Enabling technologies for a Centre-line Tiltrotor

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ABSTRACT

The particular centre-line tiltrotor concept arose from the perceived need for a gunship escort for the MV-22 Osprey. The concept sought a compact and agile tiltrotor layout, building where possible on the enabling technologies of present tiltrotors dating from the XV-15 research tiltrotor. During its research span, 1977-2003, the very successful XV-15 programme demonstrated the potential of tiltrotor aircraft where the rotors are wing tip mounted and, in cruise, are tilted forwards for fast and efficient wing borne flight. The enabling technologies proven on the XV-15 were the basis of the production tiltrotor designs of the V22 Osprey and the BA 609. By contrast this study stays with that core physics, tilting rotors and fixed wings, but re-configured to achieve a more compact centre-line layout. The rotors are removed from the wing tips to mount them on the aircraft centre-line, leading to a concept of inter-meshing rotors tilting back one-at-a-time, to act as pusher props in the airplane mode. This study first reviews present wing tip mounted tiltrotor technology and how it may develop, then reviews the advantages sought from the centre-line tiltrotor configuration, examines the enabling technologies that are necessary and discusses optimisation of selected key areas: rotor blockage, proprotor hover figure of merit, proprotor propulsive efficiency, aircraft lift over drag in airplane mode and the all important conversion process. The paper concludes with a review of progress on flight tests of a 1/10th scale model.

NOMENCLATURE

C_d	wing download coefficient
$C_{D,0}$	aircraft drag at zero lift
C_{dc}	C_d relative to basic wing
Ct/σ	blade loading
D	aircraft drag
DL	disk loading of a rotor
FM	hover figure of merit
HIGE	hover in ground effect
HOGE	hover out of ground effect
K	lift related drag factor
L	aircraft lift
L/D	lift to drag ratio
MTOW	maximum take-off weight
PL	power loading of a rotor
S	wing planform area
SFC	specific fuel consumption
TCL	Thrust Control Lever
W	aircraft weight
W/S	wing loading
VTOL	vertical take-off and landing
v_h	induced flow at rotor in hover
V_∞	relative wind
η_p	propeller efficiency
ρ_∞	air density
σ	solidity

INTRODUCTION

The proposed centre-line tiltrotor is a compact aircraft designed to have the safety, agility, speed and range needed of an escort for the MV-22 Osprey.

The need for a gunship escort had been raised in 1996 (Ref. 1), and in 2004 when it was reported (Ref. 2) 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 doubt the need has been discussed many times since as the Osprey programme progressed.

The centre-line tiltrotor concept arose from the determination to retain the advantages of range and speed achieved by the V22 Osprey, in a more compact layout by moving the proprotors from the aircraft's wing tips to mount them on its centre-line.

This approach was envisaged to be suited for military use in a light to medium utility, search and rescue, scout or gunship role, and for civil use in a wide range of

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emergency, media, surveillance, tourism and passenger transport.

To achieve the advantages of range and speed, clearly the starting point is present tiltrotor technology and so the paper proceeds as follows:

- Advantages of present tiltrotor technology and how it may develop
- Centre-line tiltrotors: advantages sought and technology needed
- Rotor blockage
- Hover figure of merit
- Propulsive efficiency
- L/D in airplane mode
- Conversion process
- Progress on 1/10th scale flight tests
- Conclusions

ADVANTAGES OF PRESENT TILTROTOR TECHNOLOGY AND HOW IT MAY DEVELOP

Tiltrotor aircraft combine the advantages of range and speed of turbo-prop airplanes with the advantages of vertical take-off and efficient low speed flight of helicopters. These advantages are being exercised on a daily basis by the US Marine Corps who have proven the worth of the V-22 Osprey in Afghanistan and in humanitarian missions in Haiti and elsewhere. In many such situations conventional airfields are not available, and helicopters may not have the range or speed vitally needed.

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: ECN-13840 Date: October 1980

XV-15 tilt rotor aircraft on VTOL stand

Figure 1. XV-15 on a VTOL stand at NASA Dryden, October 1980 (Ref. 3)

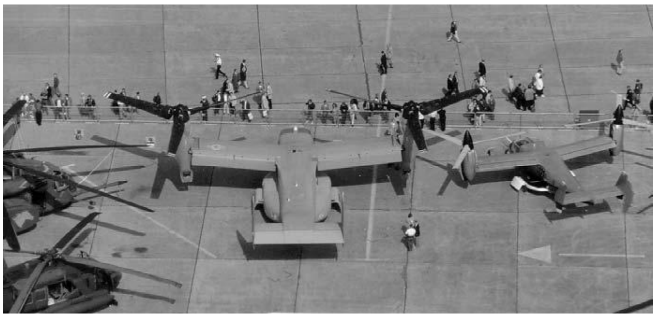
The technology base for present tiltrotor designs was established in the 1960s and early 70s when major issues such as aeroelastic stability, performance and control had to be mastered.

The resulting technology was most impressively demonstrated by the Bell XV-15 tiltrotor research program, initiated in 1973 with joint Army/NASA funding as a "proof of concept", or "technology demonstrator". Figure 1 shows the XV-15 on a VTOL stand at NASA Dryden

Aircraft development, airworthiness testing, and the basic "proof of concept" testing were completed in September 1979, (Ref. 4)

By April 1983 Navair had announced the first contract for the tiltrotor to meet their JVX requirement: this was the start of the V-22 Osprey. Figure 2 shows the Bell-Boeing V-22 alongside the XV-15 research aircraft at the 1995 Paris Air Show, and by 1997 the V-22 Osprey full scale development program (Ref. 5) was showing that the concept and technology were holding good.

Figure 2. Bell-Boeing V-22 dwarfing the XV-15



(Ref. 3, Bell Photogragh 042900)

After the Herculean effort and determination by all involved, the United States Marine Corps fielded the Osprey in 2007.

Of course the learning process is a continuous one, and looking forwards the enabling technologies of the XV-15, V-22, BA 609 approach will benefit from the steady progress in all the technologies on which fixed wing and rotary wing communities depend. Some of those will read across directly, others must be adapted to the priorities of tilt rotor aircraft. Key technologies must operate satisfactorily in dual roles, combining rotary and fixed wing functions in a single implementation.

The foremost example of the dual role is the proprotor which acts as a rotary wing in helicopter mode and as a propeller in airplane mode. Proprotor efficiency is central to determining the useful payload/fuel budget that can be lifted at take-off in the helicopter mode, and in the winged flight mode how efficiently that budget can be used. In their paper on the aerodynamic challenges in optimising high efficiency proprotors (Ref. 6) Leishman and Rosen characterise efficiency goals in terms of figure of merit, FM, for the proprotor in hover, and propulsive efficiency, η_p, when acting as propeller. Their comprehensive review and analysis of the trade between these and other key parameters shows the space for possible improvement and the challenges and issues involved.

Another example of dual roles is that of the power plant. Shaft horse power requirements are very similar across the range (Ref 4), however the operating rpm will be different. The proprotor is operated more efficiently at lower rpm in the airplane mode so this lower rpm combined with the transmission torque limit in fact determines the maximum allowable power. If the transmission is designed for max power in airplane mode then it is off design for the helicopter mode, and vice versa. Similarly the power turbine operates at these dual speeds. All rotorcraft are likely to benefit from variable rotor speeds, so it is reasonable to hope that tiltrotors can share and participate in improving these engine and transmission enabling technologies.

CENTRE-LINE TILTROTORS: ADVANTAGES SOUGHT AND TECHNOLOGIES NEEDED

The advantages sought for centre-line tiltrotors, as for present tiltrotors, are to combine the range and speed of turbo-prop airplanes with the vertical take-off and efficient low speed flight of helicopters.

The same physics of the XV-15, MV-22 and BA609 tiltrotors is proposed, namely wings for efficient airplane flight and proprotors that tilt from providing lift in helicopter mode to become propellers to provide propulsion in airplane mode.

Further advantages are sought: to achieve a more compact and agile tiltrotor, where the forward field of view and fire is freer, where wing optimisation is unconstrained by bearing the rotors, transmission and nacelles, and where the extremities of the aircraft are static rather than rotating blades.

The particular design solution (Ref. 7) considered here is for a centre-line tiltrotor, tailored to the formidable task of escorting the MV-22 throughout its mission. The proposed layout is shown in Figure 3 and a specification shown in Table 1.

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.

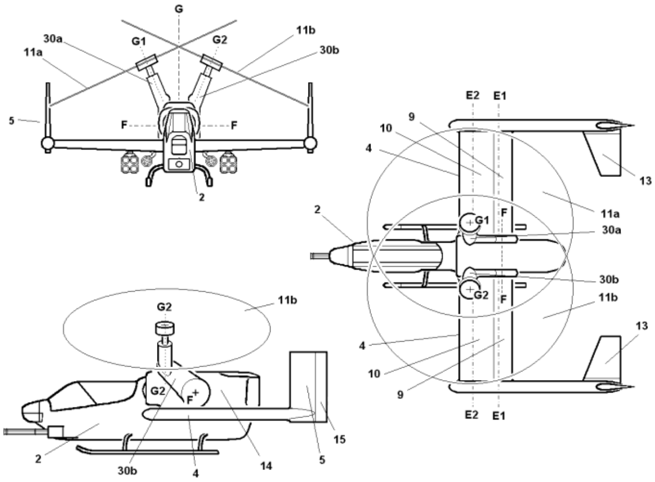


Figure 3. Three views of the escort in the hover mode. The meshing rotors are tiltable about the F-F axis.

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 1. 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 (Table 2) the escort with the assumed characteristics of the MV-22.

On an MV-22 mission 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,

Table 2. 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
MTOW, lb	52,600	19,500
Empty weight, lb	35,300	13,300
Service ceiling, ft	25,000	25,000
HOGE, 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**

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.

The configuration chosen for the escort is shown in Figure 3.

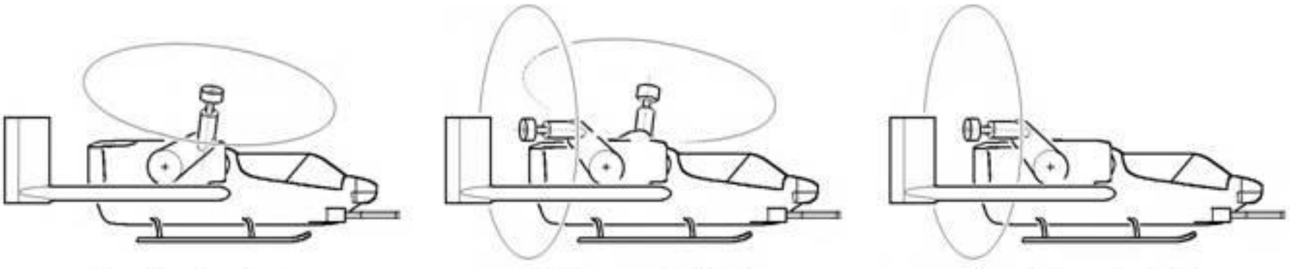
The studies made a general comparison between the escort and the MV-22 on a typical mission, the Osprey carrying 24 troops and escort assumed to be operated, equipped and armed as a typical gunship. Table 3 compares them at take-off for an unspecified mission, Table 4 at cruise for a ground assault mission.

Many of the parameters shown, such as aircraft lift to drag ratio, the proprotor propulsive efficiency and figure of merit, and rotor blockage make assumptions about the enabling technologies.

The rotor blockage figure for the escort is dominated by the fuselage and is estimated to be half that of the blockage caused by the wings of the MV-22. This assumes that the technology will be available so the wings can be articulated to align with the down wash. Then the 4.8% figure shown should be achievable.

The rotor figure of merit is based on the XV-15 plus two additional effects cancelling. First there is an assumed loss from using untwisted blades. Secondly there is an assumed gain from rotor overlap “filling in” the large hole in induced flow at the centres of conventional rotors.

Table 4 compares the MV-22 and the escort on a land assault mission. The escort is estimated to have sufficient range to allow it to loiter at the target are while the MV-22 is on the ground.



In the heli. mode, accelerate to a good forward speed so wings, tail, fins are ready to take over from the rotors .....

The left rotor continues in hel. mode to maintain the aircraft's speed, so the right can convert back to become a pusher prop...

Now the right rotor is maintaining aircraft speed, the left can be converted fully back to share the pusher prop duty.

Figure 4. The centre-line tiltrotor is shown converting from helicopter to airplane mode.

Unlike present tiltrotors where the proprotors tilt forward to become tractor propellers, this centre-line layout requires that they tilt back to become pusher props. This means their thrust must be reduced to zero during conversion and reversed when fully back otherwise they act as airbrakes. So collective pitch has to be reversed, and if the blades are twisted then twist has to be reversed as well.

The decision was taken to convert the rotors one-at-a-time so that continuity of propulsion could be retained, and this lead to meshing rotors to allow this process (Fig. 4)

Table 3. Maximum helicopter performance at take-off: escort and 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**

Table 4. 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
Take-off weight, 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**

This range depends on two assumptions, first that the proprotors, with untwisted blades, can achieve a propulsive efficiency of 0.65, and second that the proposed wing layout can achieve an aircraft lift over drag ratio of 11 in cruise.

The ability of a tiltrotor aircraft to make the conversions between helicopter and airplane modes completes its basic requirements. Figure 5 shows estimates of the escort and the MV-22 transitioning.

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.

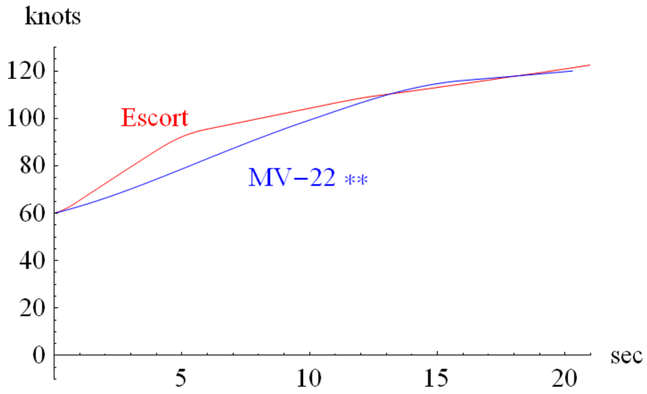


Figure 5. The escort and the MV-22 ** (author's estimates) transitioning from 60 knots in helicopter mode to about 115 knots in airplane mode. Aircraft at minimum operating weights.

The conversion process for the centre-line tilt rotor depends on managing blade meshing, asymmetric torques and forces that arise so that the aircraft has acceptable handling qualities throughout.

In summary, to achieve the advantages sought for centre-line tiltrotors to combine the range and speed of turbo-prop airplanes with the vertical take-off and efficient low speed flight of helicopters, the following performance parameters are assumed. The challenges for design and enabling technologies include:

- rotor blockage 5%
    - needs wing articulation
- hover figure of merit 0.8
    - penalty of untwisted blades
    - possible benefit of rotor overlap
- propulsive efficiency 0.65
    - penalty of untwisted blades
- aircraft L/D in airplane mode 11
    - airframe layout
- conversion process.
    - meshing
    - 16°/sec tilt actuation
    - control scheme and Pilot's control
- flight tests of a 1/10th scale model (on-going)

ROTOR BLOCKAGE

In hover out of ground effect, HOGE, where the downwash from the rotors meets fuselage and wings, there is a download that must be set against the lift from the rotors. The term rotor blockage is used here to express that download as a percentage of rotor lift.

Stepniewski & Keys (Ref. 8) reports wind tunnel tests of downloads on a tiltrotor wing suggesting a wing with just flaps would have a drag coefficient, C_d, of 0.92, or referenced to the plain wing, a C_{dc} of 0.64. Further if the wing can be aligned to the downwash the drag reduces to a C_d of 0.01.

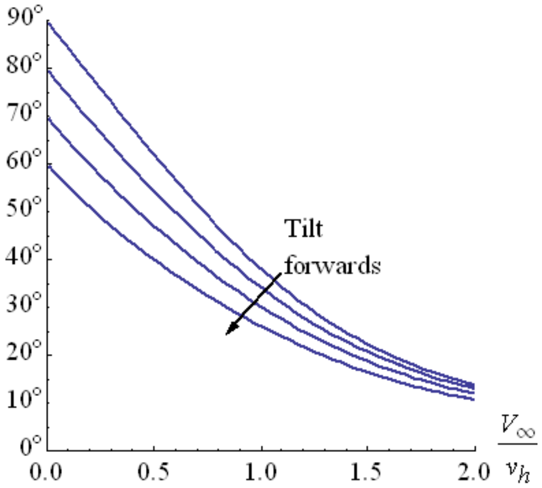


Figure 6. Downwash angle seen by wing as affected by relative wind V_∞ normalised to v_h induced velocity in hover, for different angles of rotor tilt.

On the MV-22 Osprey, flaperons are used to substantially reduce the download effect. The remaining download is significant and a worthy target for research, (Ref. 9).

On the escort, the wing blockage is larger, so greater articulation of the surfaces would be needed. For example, the plan view in Fig. 3 shows axes E1 and E2 for rotation of the leading and trailing halves of the wing to align with the rotor downwash. In principle this should achieve the rotor blockage factor estimated in Table 3.

Aligning the wings to the downwash must take into account the effect of relative wind, the induced flow and proprotor tilt (Fig. 6).

Technology challenge

To meet the suggested rotor blockage of 5%, aside from aerodynamic tidying of the fuselage, devolves to wing design:

- structure to support booms and empennage
- wing articulation and control to
    - mimimise rotor blockage in helicopter mode
    - maximise wing L/D in conversion and airplane modes

PROPROTOR PERFORMANCE IN HELICOPTER AND AIRPLANE MODES

At the start of a mission the payload achieved, comprising fuel, personnel, munitions etc, depends on the difference between the unloaded weight and the maximum take-off weight (MTOW).

MTOW in turn depends on the lift for the power actually available at take-off. The effectiveness of the proprotor in this lifting process is described by PL, its power loading, the ratio of the lift induced to the power needed by the rotor. PL in turn, depends on air density, on rotor disk loading DL and on the rotor figure of merit FM.

During the airplane mode of the mission, the range or endurance achieved depends on the fuel burn which in turn depends of the engine specific fuel consumption, SFC, the efficiency of the transmission, power to utilities, and finally on η_p the aerodynamic efficiency of the proprotor.

In principle most of the blade design strategies available to the designer of a forward tilting proprotor to optimise DL, FM and η_p will be available to the designer of the backward tilting proprotor of the centre-line tiltrotor aircraft.

For the centre-line tiltrotor because thrust is reversed from hover to airplane mode, blade collective and twist need to be reversed to achieve this. Collective can be reversed using present actuators, but reversing twist is a challenge.

Reversing blade twist

The options for reversing twist are

- fixed, untwisted blades and accept the penalties to both FM and η_p
- fixed, twisted blades to favour either FM or η_p
- controlled twist blades to match flight conditions.

Untwisted blades will have a penalty. For a helicopter, using blades that are untwisted versus ideally twisted blades, may incur a 5% reduction in FM (Ref. 10). For a centre-line approach the concept study (Ref. 7) used untwisted blades, downgrading η_p from 0.75 to 0.65 but leaving FM virtually unchanged at 0.8. The assumption was that any downgrade in FM would be compensated by gains from the contra-rotation and overlap of its meshing rotors.

Using fixed twist may have less penalty, as there may be a compromise twist that is better than untwisted. For example the fixed twist on present forward tilting proprotors is a compromise between what is ideal for η_p and that for FM (Ref. 11). The net gain in mission performance of the centre-line tiltrotor would come from choosing a twist that favours the one over the other of FM and η_p.

Using partial or full authority controllable twist is attractive because it offers the possibility of optimising FM or η_p to suit actual flight conditions. Any level of partial twist is likely to be of interest. The equivalent of partial twist should be achievable using servo-tabs, and research into different means of morphing blades is encouraging.

Other rotor effects

The meshing rotors counter rotate and overlap. Both are expected to improve proprotor performance.

The rotational energy in a helicopter wash may use 2% of power delivered to the rotor, and more for heavily loaded rotors in hover (Ref. 10). For the escort, as the washes from the two rotors merge, most of the wash rotational energy should cancel, leading to a proportional improvement in FM.

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.

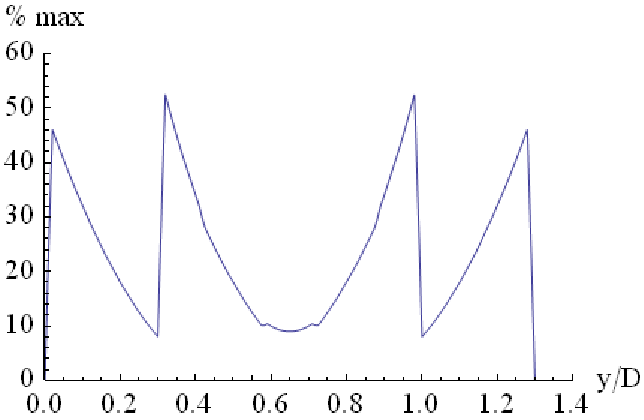


Figure 7. Local disk loading as a % of maximum; y is the lateral distance, left to right, through the rotor hubs; D the diameter of an individual disk. The plot is for disks that overlap by 0.3 D between hubs.

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.

Generally the peaks and troughs in disk loading are reduced, which helps improve the overall FM. Particularly near the lateral axis, the peaks are halved and the areas of zero lift are eliminated. Peaks in local loading will still occur near where blade tips pass at the longitudinal axis.

Technology challenge

To meet the targets of 0.65 for η_p and 0.8 for FM, then design and test work should proceed for :

- a fixed twisted blade design, with optional partial controlled twist
- a default design of untwisted blade
- exploiting rotational energy cancellation and smoothing of disk loading by rotor overlap

AIRCRAFT L/D IN AIRPLANE MODE

In the airplane mode the escort's meshing proprotors are in the pusher prop position at the rear of the fuselage, between the twin booms, aft of the wings and ahead of the empennage (Fig. 3 & 4). The target L/D for the aircraft in this configuration at cruise is 11, compared to 9 assumed for the MV-22 (Table 4).

For steady, level flight the aircraft lift-to-drag ratio, L/D, can be estimated, (Ref. 11) from

$$L / D = \left(\frac{\rho_\infty V_\infty^2 C_{D,0}}{2 W/S} + \frac{2 K}{\rho_\infty V_\infty^2} \frac{W}{S} \right)^{-1}$$

where W/S is the wing loading and, from the aircraft drag polar, $C_{D,0}$ is the aircraft drag coefficient at zero lift and K is the factor for drag due to lift. Using this formula and estimates of the drag polars for the MV-22, XV-15 and the centre-line tiltrotor escort, their L/D ratios are plotted in Figure 8 to show the influence of wing loading W/S. The point on each curve represents wing loading at cruise.

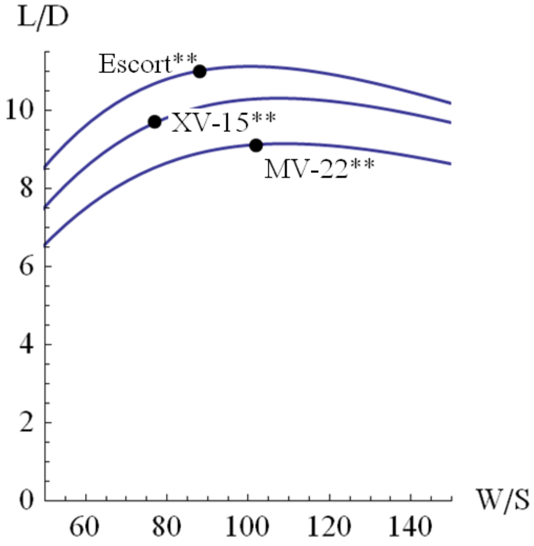


Figure 8. Aircraft lift to drag ratio L/D versus wing loading W/S. Points show cruise. **Author's estimates.

Table 4 shows that the escort needs an L/D of 11 for the assault mission, and the formula and Figure 8 show the influence that the designer has by achieving changes in $C_{D,0}$ and in K and wing loading W/S.

Technology challenge

To meet the target L/D of 11 the aircraft studies are needed for

- clean aerodynamic design for a low $C_{D,0}$
- wing aspect ratio and shape for low K
- appropriate wing area to optimise W/S

CONVERSION PROCESS

Blade meshing provides a compact centre-line tiltrotor arrangement, and must be preserved throughout the one-at-a-time conversion process (Fig. 4). Mechanical meshing is assumed.

Meshing Mechanics

The meshing arrangement is straight forward. It relies on a common cross-shaft driving the two rotors' gear boxes.

Figure 9 shows the transmission and rotors for the 1/10th scale model that uses two-bladed rotors, and Figure 10 shows blade meshing for a three-bladed rotor as assumed for the escort concept. The animated 3D math model used to investigate meshing (Fig. 10) allows the number of blades, the gearing ratio between the rotors and cross-shaft, the relative dimensions and geometry to be changed.

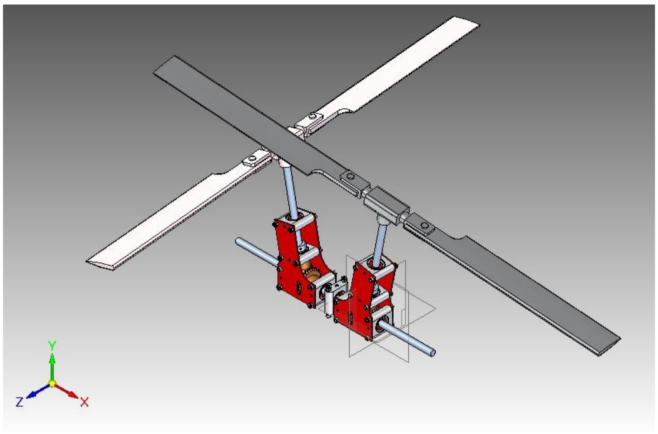


Figure 9. View of the transmission and meshing rotor arrangement for the 1/10th scale model.

For the 1/10th scale model, simple bevel gears suffice to drive the rotor from the cross-shaft and to ensure the correct meshing as the rotors are tilted one-at-a-time or together (Fig. 11).

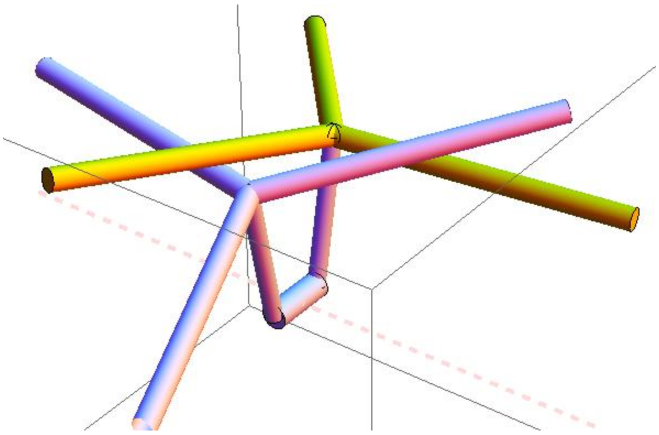


Figure 10. Snapshot from 3D animated math model of blade meshing. Rotors canted 11° to the XZ plane and tilted to 90° vertical. Axis of tilt offset vertically towards the rotor hubs. Projected area is 1.3 times a single disk.

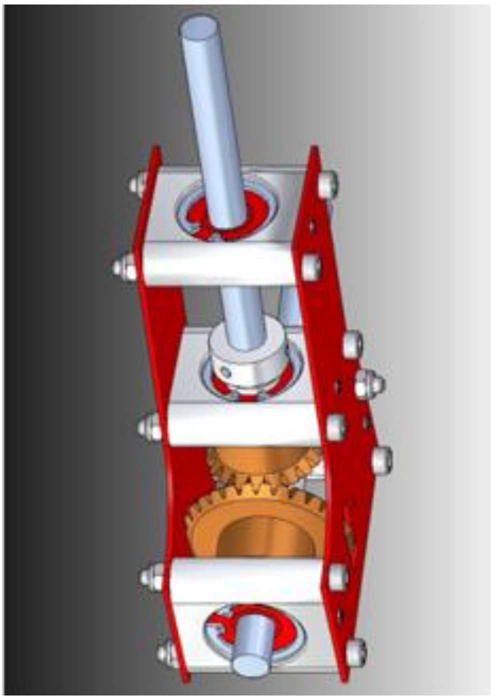


Figure 11. This shows part of the 1/10th scale model's transmission.

Actuation

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 (Fig. 5).

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 centre-line tiltrotor from that fixed mesh, non-tilting background are

- Rigid proprotors with high loading
- Cruise thrust reversal as a pusher prop
- Separate tilting masts

To achieve a successful conversion, it is important that the transitioning rotor produces zero net thrust: if there is thrust, at least one of the resolved components is in the wrong direction.

During the transition, the implications for the other rotor, the one sustaining lift/propulsion, can be visualized as having the flow field of a single rotor on the aircraft. That flow field will experience local turbulence generated by the profile drag of the zero lift rotor. The power in that turbulence is unlikely to hazard the sustaining rotor.

Achieving zero net lift throughout the range of tilt does appear feasible. The rotorcraft is in cruise so the overall flow field is continually swept clean. Aerodynamically the rotor sees only the angle of the air flow relative to its tip path, and that angle is within the usual operating envelope of conventional single rotor helicopters.

For example, consider the left hand rotor in the conversion sequence in Figure 12.

At point (a) the LH rotor is at 80 °, the airflow entering the rotor disk from above the tip path plane as in a helicopter in level cruise. At (b), 100° tilt, collective pitch has been reduced to give zero lift, so the net airflow now enters from below the tip path plane, in a mild windmill state similar to a helicopter entering autorotation. At (c), 145° tilt, the airflow enters from below, analogous to a helicopter in a steep 45° autorotational descent, except that the rotor does not need to extract energy to maintain rpm, and the collective is set for zero net thrust. Because the rotor is not fighting the "descent" it is still within the windmill regime.

As the LH rotor approaches 180° at (d), with collective still being adjusted for zero thrust, it can be regarded as a helicopter in steep descent or as a pusher propeller on the border line between braking and propulsion. Once at (d) collective is taken further negative to produce thrust to maintain aircraft speed.

Throughout the process a, b, c, d for the LH rotor, there are some general observations and issues that must be considered:

- Setting collective for zero thrust should minimise power for induced losses, but will still require power for profile losses and use of cyclic pitch.
- Torque reaction from the RH rotor will need to be balanced, principally by the airplane control surfaces, and possibly by use of LH rotor cyclic.

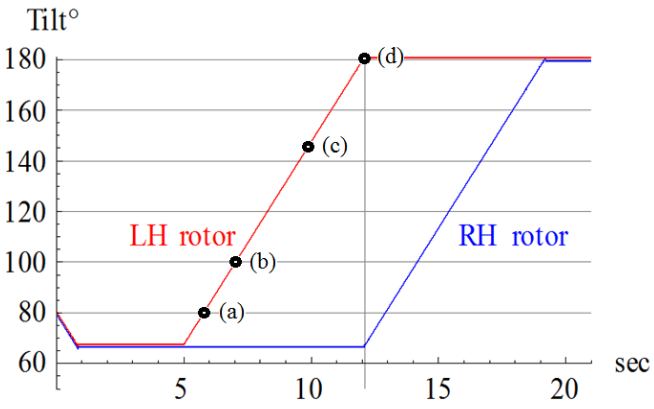


Figure 12. One-at-a-time tilting as used in the math model for the conversion of Figure 5. The text refers to points a, b, c, d to discuss airflow relative to the LH rotor as it tilts back to 180°.

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

Pilot's controls for the conversion process

From a pilot's point of view, it is proposed that the escort have the same conversion control 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 as required through the conversion (Fig. 4).

The escort's Flight Control Computers (FCCs) must achieve this objective using a suitable tilting strategy as proposed shown in Figure 12.

Technology challenge

The conversion process is central to the safety and operational effectiveness of the particular centre-line tiltrotor configuration proposed here. It depends on:

- Meshing mechanics to achieve safe and effective meshing of the rotors all modes and over the flight envelope.
- Actuation capable of 16°/sec
- Control laws to manage zero thrust of rotors in transition, and balance torques as needed
- Thumbwheel on the Thrust Control Lever to provide pilots with simple authority over the conversion process.
- Flight testing of a 1/10th scale model to investigate the conversion process.

PROGRESS ON 1/10TH SCALE FLIGHT TESTS

The building and testing of a 1/20th scale model were an important learning process leading to the design and build of the 1/10th scale model.

Figure13. Meshing, tilting rotors in helicopter mode flight tests of the 1/20th scale model

Flight testing, (Fig. 13) of the 1/20th scale model showed that its minimalist control strategy of weight shift for pitch and roll, even with fly-bar stabilisation, was unsatisfactory.

Lessons learnt were:

- The transmission and gear approach to meshing was satisfactory
- Better tilt actuation, range and resolution was needed
- Yaw control by different methods was investigated (differential use of collective, or tilt, or inboard wing surfaces)
- Roll and pitch control by weight shift was unmanageable without flybars and poor with.

The conclusion was flybars introduced a measure of cyclic at each rotor, and that full cyclic would be advisable before conversion testing could be contemplated. It was decided that a complete new build was needed and that this would be at 1/10th scale.

Design proceeded for the new model, electing for a low conversion speed to ease testing. This required extending the main wings beyond the booms (Fig. 14).

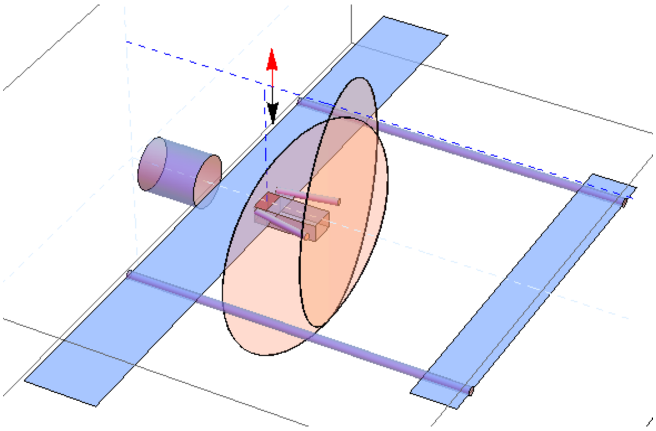


Figure 14. 3D view from parametric study of plan form options for the proposed 1/10th scale model

All the elements of the 1/10th scale model needed for helicopter mode testing have been built and commissioned in a temporary skeletal airframe. This has started hover testing, see Figure 15 from the first flight.

Figure 15. First flight of 1/10th scale model

The immediate purpose the flight tests is to establish the basic behaviour without any stabilisation from rate gyros or flybars. This should allow the addition of control trims and mixing unclouded by electronic stabilisation.

Once the basic behaviour is understood electronic stabilisation can be introduced as necessary.

CONCLUSIONS

Based on the proposal of a centre-line tiltrotor as an escort gunship for the MV-22 Osprey, the targets for design and enabling technologies are seen to include:

- rotor blockage 5%
  - needs wing articulation
- hover figure of merit 0.8
  - penalty of untwisted blades
  - possible benefit of rotor overlap
- propulsive efficiency 0.65
  - penalty of untwisted blades
- aircraft L/D in airplane mode 11
  - airframe layout
- conversion process.
  - meshing
  - 16°/sec tilt actuation
  - control scheme and Pilot’s control
- flight tests of a 1/10th scale model (on-going)

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