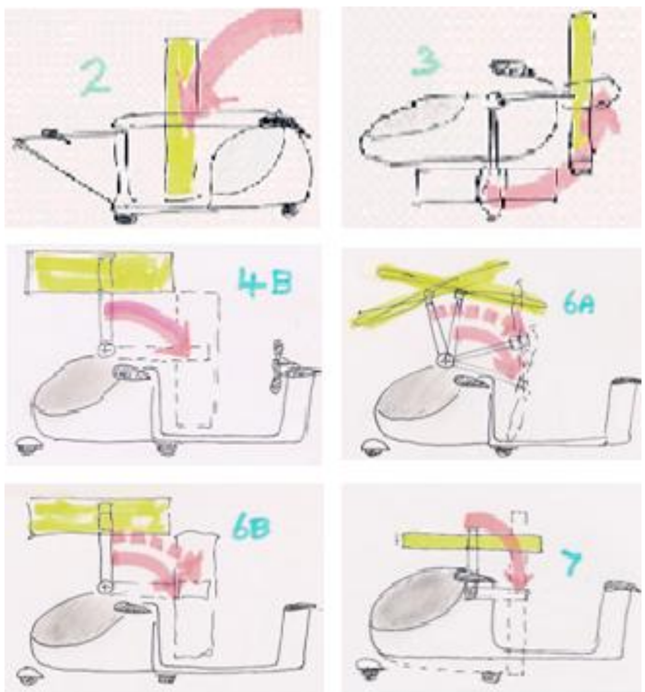

Figure 3. Six cartoons of some centre-line tiltrotor configurations showing transition from helicopter to airplane mode. A single solid arrow indicates that both rotors transition together. Two arrows, solid and dotted, show rotors that transition is one-at-a-time. 6B was the final selection.

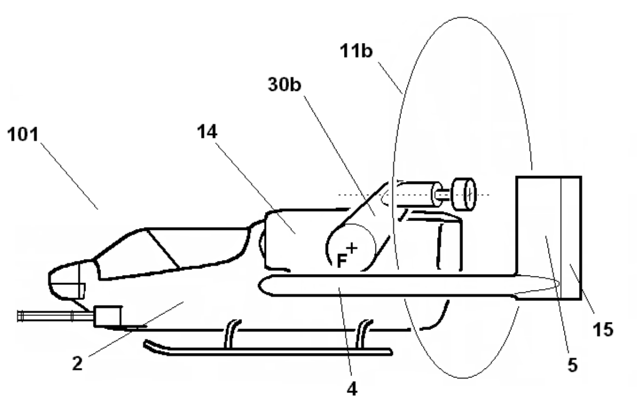

Figure 4. The 6B configuration chosen in Figure 3 is shown here in more detail in airplane mode where the rotors operate as pusher props.

The process finished with selection of configuration 6B. This concept has intermeshing rotors that are mounted on the aircraft centre line and in the airplane mode are tilted back behind the fuselage to operate as pusher props. For safety, the proprotors are tilted one-at-a-time to make the conversion between helicopter and airplane modes.

The 6B configuration was sized to the duty of a gunship escort, see Figure 4. The concept appeared novel and was granted US Patent 7,584,923 B2 in Sep. 8, 2009.

Thus the configuration shown in Figure 4 is the basis of the following proposed specification for the Escort and the assessment of its potential performance.

ESCORT SPECIFICATION AND PERFORMANCE

Figure 4 shows a side view of the proposed Escort in airplane flight mode; Figure 5 shows a 3-vu of it in hover.

The specification set out in Table 2 is proposed as the basis for assessing the Escort concept:

Table 2. Proposed Specification

Crew: pilot and co-pilot/gunner	2
Powerplant: 1 turboshaft	6,150 shp
Length, width	36 ft, 32 ft
Rotor diameter	24 ft
Empty weight	13,300 lb
Max internal fuel	5,150 lb
Vertical take-off, max weight	19,500 lb
Service ceiling	25,000 ft
Hover out of ground effect, max.	6,400 ft
Max cruise, sea level	250 knots
Mission radius @ 240 knots with 2,500lb ordnance payload	285 nm

To assess this proposed specification, it is helpful to compare the Escort with the assumed characteristics of the MV-22.

General comparison, see Table 3.

The Escort should be operated, equipped and armed as a typical gunship, but with the performance advantages of a tiltrotor so that it can escort the MV-22.

The Escort's two meshing rotors are mounted on the centre-line of the fuselage. They tilt back for cruise, give superb field of view for crew and sensors, and a wide field of fire for weapons and countermeasures. Having meshing rotors that tilt back gives a very compact design.

The suite of controls available to the Escort's flight control system is assumed to be similar to the MV-22: cyclic, collective and tilt for rotary wing, primary and secondary controls surfaces for fixed wing mode. An important addition is articulation of the leading portion of the main wings.

Table 3. Comparison of the Escort and the MV-22**

	MV-22**	Escort
Spot area, ft x ft	83x58	36x32
Field of view/fire	good	superb
Engines, max hp	2x6150	1x6150
Max VTO weight, lb	52,600	19,500
Empty weight, lb	35,300	13,300
Service ceiling, ft	25,000	25,000
Hover OGE, max, ft	5,400	6,400
Max cruise, sea level, kn	250	250
Mission radius, nm	230	285

** **Brochure, or author's estimate not validated by manufacturers**

Blade meshing is required for all relative tilt positions of the rotors. Mechanical meshing is assumed. Slewing the wings for stowage is not needed. Rotor blade stow and wing fold are assumed.

Take-off in helicopter mode

The payload achieved depends on the difference between the unloaded weight and the maximum take-off weight (MTOW).

The unloaded weight of the Escort has been estimated from an example helicopter by taking the weight groups that must change and scaling them according to rotor radius R, first to the AH-1Z and then to the escort duty.

For example mass of the blades was scaled as $R^{1.3}$, the hubs as $R^{1.5}$, and transmission as $R^{1.5}\ P^{0.82}$ (Ref. 11).

MTOW in turn depends on the lift capability in hover out of ground effect (HOGE), the power requirement of the rotors, and the power actually available. Table 4 shows the estimate of power for MTOW as a percentage of maximum power available, % max hp, plus other parameters: the rotor solidity σ, the percent of rotor lift blocked by the wing/fuselage in the rotor downwash, the effective disk loading, DL, the blade loading Ct/σ, and the figure of merit, FM, estimated from:

$$\mathrm{FM} = \left(K + \frac{\mathrm{Cd0}\ \sigma}{4\sqrt{2}\mathrm{Ct}^{3/2}}\right)^{-1}$$

Ct is the thrust coefficient, κ = 1.15, and Cd0 = 0.01 (Ref. 12).

The control power at take-off, that is the margin in lift available to accelerate the aircraft vertically, expressed as a percent of hover lift, was estimated from the maximum engine power available.

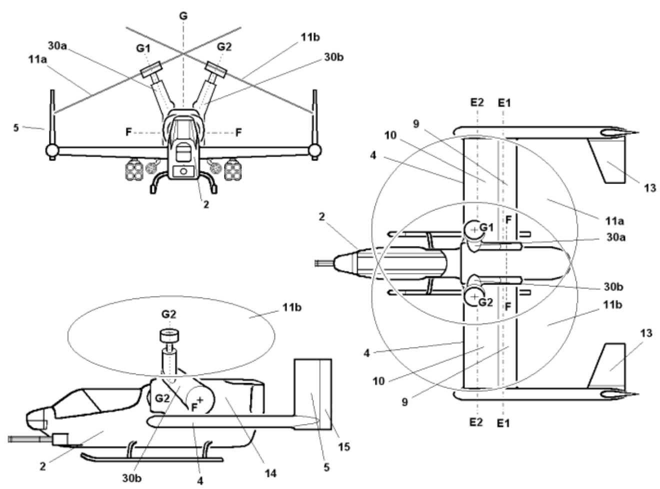

Figure 5. Three views of the Escort in the hover mode. The meshing rotors are tiltable about the F-F axis.

The Escort has its two meshing rotors set at 11° relative to the airframe XZ plane, with the hub separation approximately 0.55 R. Solidity and disk loading were estimated using the effective area of the overlapping disks projected onto the XY plane.

In hover, where the downwash from the rotors meets fuselage or wings, there is some loss of lift by blockage of part of the rotor flow. On the Osprey, the effect is halved by deploying the flaperons (Fig. 1).

On the Escort, the wing blockage is larger, and greater articulation of the surfaces would be needed. For example, the plan view of the Escort in Fig. 7 shows axes to hinge leading and trailing surfaces. In principle these should achieve the rotor blockage factor shown in Table 4.

Table 4. Take-off: Escort and the MV-22**

	MV-22**	Escort
MTOW, lb	52,600	19,500
Blades/rotor	3	3
Solidity, σ	0.12	0.2
Rotor blockage, % lift	8.9	4.8
Disk loading, lb/ft2	25.3	34.1
Blade loading, Ct/σ	0.15	0.12
Rotor figure of merit	0.81	0.80
Engine(s) % max hp	84	71
Control power, % lift	AH-1Z: 17.1**	21.4

** **Brochure, or author's estimate not validated by manufacturers**

Cruise, airplane mode

The physics of achieving range, devolves into the fuel factor achieved at take-off and the range achieved with that fuel factor at cruise speed.

Fuel factor, Fuel/MTOW, is taken as fuel available for the mission at take-off, as a proportion of the all up weight at take-off, fully manned, fuelled and equipped with communications, sensors, weapons, stores, counter measures etc to perform its part of the mission.

Range is estimated using the Breguet formula (Ref. 13)

$$\text{Breguet}\ldots\text{range} \approx \frac{\text{L} \therefore \text{D propEffic}\ \zeta\ \text{Log}[\frac{1}{1-\text{Fuel} \therefore \text{MTOW}}]}{\text{cruiseSFC}}$$

This gives a working estimate of range allowing the concepts to be compared.

As a comparison, assume identical specific fuel consumption, SFC, transmission efficiencies, ζ, and weight of fuel as a proportion of all-up-weight, Fuel/MTOW. Then what separates the designs, is their effective aircraft lift-to-drag ratio, L/D, and their propeller efficiencies.

Applying these in the Breguet formula, gives an estimate of the capability of the Escort when teamed with the MV-22 on a land assault mission, see Table 5.

Note that the Escort has been credited worse propulsive efficiency and better aircraft lift to drag ratio L/D. The net effect is better mission radius, but behind these choices is the important design issue of thrust reversal.

When the Escort's proprotors are tilted back to act as pusher props, their thrust must be reversed. So collective pitch has to be reversed, and if the blades are twisted then twist has to be reversed as well.

The low risk solution is to use untwisted blades and accept the lower proprotor efficiencies. That is the basis of Table 5.

A more satisfactory solution would be to use variable twist blades, if feasible. The technology is being researched elsewhere, and should at least be investigated for its potential for the Escort.

Table 5. Land Assault: Escort mission with the MV-22**

	MV-22**	Escort
Payload, troops or ordnance	24 troops	2,500 lb
Fuel, lb	5,940	2,685
TOW, lb	47,000	18,920
Cruise % max, shp	35	21
Cruise SFC, lb/shp/hr	0.42	0.42
Prop. efficiency	0.75	0.65
Cruise lift/drag, L/D	9	11
Mission cruise, kn	240	240
Mission radius, nmi	230	285

** **Brochure, or author's estimate not validated by manufacturers**

In designing for hover, careful attention is needed to reduce wing blockage of the rotors, and in cruise, careful attention is needed to wing design to achieve better aircraft L/D.

Conversion between helicopter and airplane modes

From a pilot's point of view, it is proposed that the Escort have the same controls and authority as the MV-22.

On the MV-22, the thumbwheels on the crews' Thrust Control Levers (TCLs) are used to control conversion via proprotor nacelle angle. For each nacelle angle, the aircraft has a viable flight envelope within speed boundaries, part of the tiltrotor's conversion corridor. At any point in the conversion the crew can choose to hold the nacelle angle, reverse or continue to the flight mode that suits.

For the Escort, it is proposed to use the same approach of thumbwheels on the crews' TCLs: at any point in the conversion the crew can hold, reverse, or continue required. The Escort's Flight Control Computers (FCCs) must achieve this objective using a different tilting strategy from the MV-22.

First, the conversion from helicopter to airplane mode is tilting backwards to pusher propulsion rather than forwards to tractor propulsion as MV-22. Second, pusher propulsion disallows the proprotor from delivering thrust while tilted between 90° and 180°. Therefore for safety, the proprotors must transit one-at-a-time, so that while one transits, the other provides all the thrust needed, see Figure 6.

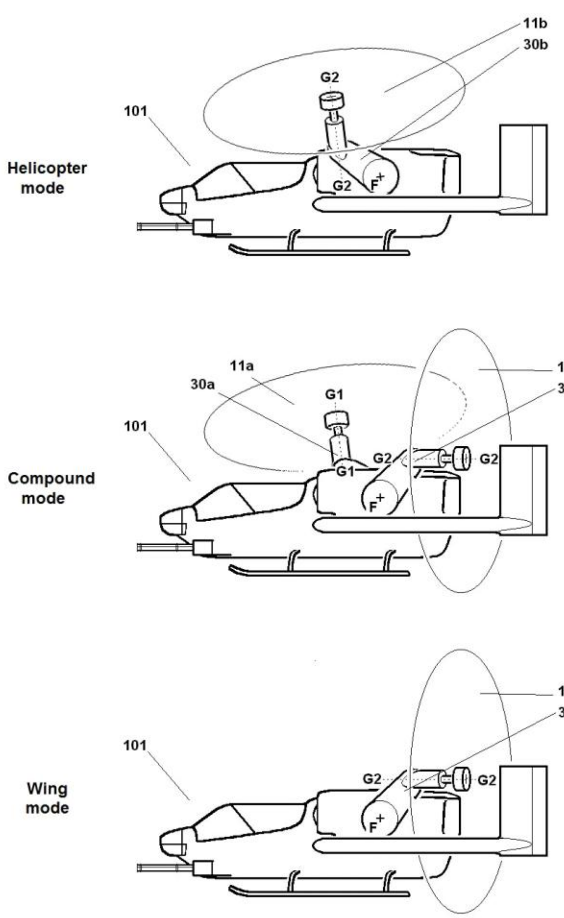

Figure 6. Within the conversion corridor, the rotors can be tilted one-at-a-time between the helicopter and wing modes. The transitioning rotor's thrust is kept substantially zero, while the other rotor maintains the flight thrust.

During the one-at-a-time transition the balance of symmetry of the two meshing rotors is lost and so the fixed wing control surfaces (see Figure 5) are sized to trim and control the aircraft. If necessary, control can be augmented by cyclic from the rotor providing aircraft propulsion.

To match the MV-22 conversion times the Escort, because of its one-at-a-time procedure, needs to tilt the proprotors at twice the speed of the MV-22. As a bench mark, a conversion system capable of tilting the MV-22 proprotors at 8°/sec should be capable of tilting the Escort's at 16°/sec. A 2-degree freedom (x, z) math model was used to compare speed, wing lift coefficient Cl and rotor blade loading coefficient Ct/σ, during a conversion.

The point chosen on their flight envelopes was sea level, starting from 60 knots in helicopter mode to about 115 knots in airplane mode, both at minimum operating weights. The math model factors in drag of fuselage, nacelles/masts, weapon stores, wing profile drag, and wing induced drag as a function of wing lift. The rotors are treated as thrust vectors, variable in magnitude and variable in direction by tilting.

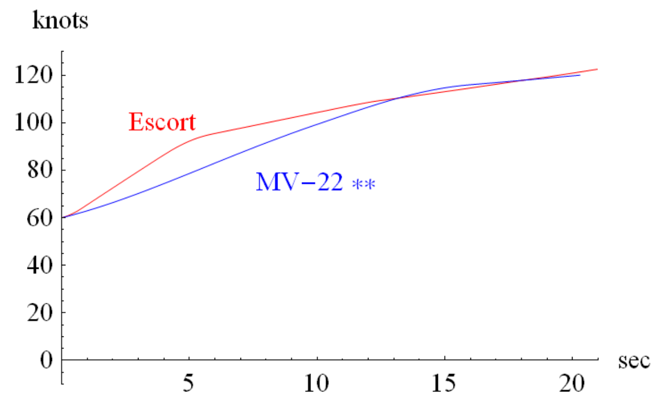

Figure 7. The Escort and the MV-22 ** (author's estimates) transitioning from 60 knots in helicopter mode to about 115 knots in airplane mode.

Level flight requires that the lift of the wings exactly makes up any deficit in vertical component of lift from the rotors. This allows the math model to be reduced to a single degree of freedom, here expressed in Mathematica® code:

$$\text{NDSolve}[\{v'[t] == \frac{\text{X} \ldots \text{lbf} - \text{wingDrag}[t] - \text{fusDrag}}{\text{TOW}} g,$$

$$v[0] == 60\text{knots} \ldots \text{fps}\}, v, \{t, 0, 21\}]$$

The Escort accelerates first then tilts its rotors one-at-a-time over the next 15 seconds to complete the conversion.

To represent this (Figure 10), piecewise functions of time were used for the pilots/FCCs inputs, flying the aircraft level, while increasing speed and making the conversion.

Solving for forward velocity v[t] gave the comparison shown in Figure 7.

This strategy keeps the wing away from stall as shown in Figure 8

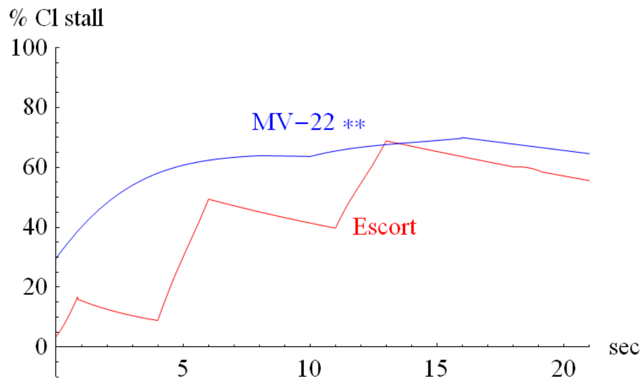

Figure 8. Wing coefficients of lift Cl, as a % of stall, during the transitions shown in Figure 7 for the Escort and the MV-22 ** (author's estimates).

The range of wing coefficients of lift Cl during the transitions seems an acceptable % of stall. The jagged shape reflects the one-at-a-time tilting of the Escort's proprotors, and shows even more clearly in Figure 9 where the thrust modulation of the proprotors determines the blade loading Ct/σ throughout the conversion manoeuvre.

The range of blade loading Ct/σ during the transitions seems acceptable.

The math model of the Escort's one-at-a-time conversion shown in Figure 7 used the piecewise functions plotted in Figure 10. Throughout the transitions the meshing rotors must be kept in strict phase to avoid blade interference.

For the point on the sea level flight envelope chosen for assessing conversion: 60 knots in helicopter mode to 115 knots in airplane mode, it is concluded that stall margins for the wings and blades were comparable with those assessed by the author for the MV-22 performing a similar conversion.

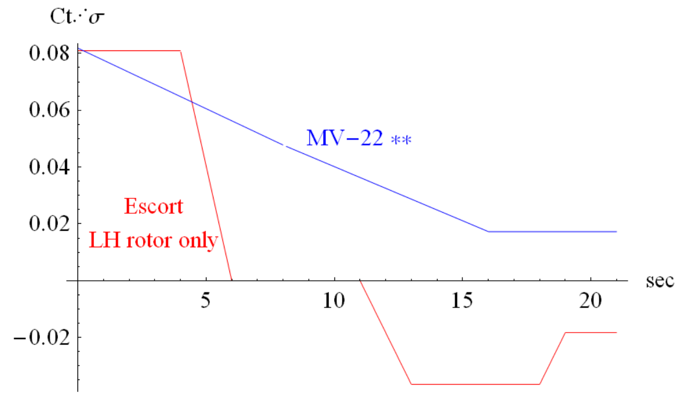

Figure 9. Proprotor blade loading Ct/σ for the conversion shown in Figure 7 for the Escort (LH rotor shown) and the MV-22 ** (author's estimates).

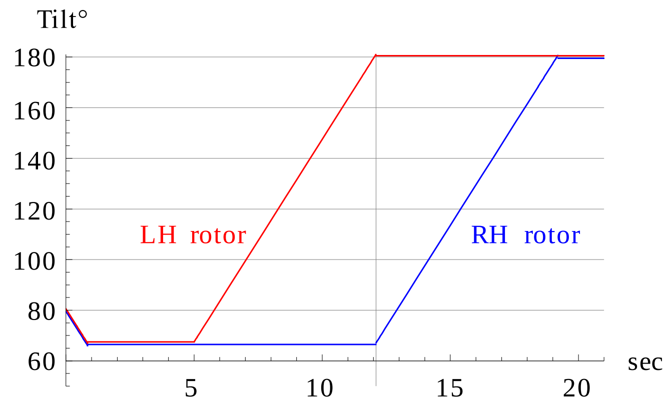

Figure 10. Piecewise one-at-a-time tilting as used in the math model for the conversion of Figure 7.

The above assessments indicate that an Escort designed to the proposed specification would be compact, agile, longer range and as fast as the MV-22, in short, an excellent gunship escort for the MV-22.

MESHING AERODYNAMICS AND MECHANICS

Meshing Aerodynamics

The aerodynamics of fixed meshing rotors has a firm foundation in research, development, manufacture and extensive operational experience. Historically, the Kaman Huskie, and currently, the Kaman K-MAX provide practical benchmarks.

The principal features that distinguish the Escort from that background are

- Rigid proprotors with high loading
- Cruise thrust reversal as a pusher prop
- One-at-a-time tilting in transition

All of these are complex problems in their own right and so to make these studies manageable, blade element theory, vortex theory or CFD were not contemplated. Instead the rotors have been treated as the simple thrust or actuator disks of conventional helicopter momentum theory. Adjustments for blade tip and root losses, blockage by wing and fuselage, and overlap of rotors, were made as seemed appropriate.

Nevertheless a lot of time was spent thinking through the broad aerodynamics of one-at-a-time tilting in transition. These are the conclusions drawn that give confidence of a successful outcome.

Firstly, it is important that, in transition, a rotor produces zero net thrust: if there is thrust at least one of the resolved components is in the wrong direction. The other rotor, the one sustaining lift/propulsion, can be visualized as having the flow field of the single rotor on the aircraft but experiencing an additional, local, turbulence generated by the profile drag of the zero lift rotor. The power in that turbulence is significant but unlikely to hazard the sustaining rotor.

Secondly, achieving zero net lift throughout the range of tilt involved does appear feasible. The rotorcraft is in cruise so the overall flow field is continually swept clean. Aerodynamically the rotor is unaware of its angle of tilt. It sees only the angle of the air flow relative to its tip path plane and in particular its normal component.

The normal component starts at zero velocity for 90° tilt, growing to full aircraft velocity at 180°. It is always in the direction expected by a rotor climbing "up" the prevailing inflow. Moreover, the induced flows for zero thrust are small compared to the normal inflow component and so the rotor is operating within the regime where momentum theory is a reliable guide.

It is concluded that zero net thrust should be easily achieved by trimming collective pitch. It will be interesting to see how the transition tests of the $1/10^{th}$ scale model perform.

Meshing Mechanics

At the start of the studies a rotor model had been constructed of two 4-bladed rotors, arranged in tandem, inter-meshing at speed that tilted back and forwards one-at-a-time. It was clear that in helicopter mode, the tandem configuration placed the rear rotor in the wash of the leading rotor, and in airplane mode created a high profile to the aircraft. Placing the intermeshing rotors side-by-side avoided these disadvantages so a mechanical model was constructed (Figure 11) that demonstrated side-by-side one-at-a-time tilting of intermeshing rotors was feasible.

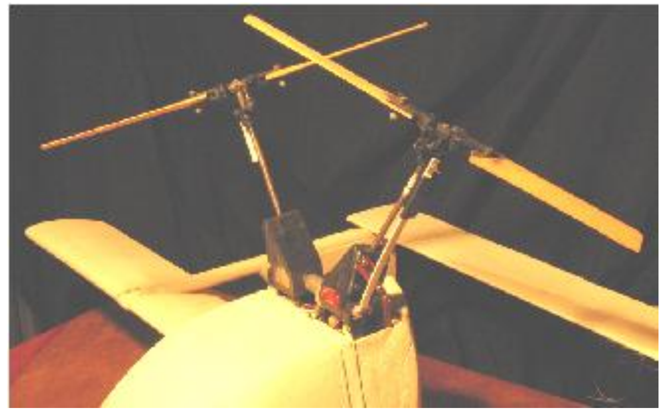

Figure 11. Mechanical model used to demonstrate one-at-a-time tilting of intermeshing rotors to a pusher prop position.

The mechanical model was also a practical way of showing that thrust reversal was an essential part of this tiltrotor strategy. To go beyond such basic observations, math models were used.

The next steps were to develop two math models of meshing and tilting: a trigonometry model for a math approach, and a 3D model allowing animation for an interactive parametric approach.

In its simplest form, the math model of meshing error θ, as a function of angle tilt φ, reduced to

$$\theta = \text{ArcCos}[-\frac{1+\text{Cos}[\gamma]+(-3+\text{Cos}[\gamma])\text{Cos}[\varphi]}{-3+\text{Cos}[\varphi]+\text{Cos}[\gamma](1+\text{Cos}[\varphi])}]$$

Where γ is the angle of cant between the meshing rotors when aligned, as when both are vertical.

This gave agreement, within measuring errors, of a bench model, see graph of Figure 12, and in its fuller form allowed investigation of the important effects of offsetting the hinge axes about which the rotors tilt.

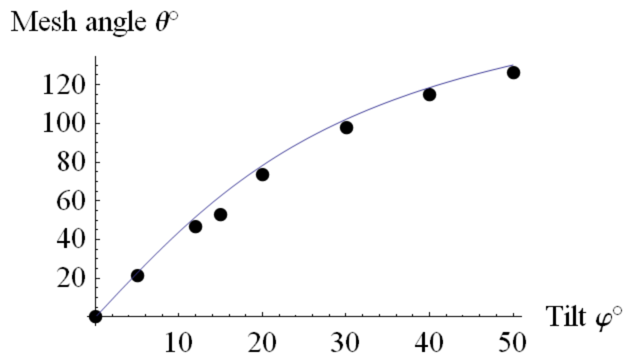

Figure 12. Mesh angle: math and mechanical models compared.

The math model was used to choose appropriate gearing to minimize the phase errors between the meshing proprotors.

Visualising the results was difficult, so a 3D animated math model was written to investigate the variables interactively. This gave the meshing process in slow motion and could be frozen at points of interest, to rotate or zoom the 3D image. Figure 13 is a snapshot from an investigation of a pair of two-bladed rotors.

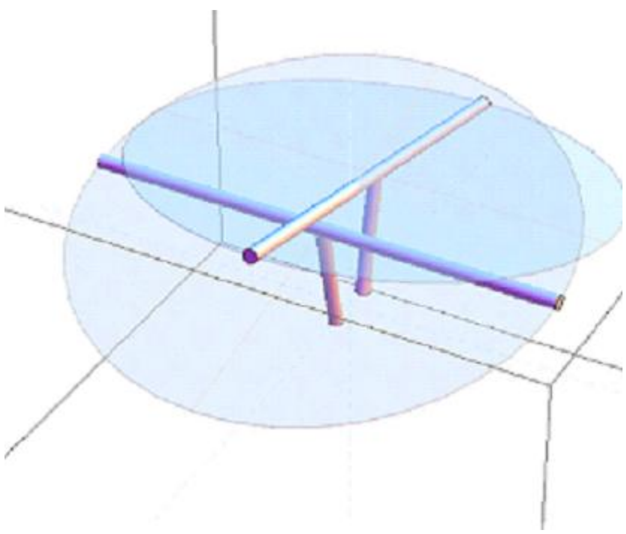

Figure 13. Snapshot from 3D animated math model of blade meshing. Rotors canted 11° to the XZ plane and tilted to 90° vertical. Axis of tilt offset vertically towards the rotor hubs. Projected area is 1.3 times a single disk.

The conclusion drawn from these differing investigations was that for correctly phased rotors, the minimum clearance occurs with the rotors aligned when each blade overflies the opposing rotor hub.

This gave the designer a clear starting point for transmission and tilting systems design.

It also provided a practical check on models, pre-test or pre-flight. This was to align the rotors to the same tilt angle, turn a rotor by hand until one of its blades is over the opposing hub, then check the blade to hub clearance and finally check that the opposing blades mesh symmetrical about it.

This assessment, based on maths and bench tests, suggests that the meshing and tilting mechanics of one-at-a-time transitions are feasible and have a logical pre-flight check discipline.

SCALE MODEL TESTS

On average, about half of the effort of the study was the design and test of scale models, initially to understand the mechanics of meshing and tilting, then progressively to explore flight related issues.

Static tests

The static tests concentrated on preparation for helicopter mode testing: checking lift capability in and out of ground effect, comparing static control torques for pitch, roll and yaw.

Different methods of achieving yaw control were investigated: differential collective, differential tilt, and the use of inboard wing surfaces. Where results were hard to reconcile with estimates, then smoke visualization, anemometer probe or other simple techniques were used to attempt an understanding. One surprise was that the rotors' downwash covered much less of the inboard wings than expected.

Helicopter mode tests using 1/20th scale model

Tethered testing of the 1/20th scale model proved problematical until fly-bar stabilization was used. This implied that the initial weight shift control strategy was flawed; it had insufficient bandwidth for rate gyro stabilization. However once the fly-bars had been introduced, the model proved flyable, see Figure 14.

The tests were flown by Paul Heckles (Ref. 14), a model airplane and model helicopter pilot and instructor, with experience of test flying of experimental designs. The longest flight was 8 minutes, the flying weight being 2.55 kg. Varying the fly-bar mass, confirmed that the model stability was dependent on the flybars.

Figure14. Meshing, tilting rotors in helicopter mode flight tests of the 1/20th scale model

The obvious way forward was to upgrade to full cyclic control, dispensing with the weight shift approach. A strip check of the transmission showed that the model still had many hours of operating life left.

However there was insufficient room to install the required cyclic servo system, so the decision was taken to go to a new model.

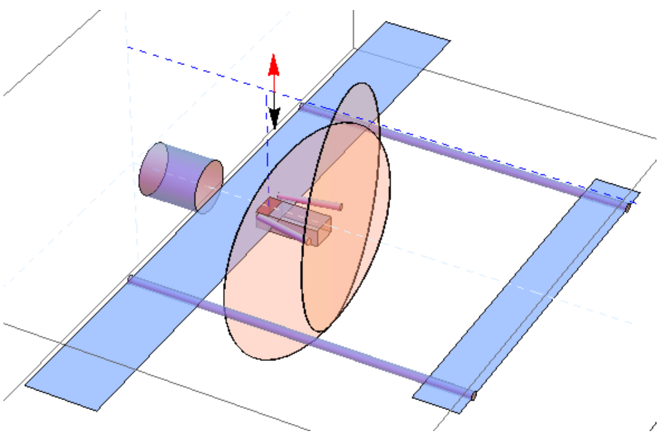

Figure 15. 3D view from parametric study of plan form options for the proposed 1/10th scale model

Progress towards 1/10th scale model

The objective of the new model is to investigate conversion in flight.

The first step is planned to prove the airplane mode, then the helicopter mode and finally to investigate conversion. Parametric studies have been made to choose an initial layout, see Figure 15, by varying the principal component locations, total wing area and ratio of tail to main, payload, rotor cant and overlap. The program computes aircraft centres of lift and gravity for helicopter and airplane modes.

A mock-up for the airplane mode has been built and flown using a pusher prop in place of the intermeshing rotors, see Figure 16.

Figure 16. This shows the airplane mode 1/10th scale model, built and flown by Chris Gladwin (Ref. 15).

Figure 17 shows a drawing of the bevels location. The lower axle is part of the cross-shaft that drives both rotors. The upper shaft is one of the rotor shafts. It is canted 11° from the XZ plane on the airframe centre-line and the ratio of the pair of bevels has been chosen to provide good blade meshing over the full range of rotor tilting.

ENABLING TECHNOLOGIES

The study, in describing the proposed Escort, has identified design features important to the aircraft concept. Freeing up the design of the wings is achieved by moving the proprotors to the fuselage. The forward field of view and field of fire is improved by tilting the proprotors back to pusher-prop position for the airplane mode. Tilting them one-at-a-time gives safe conversion between helicopter and airplane modes. These enabling technologies should allow the Escort to meet and exceed the specification and performance proposed in Table 2.

Proprotors

In choosing the tiltrotor physics for the Escort the study assumed 0.75 proprotor efficiency, and aircraft L/D of 9, in cruise. Then in Table 5 the proprotor efficiency is downgraded to 0.65 for untwisted blades. The disadvantage was addressed by targeting that the aircraft L/D to increase to 11.

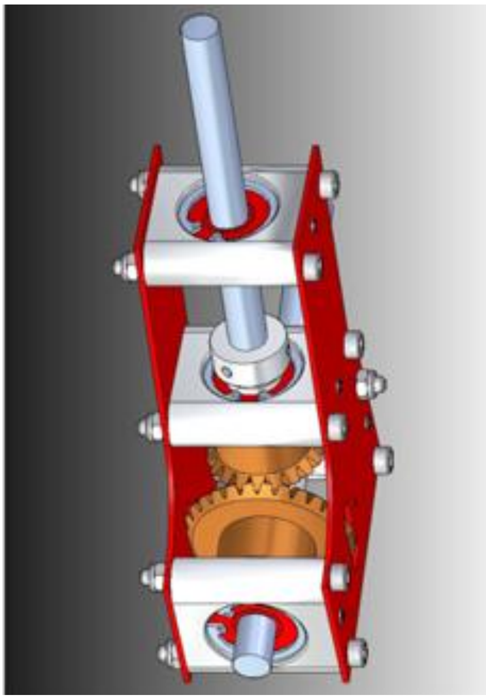

Figure 17. This shows part of the 1/10th scale model's transmission.

Another solution needs assessing: varying twist during flight. The study was aware but unable to take account of progress by different teams that were researching and demonstrating variable blade twist for proprotors and other rotorcraft applications.

The high overlap of the intermeshing proprotors used in the Escort determines the effective disk and blade loadings that are fundamental to the rotors' performance.

However the amount of overlap is also a useful method of improving efficiencies by balancing disk loading across the rotors. Figure 18 shows an assessment in hover, of how overlap could spread disk loading, at least along the lateral axis through the two proprotor hubs.

The figure assumes local loading is proportional to radial distance squared, includes losses at blade tip and root, but assumes uniform induced velocity, and uniform untwisted blades.

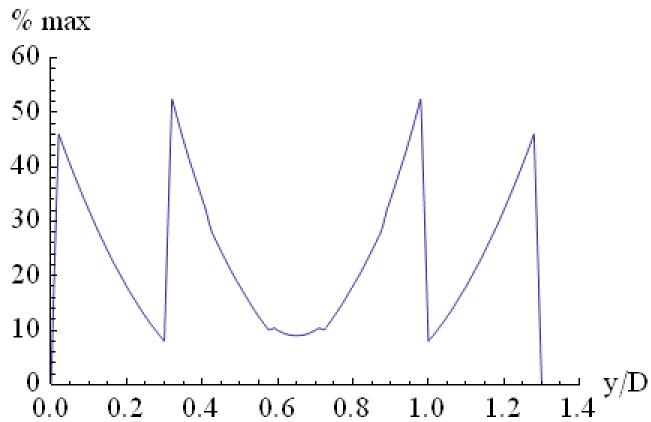

Figure 18. Local disk loading as a % of maximum; y is the lateral distance, left to right, through the rotor hubs; D the diameter of an individual disk. The plot is for disks that overlap by 0.3 D between hubs.

Maximum local loading will still occur near where blade tips pass at the longitudinal axis. Elsewhere, particularly near the lateral axis, the peaks are halved and the areas of zero lift are eliminated.

Wings

Once the wing design has played its part in achieving speed and range, further improvements in L/D must take lower priority than other wing issues: hover down-wash from rotors; location of universal wing store stations; wing fold for compact stowage; wing fuel cells; and booms to support the empennage.

As mentioned in discussing take-off performance in Table 4, the Escort needs greater articulation of wing surfaces than MV-22 to achieve equivalent low blockage of rotor down wash. This needs investigating.

Raising the tilt axis

Figure 4 showed the configuration chosen for the studies: twin booms to support the empennage and give room for the tilting proprotors.

If, however, the aircraft dynamics and aerodynamics would allow the tilt axis to be raised, and the rotors to be separated a little more, then extending the fuselage as a single boom through the lower "meshing gap" could be very attractive, broadly as Chris Gladwin's suggestion (Ref. 15) for the 1/10th scale test model of Figure 19.

For the full scale Escort, the advantages sought would be reduced aircraft empty weight; simplified wing, fuselage, empennage design and manufacture; to achieve rolling take-offs and/or CTOL for higher payloads or higher altitudes;

simpler deck handling; simpler wing fold; and simpler conversion and meshing systems.

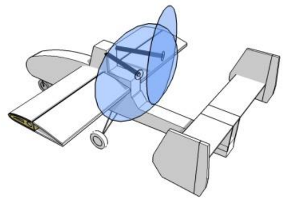

Figure 19. This is a suggestion for a single boom configuration for the 1/10th scale model flight tests.

Flat-rated engine

At sea level, assuming that the engine has power in hand, the flight envelope of a rotorcraft is limited by the torque capacity of the transmission. In effect the pilot, torque limiter or equivalent device, flat-rates the engine for these low altitude conditions.

The selection of a suitable flat-rated engine would extend the Escorts performance to higher altitudes, potentially to the limits of its blade loading capabilities.

Manoeuvre envelope

If the engine is generously flat-rated, then the Escort is able to manoeuvre to the transmission torque limits. Again this leaves blade loading as a potential limit.

Lowering the blade loading would enable the rotors to pull higher g-forces at the maximum blade stall limited loading. If higher manoeuvrability is essential, then some increase in effective rotor solidity and/or in blade tip speeds may need to be considered.

NEXT STEPS TOWARDS A PROJECT

A firm basis for the project is to be created by undertaking a feasibility study:

- Discussions with potential customers and partners on the concept and the possible ways forward.
- Mission and piloting models, to provide design criteria and assess progress on the concept as an escort for the MV-22 and for other applications.
- Databases and CAD/CAM designs for analysis of the concept at full scale, and for manufacture of components and models.
- Math and computer models validated against existing tiltrotor aircraft, to analyse and assess the concept, and design and test data.
- Procurement and testing of components and models as needed for proof of enabling technologies and assessment of design solutions.
- Produce and present a detailed feasibility report and proposals for a full scale demonstration.

From this base it will be appropriate to discuss and propose full scale flight demonstration.

CONCLUSIONS

- The success of the MV-22 has created the opportunity for a gunship escort
  - The escort needs to be compact, agile, longer range and as fast as MV-22
- The solution proposed is a compact tiltrotor
  - Place the rotors on the fuselage: this gives an efficient wing, and a compact and agile design
  - Tilt the rotors backwards for a wide field of view and fire
  - The configuration was granted US patent 7784923 in 2009
  - These studies show that it has excellent potential as a gunship escort for the MV-22 Osprey
- The next steps are proposed to be feasibility studies as a precursor to proposals for full scale flight demonstration.

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