

1/10th Scale Model Tests of a Centre-line Tiltrotor:**Conversion between rotary and fixed wing modes**

Bob Burrage
Director

Rotorcraft Operations Ltd., Oxfordshire, United Kingdom
bob.burrage@ntlworld.com

ABSTRACT

In the centre-line tiltrotor configuration considered here, the rotors are mounted on the aircraft centre-line to allow the wings to be optimised without the constraints of carrying wing tip mounted rotors. Both approaches (wing tip mounted and centre-line mounted) provide the major advantage of speed and range over other edgewise operating rotorcraft. As described elsewhere, the centre-line configuration offers the additional important benefits of a more compact, agile design with improved field of view. The challenge is optimising the aerodynamics and control of the proprotors and airframe for rotary and winged flight over the complete flight envelope, and in particular the conversion process between helicopter and airplane modes.

A 1/10th scale model of a centre-line tiltrotor is being used. The airframe will develop to have the same general layout as that proposed for the full scale aircraft but targeted for a 10 kg take-off weight and to be operated safely within the flight envelopes of conventional fixed and rotary wing radio-controlled models.

The test programme has four stages of investigation: hover rig, helicopter mode, airplane mode, and conversion. For the hover rig, the airframe is reduced to just landing skids so that it is flown as a meshing rotor helicopter. For the helicopter, airplane and conversion testing, the full fuselage and fixed wing surfaces are used, with a conventional wheeled, fixed undercarriage. The conversion testing starts with the rotors tilted to different fixed. For the full mode the pilot is free to fly all the flight modes, using conversion as appropriate. Flight test results to date are discussed.

NOMENCLATURE

CTOL	conventional take-off/landing
LH	left hand
L/D	lift to drag ratio
LZ	landing zone
RH	right hand
SFC	specific fuel consumption
TCL	Thrust Control Lever
VTOL	vertical take-off and landing

flight. This led to the production tiltrotor designs of the V22 Osprey and the BA 609.

This wing-tip approach has been successful: the V22 Osprey is in service with the US Marine Corps as the MV-22 and in service with the US Air Force as the CV-22. What the Osprey provides is the ability to carry 24 troops at an unprecedented combination of speed and range, unmatched by existing rotorcraft. That success also places the Osprey totally outside the flight envelope, speed and range of helicopter gunships, and presents an opportunity for a suitable gunship escort such as the centre-line tiltrotor considered here.

INTRODUCTION

The concept is to apply a Centre-line Tiltrotor to the task of being a Gunship Escort for the MV-22 Osprey.

During its research span, 1977-2003, the XV-15 programme demonstrated the potential of tiltrotor aircraft where the rotors are wing tip mounted and, in cruise, are tilted forwards to gain the speed and range advantages offered by fixed wing flight over edge-wise rotary wing

In this centre-line tiltrotor configuration, the rotors are mounted on the aircraft fuselage to allow the wings to be optimised without the constraints of carrying wing tip mounted rotors. Both approaches (wing tip mounted and centre-line mounted) provide the major advantage of speed and range over other edgewise operating rotorcraft. As described elsewhere, the centre-line configuration offers the additional important benefits of a more compact, agile design with improved field of view. The challenge is optimising the aerodynamics and control of the proprotors and airframe for rotary and winged flight over the complete flight envelope, and in particular the conversion process between helicopter and airplane modes.

Conversion of this Centre-line Tiltrotor is different, and so this paper addresses the issues involved and the progress to-date on flight testing a 1/10th scale model, as follows:

The concept

- A centre-line tiltrotor gunship to escort the MV-22

Flight testing the 1/10th scale model

- Flight test plans
- Flight test results to date

Concluding remarks

A CENTRE-LINE TILTROTOR GUNSHIP TO ESCORT THE MV-22 OSPREY

Need for a Gunship to escort the 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 progresses.

The escort must have speed in hand throughout the mission, and have the additional range/endurance to be effective at the landing zone, Figure 1, to protect the MV-22 at its most vulnerable.



Figure 1. When the MV-22 reaches the LZ it will be at its most vulnerable: an effective escort would need to stay with the MV-22 throughout its mission and have reserves to loiter over the LZ to protect MV-22 ingress and egress, and support ground forces.

To be effective at the LZ the escort must protect MV-22 ingress and egress, suppress threats to the LZ, to provide or call up the support needed by the ground forces.

Centre-line Tiltrotor Gunship

The tilting rotors are mounted on the fuselage centre-line, see Figure 2, and tilt back for cruise.

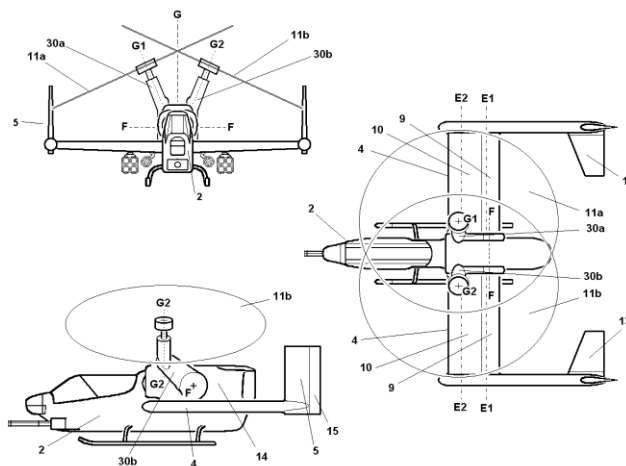


Figure 2. Concept design of a centre-line tiltrotor configured as gunship escort for the MV-22 Osprey

By comparison with existing tiltrotors, this configuration brings the power plant and proprotors to the aircraft centre-line to achieve a more agile and compact layout. With no transmission or proprotors to carry, the wing design can be cleaner structurally.

There is potential for better safety. The location of proprotors above and behind the fuselage provides a clear view forward for crew and sensors. In the helicopter mode, all the rotorcraft extremities are fuselage rather than rotor tip so that ground hazards are reduced.

It 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 suite of controls available to the flight control system is assumed to be similar to the MV-22: cyclic, collective and tilt for rotary wing flight mode, primary and secondary controls surfaces for fixed wing mode. An important addition is articulation of the main wings to align to the rotor wash at hover and low speeds.

Consider the challenge of escorting the MV-22 on a Mission: assume a 230 nmi radius and that the MV-22 cruises at 240 kn, see Ref 3.

Assessment of a land assault mission

Table 1 compares the MV-22 and the centre-line tiltrotor as its escort on an assumed land assault mission. The key to the escort’s success is to have 100 nmi range additional to that of the MV-22.

Table 1. 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 additional 100 nmi range depends on many assumptions, and raises challenges for design and enabling technologies of the centre-line tiltrotor, including:

- 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

Those design targets are summarised from Ref. 3, which in turn relies on others, in particular on Ref. 4 for the effects of wing blockage of rotor downwash, Ref. 5 on relating rotor figure of merit to blade twist, and Ref. 6 on aircraft lift to drag ratios.

At this stage in the studies it was decided that the priority was that the conversion process should be investigated experimentally, and to that end a 1/10th scale centre-line tiltrotor is being constructed and flight tested.

PLANS FOR TESTING THE 1/10TH SCALE MODEL

The plans focus on the conversion process with the objective that, from the pilot's point of view of control and aircraft response, the conversion process should be as simple and safe as if deploying flaps and slats on a fixed wing aircraft.

A 1/10th scale model of a centre-line tiltrotor is being used. The airframe is evolving to suit the different flight test stages and will have the same general layout as that

proposed for the full scale aircraft but targeted for a 10 kg take-off weight and to be operated safely within the flight envelopes of conventional fixed and rotary wing radio-controlled models.

It is flown manually from the ground by the test pilot using a programmable 14-channel transmitter with two thumb-sticks, left for thrust and yaw, right for pitch and roll, and a single control for conversion. The commands transmitted to the scale model go to a matching 14-channel receiver that performs basic conditioning and safety before passing the commands to other on-board units. Most scheduling and mixing is programmed within the transmitter, however provision has been made for stabilisation and swash-plate mixing using on-board units. The control system functions are separated into primary, secondary and stability augmentation.

The primaries are conventional. They comprise swash-plate based collective and cyclic controlled independently for each of the meshing rotors, and for the airplane surfaces comprise elevator, ailerons and rudders.

The secondary controls are unconventional. For the rotors, the tilt actuators are controlled independently for each of the masts to allow one-at-a-time conversion between rotary and fixed wing modes. For the wings, the inboard portions in the rotors down wash are vectored to minimise rotor blockage in hover.

The stability augmentation system comprises two independent units, one mounted on each tilting mast. Each unit has a 3-axis rate gyro aligned to the local mast attitude, and accepts raw cyclic, collective and gain commands from the 14-channel receiver. It mixes all these to operate its local swash-plate.

As a general objective, the higher bandwidth control, safety and mixing functions are performed on board, while lower bandwidth direction commands and scheduling are performed on the ground by the pilot's unit.

The test programme has four stages of investigation: hover rig, helicopter mode, airplane mode, and conversion. For the hover rig, the airframe is reduced to just landing skids so that it is flown as a meshing rotor helicopter. For the helicopter, airplane and conversion testing the full fuselage and fixed wing surfaces are used, with a conventional wheeled, fixed undercarriage. The conversion testing starts with the rotors tilted to different fixed positions corresponding to the pilot's conversion beeper button being frozen in those parts of the conversion range that must be explored. For the full mode the pilot is free to fly all the flight modes, using conversion as appropriate.

In describing each stage of the tests, the purpose will be summarised, and in the case of conversion, a more detailed explanation given of the design issues. Results to date are discussed.

The test stages planned are:

- Hover rig
- Helicopter mode
- Airplane mode
- Conversion

FLIGHT TESTING THE HOVER RIG

Purpose of the hover rig is to flight test the 1/10th scale rotors and power plant.

The hover rig comprises a simple airframe (no wings, booms, empennage), the transmission and meshing rotors. The power plant is a single out-runner motor using lithium polymer batteries.

Initially no stability augmentation is installed.

The tilt actuators are fully functional, but restricted to use as longitudinal trims. Differential trim is possible if needed.

Each rotor has full cyclic and collective, and these are mixed within the transmitter to provide pitch, roll and yaw. Yaw is obtained from differential longitudinal cyclic.

The hover rig was bench tested, and short tether tested to check basic functionality, and then taken to the test site for the pilot to assess for suitability to start test flights, see Figure 3, a frame taken from video of the first flight.



Figure 3. First flight of hover rig.

The general conclusions from the flight testing to date, are that it is unstable, but sufficiently responsive to allow manual flight control without stability augmentation.

Aircraft trim should allow for the residual pitching torque from driving the contra-rotating rotors: as these are angled at 11° to the aircraft XZ-plane their torques do not quite cancel.

HELICOPTER MODE

The principal issues are the addition of the airframe to the hover rig and its affect on the aerodynamics so far established. The additional mass is distributed away from the centre of gravity so that moments of inertia are

changed. The inboard wings are within the downwash of the rotors and therefore must vector to align to the flow rather than block it.

AIRPLANE MODE

The fixed tricycle undercarriage comes into its own for CTOL testing of the airplane: without it, take-off and landing would be complicated at best.

The aircraft configuration is fixed tricycle undercarriage, inboard wings fixed at cruise, and rotors tilted fully back 180° to act as pusher props.

Pitch control is available via elevators or longitudinal cyclic.

Roll is available via ailerons, and possibly via differential longitudinal cyclic.

Yaw is available via rudders or lateral cyclic.

Testing has two objectives: establishing the cruise capability of the aircraft and exploring the flight envelope where the conversion corridor lies.

Armed with flight experience and a good CTOL capability the aircraft should be fit to start the early stages of conversion testing.

CONVERSION

Before discussing the flight test plans, it is helpful to review the conversion process. It is novel and different from the existing tiltrotor approach principally because the proprotors are tilted back for cruise rather than forwards, as on the MV-22 and related tiltrotor aircraft.

Tilting back

A compact and agile aircraft has been achieved by bringing the engine nacelles and rotors from their traditional location on the wing tips, to mount them on the fuselage centre-line.

In this centre-line location, if the proprotors are tilted forwards for cruise this places them close to the cabin and reduces the forward view available to the crew.

So it was decided that the proprotors would be tilted back for cruise. This moves them away from the cabin and frees up the forward view for the pilots.

Thrust reversal

A consequence of tilting back is that the proprotors must reverse their thrust to perform as pusher props in the cruise mode. And when partially tilted back it is best to set thrust to zero.

This is summarised below. Note that tilt is defined as 0° fully forward, 90° for hover as in a helicopter, and 180° as fully back as a pusher prop.

- 70° to 95° tilt for helicopter flight: the z-component of thrust gives lift and the x-

component accelerates or decelerates the aircraft along its line of flight.

- 95° to 180° tilt for conversion: either the thrust x-component or z-component is in the wrong direction. Therefore set thrust to zero.
- 180° tilt for airplane mode: thrust must be reversed so that the x-component acts to propel the aircraft.

So during the conversion, while a proprotor is tilted between 95° to 180°, its thrust must be set to zero.

The purpose of one-at-a-time tilting

It is unacceptable to have both proprotors tilting back at the same time because this would leave the aircraft unpowered for the 20 or so seconds that it takes to complete the conversion.

The design solution chosen was to use meshing rotors co-located on the fuselage centre-line, and synchronised so that meshing is preserved whilst tilted back one-at-a-time.

By this means, while one rotor is in conversion, tilted between 95° to 180°, the other is available to sustain and control aircraft forward speed.

Meshing and tilting

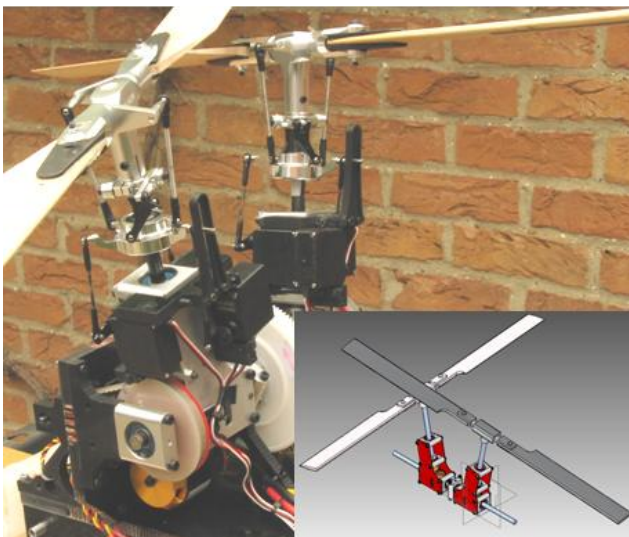


Figure 4. View of the transmission and meshing rotor arrangement for the 1/10th scale model.

The meshing arrangement is straight forward. It relies on a common cross-shaft driving the two rotors' gear boxes, (Fig. 4). This keeps the rotors and blades running synchronously at any relative position. However as the relative tilt changes, a phase correction is needed to keep in mesh. In its simplest form this is provided by the gear

ratio of the gear box connecting the cross-shaft to rotor shaft.

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. Figure 5 shows a close up of the bevel gears in the actual model gear box, and an inset of the bare installation. The large white gear is the spur gear driving the cross-shaft.

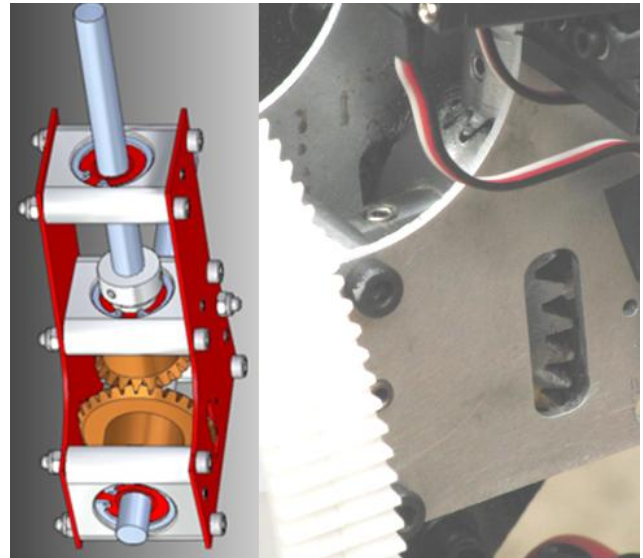


Figure 5. This photo shows the RH pair of bevel gears installed in the 1/10th scale model's transmission, and inset, the arrangement of its RH gear box.

The bevel gear ratio is 29:19, and this was chosen by analysis as suitable for the model using 2-bladed rotors. Key design parameters in the analysis are the angle at which the rotor masts are canted relative to the airframe XZ-plane, here 11°, the length of the mast from hub to the cross-shaft, and the length of the cross-shaft.

Pilot's controls for the conversion process, full scale escort aircraft

For the full scale aircraft, from a pilot's point of view it is proposed to 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.

The escort's Flight Control Computers (FCCs) must achieve this objective using a suitable tilting strategy as shown in Figure 7.

Pilot's controls for conversion, 1/10th scale model

For the 1/10th scale model, the schedule of Figure 7 is programmed in the transmitter unit and the test pilot operates it via a simple control alongside the normal collective thumb-stick.

Description of conversion sequence

Referring again to the schedule of Figure 7 the conversion starts with both rotors tilting forwards to build up aircraft speed. When sufficient speed has been achieved for the wings, ailerons and tail to be fully capable of control, then the one-at-a-time tilting can start.

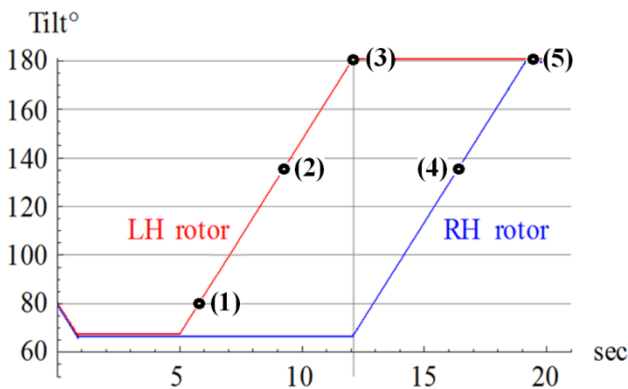


Figure 7. One-at-a-time tilting: initially both rotors are tilting forwards to build up aircraft speed, then the LH rotor starts tilting through (1) and (2) to arrive first at (3) tilted back fully 180° to take-over propulsion; now the RH rotor starts tilting back through (4) to arrive at (5) tilted back fully 180° to share the propulsion task.

After a few seconds tilting has started and at point (1) on Figure 7 the LH rotor is at 80°, the airflow enters the rotor disk from above the tip path plane as in a helicopter in level cruise.

At (2), with the LH rotor now tilted at 135°, the flow field seen by the rotor being analogous to a helicopter in a steep 45° auto-rotational descent, except that the rotor does not need to extract energy to maintain rpm, and that the collective is set for zero net thrust. Super-imposed on this relative flow field is the wash from the RH rotor.

As the LH rotor approaches 180° at (3), with collective still being adjusted for zero thrust, the rotor can be regarded as seeing the airflows as seen by a helicopter in near vertical descent, or as seen by a pusher propeller on the border line between braking and propulsion. The tilt configuration of point (3) is shown in Figure 8 with the hover rig firmly attached to a bench for to test tilt and meshing. The inset shows how the full size escort aircraft would look.

Once at point (3) the LH rotor reverses collective to take over propulsion of the aircraft. Then the RH rotor can start converting back.

At point (4) the RH rotor is now tilted at 135° and sees a flow field similar to that at point (2) for the LH rotor.

At point (5) the RH rotor is fully back at 180° and reverse collective can be applied to share propulsion of the aircraft with the LH rotor.

The conversion process is reversible.

It can be halted at any time in the process for sustained flying, at that intermediate tilt configuration, within the conversion flight envelope; and the conversion continued as and when wanted.

The conversion process is asymmetric.

When the rotors are at significant angles of relative tilt there are asymmetric thrust and torque components. Balancing these uses part of the authority of the aircraft controls. The controls then have less authority available to balance side winds or for manoeuvring.

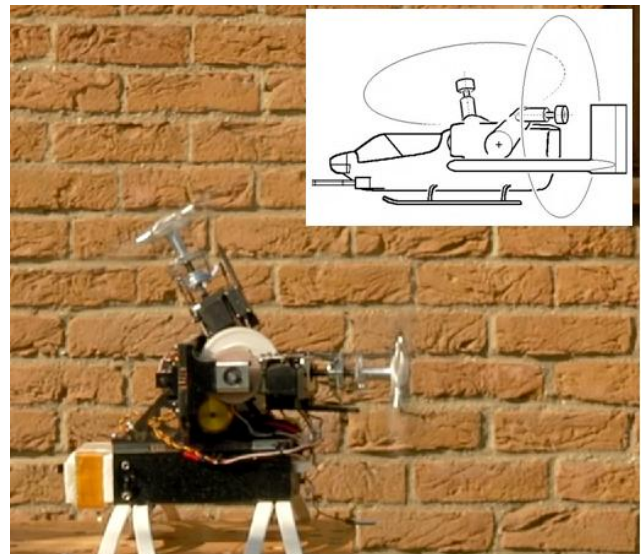


Figure 8. Meshing at about 1,500 rpm rotor speed: the rotors are tilted at about point (3) of Figure 7; the inset illustrates the full size escort at the same point.

The asymmetry can be reversed by starting tilting with the RH rotor rather than the LH: so there may an advantage to pilots having this as a pre-selectable option.

Summary of conversion issues

Throughout the conversion process there are some general observations and issues that must be considered, and apply equally to both rotors and whether the

converting rotor is moving forwards, backwards or held at a fixed position of tilt:

- It is essential that there is full control of aircraft speed along its flight path throughout the conversion. This is provided by the thrusting rotor that is either forward in helicopter mode, or fully back in propulsion mode.
- Torque reaction and thrust asymmetry from the thrusting rotor will need to be balanced, principally by the airplane control surfaces, and possibly by use of the other rotor's cyclic.
- For the rotor that is converting, setting collective for zero thrust reduces its asymmetric components of thrust and torque. Power will still be required power for profile losses and for any use of cyclic pitch.
- Conversion asymmetry can be reversed by reversing the order of tilting: pilots may wish to have this as a pre-selectable option.

FLIGHT TESTING CONVERSION

Two stages of flight testing conversion are involved: fixed point conversion and full conversion.

The fixed point tests allow discrete parts of the conversion process to be explored at minimum risk. Once confidence has been established in the discrete parts and that their flight envelopes overlap, then testing of fully variable conversion can proceed.

Flight testing fixed point conversions

A typical flight test of a fixed point conversion, for example with the rotors fixed in the tilt position of point (4) of Figure 7, starts with a conventional fixed wing take-off. The LH rotor is fully back at 180° and acts as the propeller, the RH rotor is at 135° set for zero thrust in order to minimise hindering the take-off.

The challenge for the pilot will be handling the asymmetry through ground roll through to rotation, then in flight to establish the flight envelope, and finally to land safely.

Each of the different fixed conversion points will have to be mastered in a similar way.

Flight testing full conversions

The preparation for conversion has been set out above, by flight testing:

1. hover rig mode
2. helicopter mode
3. airplane mode
4. fixed point conversion modes

The full conversions start from airplane or helicopter flight modes and finish in helicopter or airplane flight. A typical flight is:

- vertical take-off
- accelerate into conversion corridor
- convert to airplane mode
- accelerate to cruise
- fixed wing flight
- decelerate into conversion corridor
- convert to helicopter mode
- land vertically

By this process the flight envelope of this centre-line tiltrotor may be explored.

CONCLUDING REMARKS

The concept is of a Centre-line Tiltrotor Gunship to escort the MV-22 Osprey. The advantages of its compactness, agility, safety, speed and range have been summarised, and some of the technical challenges identified.

However this centre-line configuration differs from that of wing-tip mounted tiltrotor aircraft such as the Osprey. In particular the conversion process is very different, so a 1/10th scale model is being developed and used for flight testing the concept.

In outlining the testing necessary to explore the conversion concept, this paper discusses the issues involved in the flight testing plans that relate.

The progress to-date on flight testing the 1/10th scale model is described.

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