

Utility of a Mono Tiltrotor (MTR) Scaled Demonstrator

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Abstract

The Mono Tiltrotor (MTR) is a proposed, innovative cargo rotorcraft architecture. The capabilities of the MTR are predicated on the combination of an advanced coaxial rotor system and sophisticated kinematics that morph the aircraft topology for efficient flight over the entire operational envelope. The MTR rotorcraft integrates a coaxial rotor, a folding lifting wing system, a lightweight airframe and an efficient cargo handling system that is capable of rapidly and economically transporting a variety of mission tailored payloads. This paper identifies the utility of the MTR Scaled Demonstrator as an object of further research, as a producible end item, and as an empirical baseline for design of larger scale systems.

Introduction

The Mono Tiltrotor (MTR) is a proposed, innovative cargo rotorcraft architecture. The capabilities of the MTR are predicated on the combination of an advanced coaxial rotor system and sophisticated kinematics that morph the aircraft topology for efficient flight over the entire operational envelope. The MTR rotorcraft integrates a coaxial propotor, a folding lifting wing system, a lightweight airframe and an efficient cargo handling system that is capable of rapidly and economically transporting a variety of mission tailored payloads.

The MTR aircraft architecture was subjected to a conceptual design study and subsequently to a preliminary design and analysis. The scope of the conceptual design study was to compare the MTR with legacy helicopter concepts for a design mission range of 1000 nautical miles (nm) and for design payloads of between 2 tons and 20 tons [1] [2]. The study concluded that when compared to legacy single main rotor and legacy coaxial rotor helicopter concepts, the MTR was 1/2 the size, 1/3 the weight, and had 1/3 the fuel burn of these legacy concepts. This favorable comparison was attributed to its high effective cruise lift-to-drag (L/De) ratio compared to legacy concepts. For this 1000 nm vertical lift mission scenario, the MTR concept gross takeoff weight was triple (3x) the cargo weight, and fuel weight was 1/2 the cargo weight. The efficient cruise

speed of the MTR was found to be approximately double that of legacy helicopter concepts.

The subsequent preliminary design and analysis of the MTR Scaled Demonstrator (MTR-SD) had a design mission profile of 700 nm range while transporting a 1.5 ton load [3]. Unlike the conceptual design study which was performed using parametric equations for a top-down estimate of weight and drag, this MTR-SD design method included a bottoms-up tabulation of weights and drags based on a preliminary design of the drive system, including a commercial off-the-shelf engine, and based on a preliminary engineering analysis of the structural weight of all other primary subsystems. MTR-SD predicted performance matched the expectations established by the former conceptual study. Total gross weight is 9400 lbs, which is approximately triple the payload weight. Fuel weight is 1500 lbs, which is 1/2 of the cargo weight. The most efficient cruise speed is 200 knots (kts), approximately double that of comparable class legacy helicopters.

The purpose of this paper is to identify the utility of the MTR-SD as an object of further research, as a producible end item, and as an empirical baseline for the design of larger scale systems.

Research Methodology

A definition of utility as used by economists is the capacity of a commodity or service to satisfy some

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human want [4]. The approach taken in this paper is to define categories of economic utility, and then examine publicly available information about the MTR-SD to characterize its utility in each of these categories. One category of utility is the advancement of knowledge through original research. The criteria used in this paper is to identify MTR-SD systems or subsystems for which no equivalent research has been performed, and for which the research results would have broad applicability beyond the MTR-SD and beyond the MTR concept. Another category of utility is for the MTR-SD to provide operational capability as a producible end item. Since history has shown that new aircraft concepts are proven through military application before the development of a civil market, this study will focus exclusively on military capability. Furthermore, it is insufficient to simply perform better than existing platforms. The military capability must be unique and enable unique operational concepts. A final category of utility examined is the establishment of an empirical baseline from which larger scale MTR are shown to be feasible. An initial motivation for the US Government to fund the MTR concept studies was to examine its potential as a VTOL heavy lift platform [5].

Results and Discussion

Several unique and prominent opportunities for creating value through the development of economic utility were identified. The utility of the MTR-SD is itemized below in each of several categories: Advancement of Knowledge, Operational Utility, and Baseline for Scalability.

Advancement of Knowledge

The MTR vehicle concept originated with the simple idea of suspending the payload about the pitch axis of an aircraft. Over time, the configuration evolved with refinements to address practical engineering and operational constraints [6]. As a result, the MTR aircraft architecture embodies subsystems and techniques that are unique in the field of vertical take-off and landing (VTOL) aircraft. These unique features, however, are of potential value and utility to the designer of future innovative rotorcraft, or for modifying and enhancing legacy rotorcraft.

Coaxial proprotor

Before the jet age, coaxial propellers were researched as a means to increase the performance of propeller driven aircraft [7]. Perhaps the most famous large production aircraft with coaxial propellers is the Tupolev TU-95 "Bear" strategic bomber [8]. More recently, coaxial

rotors were manufactured for the Sikorsky X2 technology demonstrator aircraft [9], and they are integral to most Kamov helicopters, for example the Ka-52 Hokem [10]. However, the fact that coaxial propellers and coaxial rotors are known producible subsystems, does not imply the same for coaxial proprotors. The coaxial proprotor is unique in that it must maintain a torque balance with good aerodynamic efficiency in both hover and in a high inflow axial mode of operation, and it is gyrodynamicly balanced which advantageously eliminates the significant gyroscopic forces of single proprotors.

The MTR-SD incorporates a coaxial proprotor. In the history of aviation only a few research aircraft have incorporated coaxial proprotors, and none have been incorporated into production aircraft. The Convair XFY Pogo tailsitter aircraft had a coaxial drive system for both hover and axial thrust [11], as does the AeroVironment SkyTote [12]. Nevertheless, the study of coaxial proprotors as a unique subsystem has inherent value independent of any particular air vehicle. This subsystem is torque balanced and gyrodynamicly neutral, unlike conventional proprotor subsystems which produce torque in all flight modes and have gyroscopic behavior. Conventional tiltrotor concepts styled after the Bell XV-15 could potentially benefit from incorporation of a coaxial proprotor to reduce the potential for whirl flutter mode and thus reduce airframe structural weight.

The ability to achieve a torque balance and have good aerodynamic efficiency in both hover and high inflow axial mode has been shown to be achievable through preliminary design and analysis. This result was initially reported at the AHS Forum in 2006 [13], and presents an opportunity for original research and validating hardware demonstrations. The aeroelastic behavior of a coaxial proprotor offers another research and demonstration opportunity, as a check against analyses which have predicted the separation distances between upper and lower tip path planes during conversion [14]. Freud and Mach scale testing coupled to aeroelastic and aerodynamic analytical techniques would have utility not only for the MTR-SD and MTR vehicle architecture, but also provide a proven coaxial proprotor subsystem for the designer of future tiltrotor concepts.

Vertically suspended payload

Untreated slung containers are practical but risky due to unsteady aerodynamic loads associated with bluff bodies having square corners. These unsteady aerodynamic loads can cause the slung container to rotate and translate, resulting in unstable motions that can increase in amplitude with airspeed. A vertical stabilizer at the container has been shown to increase stability allowing higher cruise speeds [15], but this technique does not appreciably reduce bluff body drag. One conceivable

technique to increase stability and reduce drag is to develop a structure that can envelope and streamline the slung load [6]. Of course, this structure would add weight to a helicopter, and in fact no such structure has proven to be economically desirable in the commercial marketplace and it is generally absent from military operations.

However, tiltrotor aircraft have a much higher cruise efficiency than helicopters, and the added weight of this enveloping and streamlining structure can be justified. For instance, the MTR-SD cruise performance is predicated on having a containerized load that is enveloped and streamlined to minimize drag and improve payload stability. Furthermore, suspending this enveloped and streamlined load about the pitch axis of a tiltrotor aircraft can be an advantageous arrangement for longitudinal stability and control.

One container that is a potential candidate for further study is the Joint Modular Intermodal Container (JMIC) [16]. The JMIC is a component of the Joint Modular Intermodal Distribution System (JMIDS) Joint Capability Technology Demonstration (JCTD) with testing scheduled to be completed in 2007. A key goal of the JMIDS JCTD is to demonstrate an all-mode transportable container that facilitates original source to final destination delivery without repacking of its contents. The JCTD JMIC has a 3000 lbs gross weight, 42 inch X 44 inch X 54 inch external dimensions, can be interconnected to form larger packages for transport by commercial container ships, and is collapsible and stackable for retrograde.

Research on treatment of the JMIC for pitch axis suspended load operations is potentially of fundamental value for any of the higher L/De VTOL concepts. The JMIC fuselage design of the MTR-SD can be made generally applicable to any VTOL aircraft for transporting JMIC form factor payloads.

Passive wing morphing

In general, wing morphing can be achieved through the use of active mechanical systems or passively through aerodynamic forces. Mechanized wing morphing is a mature technology incorporated into conventional takeoff and landing (CTOL) production airplanes. Examples of mechanized wing morphing include swing wing systems on the Grumman F-14 Tomcat and the Rockwell B-1 Lancer. Passive wing morphing in the form of aerodynamically deployed wings have been proposed and tested for air-dropped fixed wing aircraft, for example the NASA ARES Mars scout aircraft [17].

However, passive wing morphing is novel for aircraft that have self-contained takeoff and landing ability, and perhaps only practical for vertical take-off and landing

(VTOL) concepts. The author is unaware of any CTOL concept that incorporates passive wing morphing. One example of passive wing morphing is the MTR wind tunnel test of aerodynamic wing deployment performed in 2006 [18]. These tests were successful in that the measured behavior matched theoretical predictions, and the wing panels deployed controllably, consistently, symmetrically, and repeatedly [19]. Also, on 17 March, 2007, a remote control helicopter was flown with aerodynamically deployable wings panels, showing that wing panels can deploy in the presence of a rotor wake [20].

The projected advantages of aerodynamic wing deployment for VTOL aircraft are that it reduces hover download, avoids hover gust loads, and eliminates the weight of mechanized actuation, while providing a high cruise L/D. One key advantage to the MTR implementation of wing morphing is that in helicopter mode the wing leading edge is fully aft of the rotor mast like a horizontal stabilizer; and in airplane mode the wing $\frac{1}{4}$ chord is located over the aircraft center of gravity (CG) like an airplane with a good static margin. Even though aerodynamic wing deployment for VTOL was conceived to address practical engineering and operational constraints of the MTR aircraft architecture, this subsystem has potential value for other VTOL aircraft concepts.

Passive wing morphing technologies for VTOL aircraft need not be exclusive to the MTR concept. Novel concepts that incorporate aerodynamically deployable wing panels for extended range performance are conceivable. Research and development of passive wing morphing can create new possibilities for the designer of future VTOL concepts.

Multi-body VTOL assessment methods

A universally accepted, multi-body, aeroelastic method of validating or invalidating a novel multi-body configuration is needed. Purely analytic methods have been proposed and attempted for validating the MTR, and to-date none have yielded conclusive results [14]. Furthermore, the author has been advised that any one aeroelastic method would not be sufficiently conclusive, so several independent techniques should be applied and their results compared. A problem with this approach is that the final result is never conclusive. An approach of requiring validation through analysis before committing to hardware can exclude the MTR and other potentially viable novel concepts.

On the other hand, committing to hardware before validating a concept presents its own difficulties. Very small sub-scale hardware can be judged non-representative of the aerodynamic and aeroelastic

behavior of full scale hardware. Yet, larger scale hardware construction and testing that is performed without an understanding of real physical behavior can introduce financial risk. A hardware approach implies some level of trial-and-error which inherently has indeterminate projected outcomes. Furthermore, exclusively empirical methods generate knowledge exclusive to a particular configuration with limited applicability outside the scope of a particular design.

A systematic and efficient approach to avoiding this potential stalemate would facilitate innovation. A proposed approach is to combine newly cost effective hardware techniques of the UAV industry, with known aircraft analysis and simulation methods. Low cost flight hardware with telemetry and on-board control laws can be combined with ground based analysis and simulation in an integrated research effort. Simulations that map faithfully to small scale behavior can then be scaled up with suitable judgment to project larger scale behavior. The MTR-SD design offers an opportunity to couple analytical and UAV based empirical methods to rapidly validate a very non-traditional concept. A cost efficient UAV-based approach coupled with known analysis and simulation methods applicable to vetting novel multi-body concepts would facilitate technical innovation.

Operational Utility

It is not sufficient for an innovative system to provide operational utility that is better than fielded systems. Market acceptance of innovation requires breakthrough utility that for fielded systems would be impractical or impossible. Economic history shows that the identification of breakthrough utility emerges through dialog between the vendor and the customer [21]. To that end, the following suggestions are offered:

Cargo unmanned aerial vehicle (UAV)

Supply ships operating within the littorals in support of expeditionary troops require survivability features. The level of survivability needed is commensurate with the assault ships operating within this same region [22]. While future operational concepts will continue to include supply from the littorals, an alternative and complementary operational concept can be suggested that exploits MTR-SD size, range, and speed.

The complementary operational concept is to position more vulnerable supply ships safely beyond the littoral region, and employ the 700 nm range and 200 kt speed of an MTR-SD for vertical sustainment from beyond the littorals directly to the expeditionary troops. The material solution needed to implement this operational concept is comprised of the currently fielded Maritime

Preposition Ship (MPS), the recently produced and tested Joint Modular Intermodal Container (JMIC), and a “squadron” of container-stowable MTR-SDs. A Waterman-class MPS (e.g., T-AK 3007 SS Maj Stephen W. Pless) has cranes capable of handling commercial containers and has a helicopter deck that could support MTR-SD simultaneous operations [23]. This MPS, densely packed with 20ft long commercial containers of mostly JMICs and some MTR-SDs, can sustain expeditionary troops at a relatively safe 350 nm radius of action in this notional operational concept. MTR-SDs requiring intermediate or depot level maintenance are re-containerized and stowed out of the way in the hold of the ship. Similarly, spare MTR-SDs can be unpacked from their containers and placed into operation.

Within this concept, the dirty, dull, and sometimes dangerous mission of providing daily sustainment of expeditionary troops is performed by relatively low-cost, smaller, unmanned platforms, which frees larger manned VTOL assets to perform maneuver operations and other primary missions. Assault ships and carrier groups are relieved of a sustainment burden which frees up deck and hold space for other activities. Sustainment throughput to the expeditionary troops is scaled up by adding another MPS to the group. In summary, this notional concept disencumbers the assault ships, carrier group, and vertical lift assets of a significant sustainment burden while delivering scalable sustainment to expeditionary troops.

Aerial fuel re-supply

Some VTOL missions require that legacy helicopters and V-22 Osprey troop transports be aerial refueled for extended range operations. The MPS has bulk fuel capability, and in combination with the Cargo UAV operational concept above has the potential to give fuel for extended range VTOL operations. An MTR-SD operating from an MPS with a container of fuel and towing a refueling drogue could give fuel at slower speeds to helicopters and at a higher speed to the V-22 Osprey. Fuel delivery would be feasible within a 350 nm radius from the MPS and at altitudes up to 20,000 ft.

Under current doctrine, the Boeing F/A-18 with a 330 gallon centerline mounted Aerial Refueling System (ARS) and up to four 480 gallon external wing mounted tanks [24] have taken over the primary carrier-based fixed-wing refueling mission. While operating as a tanker, the F/A-18 is not available for its primary role as a fighter or attack aircraft, and at the same time is expending its fighter and attack serviceable life. Under the notional operational concept, an MTR-SD operating from an MPS could give fuel to carrier based fixed-wing aircraft while operating at 200 kts and up to 20,000 ft altitude, which potentially frees up some carrier based

F/A-18s for their primary fighter and attack roles, effectively extends the life of these F/A-18s for their primary missions, and reduces the fuel demanded from the carrier to support flight operations.

Finally, the MTR-SD operating as a tanker can climb to higher altitudes and give fuel to aircraft in-route over the carrier group. By employing the 700 nm range of the MTR-SD, a series of tactical fuel deliveries could be provided to a larger strategic aircraft operating in the region in the event strategic tankers were unavailable.

In summary, this notional operational concept extends the operational range of VTOL assets, increases the fighter and attack utility of F/A-18s by unburdening them from their secondary tanker role, reduces the fuel demanded of the aircraft carrier to support flight operations, and provides a tactical fuel supply to aircraft in-route over the carrier group.

Derivative applications

Conventional fixed wing and rotary wing aircraft concepts require that the fuselage design be of a predetermined size and shape sufficient for all possible future missions and derivative aircraft applications. Furthermore, any extensive customization of the fuselage requires that the aircraft be taken out of service for maintenance and upgrades. In contrast, the modular design of the MTR enables “fuselage swapping”, the complete replacement of the fuselage and its contents between missions. Swapping can facilitate rapid aircraft turns during high tempo operations, for instance enabling rapid disconnect of a fuselage of retrograde containers and then connection of a fuselage containing supplies for expeditionary troops. Furthermore, derivative applications for the MTR-SD can be created by designing mission specific fuselages and swapping them onto fielded MTR-SDs.

This ability to swap fuselages on an operational system suggests several mission customization opportunities. A multiple litter medical evacuation (MEDIVAC) fuselage housing state-of-the-art, autonomous life sustaining medical technology could be prepositioned by the MTR-SD at the battlefield, and then when required an MTR-SD returns and connects to the MEDIVAC fuselage for evacuation. When the state-of-the-art in medical technology changes, the MEDIVAC fuselages can be upgraded or replaced with no impact on the MTR-SD.

Another mission customization opportunity is to design a fuselage comprised of offensive weapons to enable a high altitude capable, long range, vertical lift, hover capable ground attack platform. The offensive weapon package could be optionally disconnected on the battlefield to establish or support a fixed base of operations.

Other opportunities beyond MEDIVAC and weaponization are conceivable, such as: developing a fuselage of sensors and surveillance equipment; or a search and rescue fuselage; or a fuselage specifically designed for fire fighting operations. These and other fuselage configurations are possible, all without impacting the MTR-SD, and all rapidly interchangeable while turning the aircraft during high tempo operations.

Baseline for Scalability

The MTR aircraft architecture is scalable, from implementations as small as the recent remote control helicopter-based demonstration of wing deployment with a suspended load, to very large designs addressing the Joint Heavy Lift (JHL) notional requirements. The initial Government funded concept study addressed scalability from 2 ton to 20 ton payloads, with a particular interest in the transport of a 20 ton container. These larger designs indicate that if proven feasible, the MTR concept would provide breakthrough capability at a JHL scale. The MTR-SD provides the empirical baseline for predicting JHL scale feasibility.

Conclusions

The Mono Tiltrotor (MTR) is a proposed, innovative cargo rotorcraft architecture. The capabilities of the MTR are predicated on the combination of an advanced coaxial rotor system and sophisticated kinematics that morph the aircraft topology for efficient flight over the entire operational envelope. The MTR rotorcraft integrates a coaxial rotor, a folding lifting wing system, a lightweight airframe and an efficient cargo handling system that is capable of rapidly and economically transporting a variety of mission tailored payloads. This paper identifies the utility of the MTR Scaled Demonstrator as an object of further research, as a producible end item, and as an empirical baseline for design of larger scale systems.

The following conclusions have been drawn from this study:

1. Three categories of MTR-SD utility have been identified: the advancement of knowledge, the development of breakthrough operational concepts at an MTR-SD scale, and the establishment of an empirical baseline for larger scale designs.
2. The MTR-SD is a catalyst for the advancement of knowledge in the following four areas: coaxial proprotor subsystems, vertically suspended payload subsystems, passive wing morphing techniques, and the development of efficient, multi-body VTOL concept vetting methods. This knowledge is of value

and use to designers of future innovative rotorcraft, or modification to legacy rotorcraft concepts

3. The MTR-SD enables a breakthrough operational concept for vertical sustainment of expeditionary troops from supply ships stationed safely beyond the littorals. The material solution needed to implement this concept is comprised of the currently fielded Maritime Prepositioning Ship (MPS), the recently produced and tested Joint Modular Intermodal Container (JMIC), and a "squadron" of container-stowable MTR-SDs.
4. The MTR-SD, when operating from an MPS containing bulk fuel, further enables a breakthrough operational concept that can provide aerial refueling of rotary-wing and fixed-wing aircraft operating from Sea Level to 20,000 ft altitude and within 350 nm of the MPS.
5. The MTR-SD operating as a vertical sustainment platform and as an aerial refueling platform frees the larger manned VTOL assets to perform maneuver operations and other primary missions, and frees the F/A-18s from their tanker role so they can perform their primary fighter and attack missions.
6. The "fuselage swapping" modular design of the MTR-SD facilitates rapid aircraft turns during high tempo operations, and furthermore facilitates the development of mission specific fuselages that can be swapped onto fielded MTR-SDs. This modularity enables further operational concept breakthroughs by employing customized mission fuselages for MEDIVAC, attack, surveillance, firefighting, and possibly other unforeseen roles.
7. The MTR-SD provides the empirical baseline for predicting Joint Heavy Lift (JHL) scale feasibility.

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