What is a Tiltrotor? A Fundamental Reexamination of the Tiltrotor Aircraft Design Space

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Abstract

The objective of this work is to fundamentally reexamine the design space of tiltrotor aircraft beyond the very successful conventional vehicle configuration with tractor-type twin proprotors that are nacelle-mounted at the wing tips. This work seeks to define a broad aircraft design space for alternate tiltrotor configurations. It is hoped that this work will not only provide design inspiration for future aircraft developers, but also help realize in the future new applications and missions for both passenger-carrying vehicles and vertical lift UAVs.

Introduction

After a multi-decade development effort, the first production tiltrotor aircraft, the MV/CV-22 Osprey, has become a key element of U.S. military aviation. After its own long fitful development effort, the AW-609, the first civil tiltrotor aircraft, seems to be finally nearing certification. Design studies continue to show the promise of large civil tiltrotor aircraft for commercial passenger transport – particularly as such aircraft might help enable significant National Airspace System (NAS) throughput increases and delay reduction through their VTOL/runway-independent nature. Tiltrotor aircraft have finally arrived.

Meanwhile, though, a recent resurgence of development activity in compound helicopters, notably the X2 and X3 compound helicopters, has narrowed the speed/range advantage of tiltrotor aircraft over such vehicles. In parallel with these advances in manned rotary-wing aircraft, aviation as a whole is poised to see a rapid expansion in uninhabited VTOL UAV's supporting new civilian/commercial missions/applications. Finally, the NASA LCTR2 reference design – as well as similar NASA-sponsored conceptual designs from industry – has seen some modest refinement over the past few years, but may not reflect the current NASA ARMD interests in fostering/exploring "disruptive," "transformative," or "convergent" aeronautical technologies consistent with NASA aeronautics strategic thrusts. Some previously proposed alternate tiltrotor configurations include the Bell quad-tiltrotor and the Augusta Westland ERICA hybrid tiltrotor/tiltwing concepts. More recently, proposed alternate tiltrotor configurations (or

Presented at the AHS International Technical Meeting on Aeromechanics Design for Transformative Vertical Flight, San Francisco, CA, January 16-18, 2018.

at least tiltrotor-like) include the NASA Langley "Puffin" and the Joby Aviation S-2 concepts. It would seem timely, given all of the above, to reexamine the tiltrotor aircraft design space and investigate whether there are opportunities to define and investigate vehicle configurations that are two or three generations (or more) beyond the current state-of-the-art for uninhabited and manned tiltrotor aircraft. For this paper, such a generation of tiltrotor aircraft will be referred in the following discussion as "N+beyond." In short, this discussion will seek to ask – and partially answer – the question: what is a (future) tiltrotor aircraft? In this regard, several notional vehicle concepts are either revisited from earlier work or introduced for the first time. Some of the proposed vehicles will intentionally challenge the reader as to whether or not the proposed vehicle is a "tiltrotor aircraft" or not.

The vehicle concepts to be introduced (or reintroduced) are intended to promise improvements in speed, passenger-carrying capacity, and mission flexibility/capability beyond that achievable with concurrent technology and conventional configuration tiltrotor aircraft. The concepts presented are very speculative in their current state of development. This is consistent with the overarching goal of defining vehicle configuration two or three generations beyond the current state-of-the-art. Some vehicle concepts will be more compatible with uninhabited versus manned vehicle missions/applications; others will be generally applicable to both types of missions/applications. Some vehicle concepts could gain critical benefit from advances in autonomous systems and hybrid-electric-propulsion technologies whereas the success of other vehicle concepts will be relative insensitive to the influence of those same technologies. In some cases, wholly new ways of operating aircraft may need to be developed to successfully realize these vehicle concepts.

In the synthesis, or rediscovery, of the vehicle concepts presented, several design attributes are highlighted and explored. These attributes include: (a) hybridization, or fusion, with other vehicle types or concepts stemming from the fixed-wing aircraft world; (b) novel variable-geometry and/or morphing vehicle configurations; (c) embodiment, as appropriate, of heterogeneous rotor systems and asymmetric planform; (d) novel operational flight regimes, modes, and CONOPS; (e) vehicle configurations whose drive train complexity could potentially be greatly reduced – and reliability greatly improved – by emerging electric-propulsion-systems; and (f) vehicle concepts that promise significant scalability between small UAV-type applications and large manned aircraft applications.

Conventional (current generation) tiltrotor aircraft are already comparatively complex and relatively heavy machines. Many of the vehicle concepts presented will add to this complexity and increase vehicle weight. However, it is anticipated that a combination of advanced technologies will help offset any increase in vehicle weight and, further, that enhanced mission capability will help justify increased vehicle complexity. Accordingly, a critical next step to design trade space reexamination is a system analysis investigation to both better assess mission capability and to identify an enabling technology portfolio that could help realize one or more of the vehicle concepts presented.

This paper has one absolute requirement for defining an aircraft as a tiltrotor: the vehicle's rotors must tilt through a range of approximately ninety degrees, from near vertical rotor rotational axes for hover and takeoff and landing to nearly horizontal for higher speed cruise in forward-flight. In addition to this one requirement, other constraints might be relaxed to yield advanced tiltrotor configurations that might otherwise be seriously considered by rotorcraft designers and the overall research community.

The design space to be considered in this paper is principally enabled by changing the following implied design constraints and design engineer preconceptions:

1. Tiltrotors can only have tractor-type proprotors;
2. Tiltrotors can only have their proprotors mounted at their wing-tips;
3. Tiltrotor proprotors can only be of one type, size, and general design;
4. Tiltrotor proprotor nacelles can only have one degree-of-freedom (tilting);
5. Tiltrotor airframes and wings (with the exceptions of flaperons, elevators, and rudders) can only have fixed/static geometries/configurations.

By relaxing the above list of design constraints and moderating some of these preconceptions, wholly new types of tiltrotor aircraft configurations might be realized. This is the fundamental premise of this paper.

Finally, it is important to note and to recognize that many previously studied advanced tiltrotor configurations are not discussed in this paper. I.e., folding-proprotor tiltrotors, joined-wing tiltrotors, and variable-diameter tiltrotors, for example, are not discussed. This is because these configurations have all received relatively recent and extensive study as compared to the concepts herein presented.

Pusher Proprotor Tiltrotor (PPT)

It is proposed to revisit an "old" VTOL (vertical take-off and landing) concept for possible -- small and large -- applications to rotary-wing UAVs and manned aircraft. One "old" VTOL concept that has merit for re-examination is the pusher-proprotor-type tiltrotor (Fig. 1).[†] The best-known example of this VTOL configuration is the Focke FA-269. The Focke FA-269 never made it beyond the concept study phase. In particular, the pusher-proprotor-type tiltrotor might have advantages over the conventional (tractor-type) tiltrotor aircraft in terms of reduced hover download, reduced wing stiffness requirements, and improved whirl-flutter aeroelastic stability characteristics that might make it attractive for rotary-wing UAVs and manned aircraft. Figure 1a-c illustrates one notional PPT configuration in three stages of flight: hover, transition, and cruise. Figures 2-3 are initial CFD predictions of the same configuration in hover and cruise.

† The NASA LCTR2 reference design (e.g. Ref. 12) is used throughout the paper as a reference source for some of the described advanced vehicle concept rotor, wing, and fuselage elements.

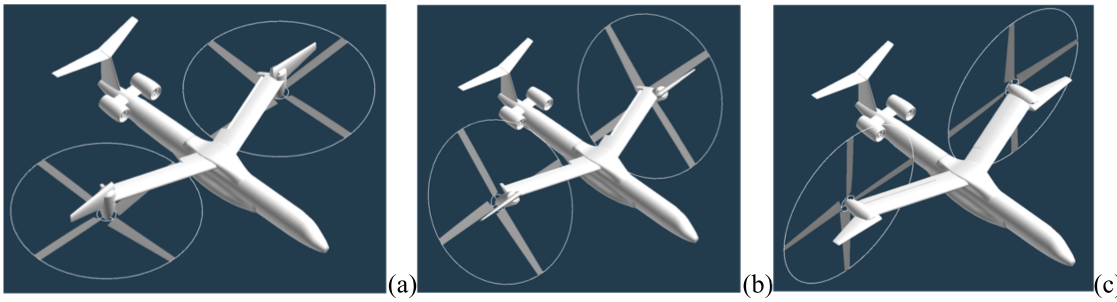


Figure 1. Pusher Proprotor Tiltrotor (PPT): (a) hover, (b) transition, (c) cruise

Ground clearance issues will be very important for this concept. Additionally, passengers and cargo would have to be loaded from the rear of the aircraft from jet-ways or stairs. Because of the unique nature of a pusher-proprotor configuration, turbine engine mounting cannot be wingtip mounted (coincident with the rotor nacelles) as is conventional tractor-type tiltrotor aircraft. Turbine exhaust gas temperatures would be much too high to run the risk of their ingestion into the rotor disk plane – and thus run the chance of damaging the rotor hardware. Therefore, pusher-proprotor tiltrotor aircraft will have to have the turbine engines fixed-mounted horizontally at the wing/fuselage junction, or, alternatively, on the empennage/tail of the aircraft. Either location will require some creative drive-train designs to allow for lightweight but robust interconnect shafting between the engines and the rotor nacelles. Alternatively, such large drivetrain layouts might be ideal candidates to greatly simplify by the incorporation of hybrid electric-propulsion subsystems.

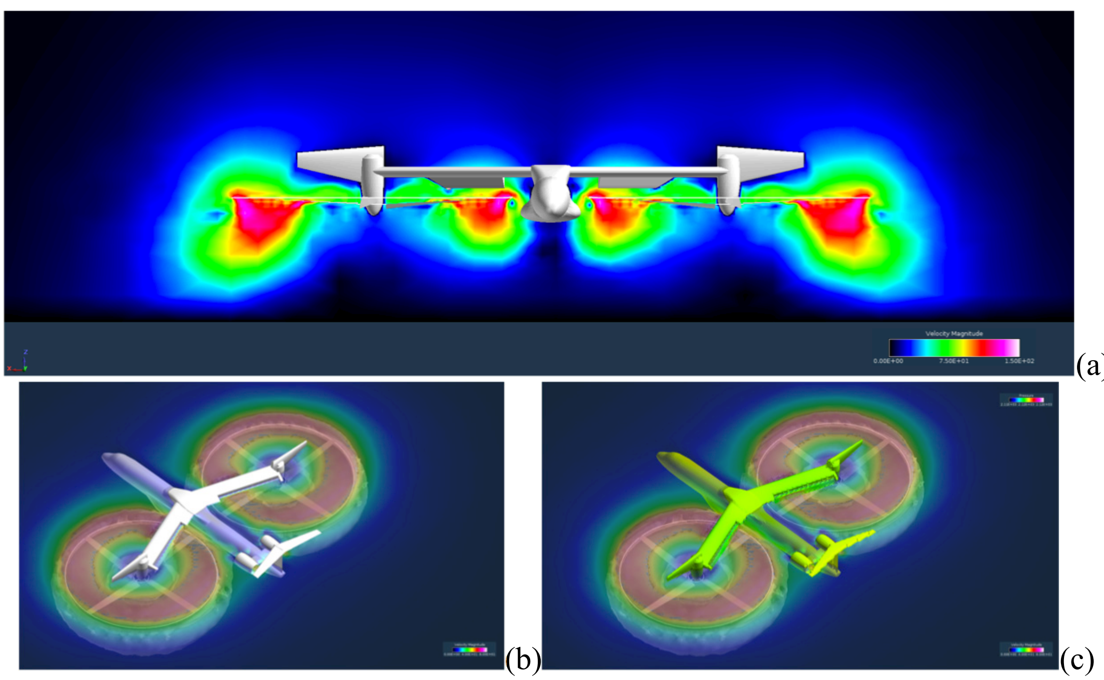


Figure 2. RotCFD prediction of a PPT in hover in ground effect

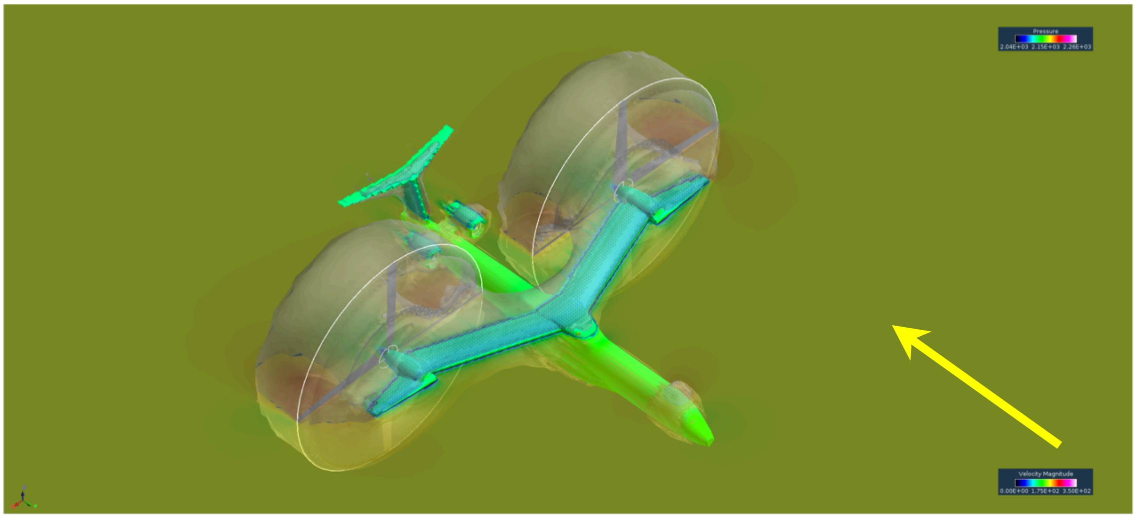
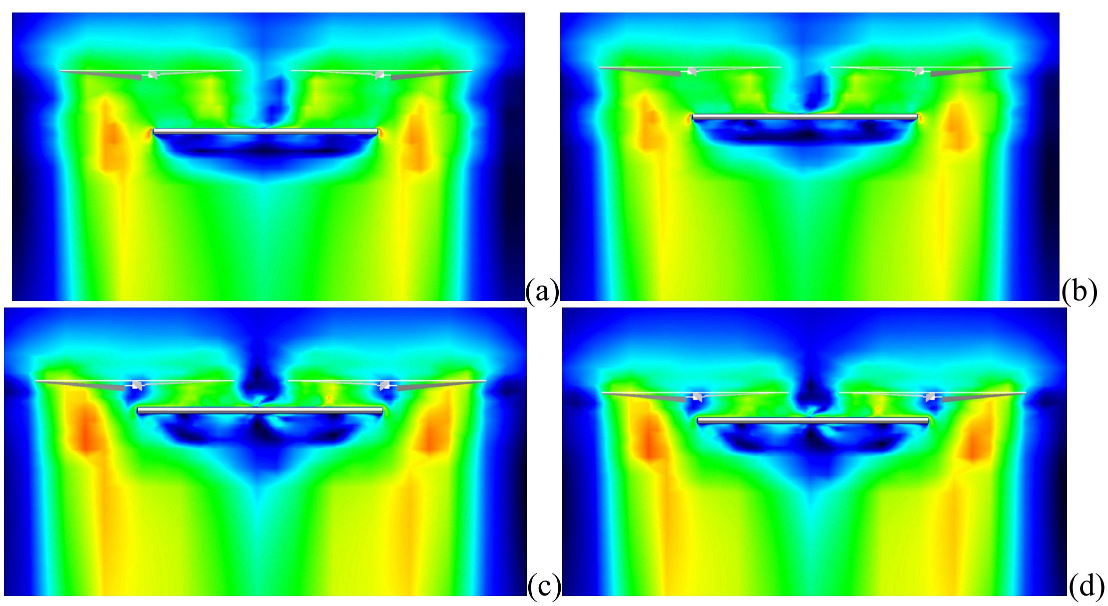


Figure 3. RotCFD prediction of a PPT in forward flight

A simplified aerodynamics model of two rotors and a wing was developed for the PPT. The wing was unswept, had zero dihedral, used an NACA 0024 airfoil, a constant chord of c/R=0.246, and did not model any flaperons; the rotors were based on the LCTR2 NASA reference design (Ref. 12). This model was used to examine whether or not a pusher proprotor tiltrotor configuration could, indeed, exhibit significantly less hover download than a conventional tractor-type configuration. Figure 4a-h is a set of velocity magnitude contour predictions for the simplified aerodynamics model. The rotor hub-height-to-rotor-radius ratio, h/R, where h is the height above or below the wing, are parametrically swept from ±0.615≤h/R.



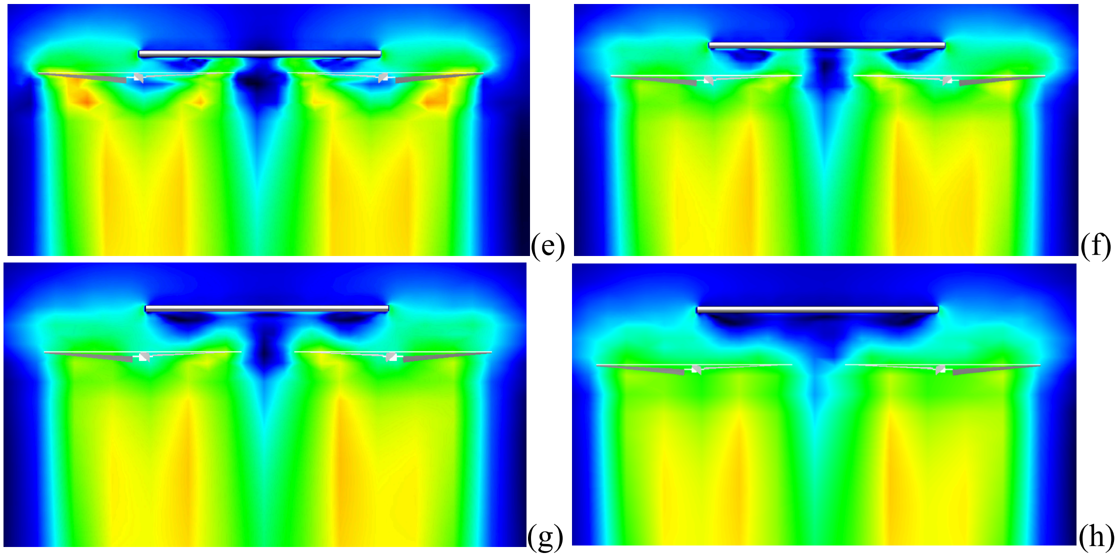
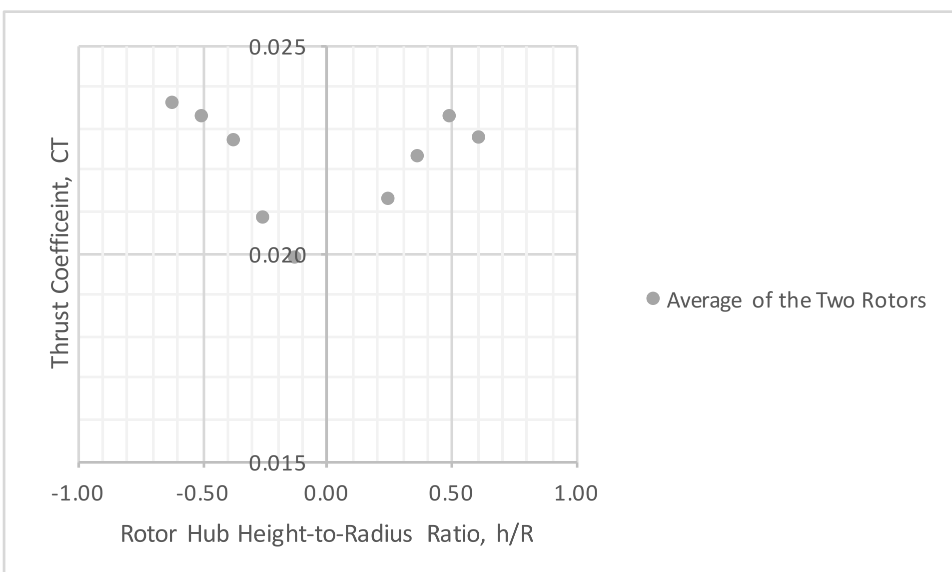
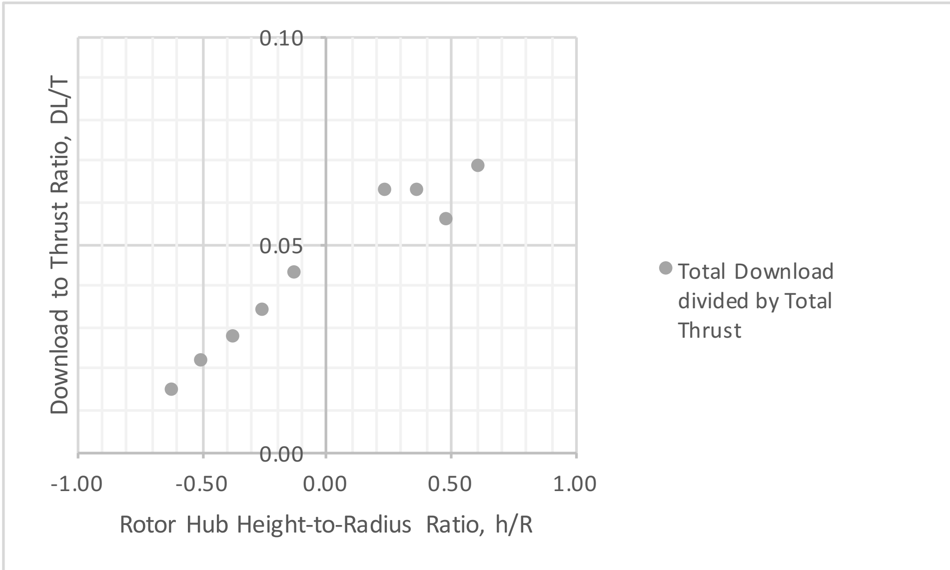


Figure 4. Velocity magnitude contour predictions: (a) h/R=0.615; (b) 0.492; (c) 0.369; (d) 0.246; (e) h/R=-0.246; (f) -0.369; (g) -0.492; (h) -0.615

Figure 5 is a set of predictions for the influence of h/R on the hover rotor thrust (average between the two rotors) and wing download for the simplified rotor/wing aerodynamic model. As can be seen from Fig. 5a-b, the simplified PPT hover aerodynamics model confirms one of the key conjectures of the vehicle concept, which is that having rotors below the wing results in reduced wing download in hover. Further, increasing the spacing of the rotors from the wing increases the total thrust of the rotors. These predictions were made for fixed collective and rotor tip speed.



(a)



(b)

Figure 5. Influence of h/R (above and below the wing) on (a) rotor thrust and (b) wing download

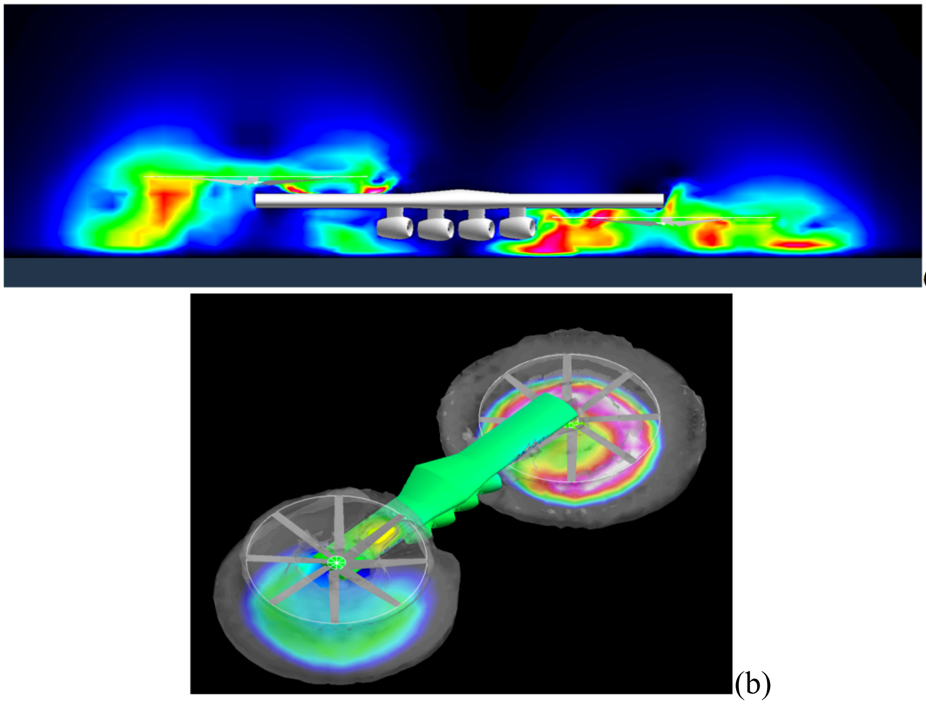
The above results suggest, as do many of the initial aerodynamic assessments in this paper that, unsurprisingly, novel vehicle configurations present opportunities to explore novel aerodynamic phenomena.

Tiltrotor Oblique Wing (TOW)

Oblique wing and oblique flying wing configurations have been proposed for the fixed-wing world since the 1950's. One of the strongest advocates for the concept was R.T. Jones of NASA Ames. The XV-15 tiltrotor and the AD-1 oblique wing are considered hallmarks of the NASA Ames aircraft development efforts. The Tiltrotor Oblique Wing (TOW) is a both a hybrid of both aircraft types, as well as a homage to the Ames' aviation heritage over the past seventy-five years. The proposed concept also embodies all of the other key vehicle design attributes that this paper seeks to emphasize in defining N+beyond type tiltrotor aircraft.

Operationally, the TOW vehicle would takeoff/land and low-speed air taxi as a quasi-tandem helicopter. At lower flight speeds, up to the beginning of transition, the flying-wing vehicle would then pivot such that wing sweep would be effectively zero so as to effect nacelle tilt conversion. Once conversion was completed, the vehicle would then pivot to an effective sweep angle magnitude of approximately 30-45 degrees for forward-flight cruise. Figures 6-9 illustrate these phases of flight.

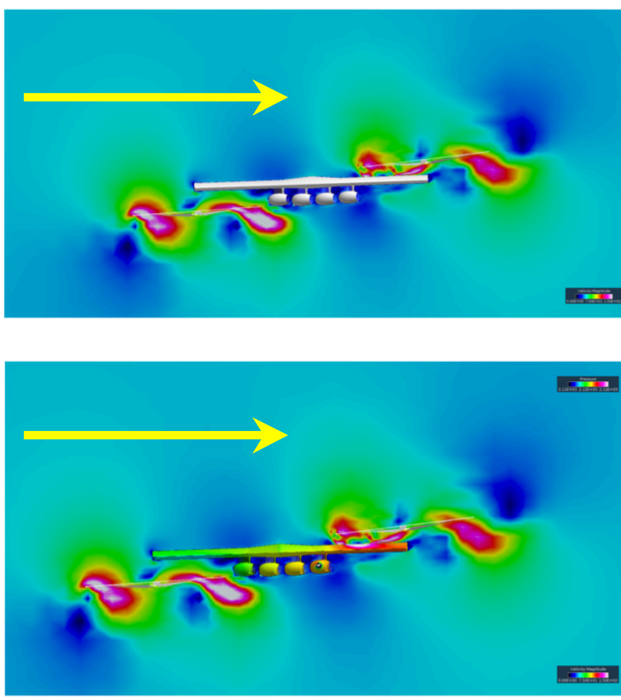
Why pivot/sweep the wing forward during cruise? The answer for the TOW concept is unique as compared to the fixed-wing oblique flying wing – of which almost all conceptual designs flew at supersonic speeds, where reducing compressible drag was an important aerodynamic performance consideration. Instead, the goal of a TOW vehicle is conjectured to transform tiltrotor dynamic stability considerations from aeroelasticity-dominated to more rigid-body-vehicle flight dynamics dominated.



(a)

(b)

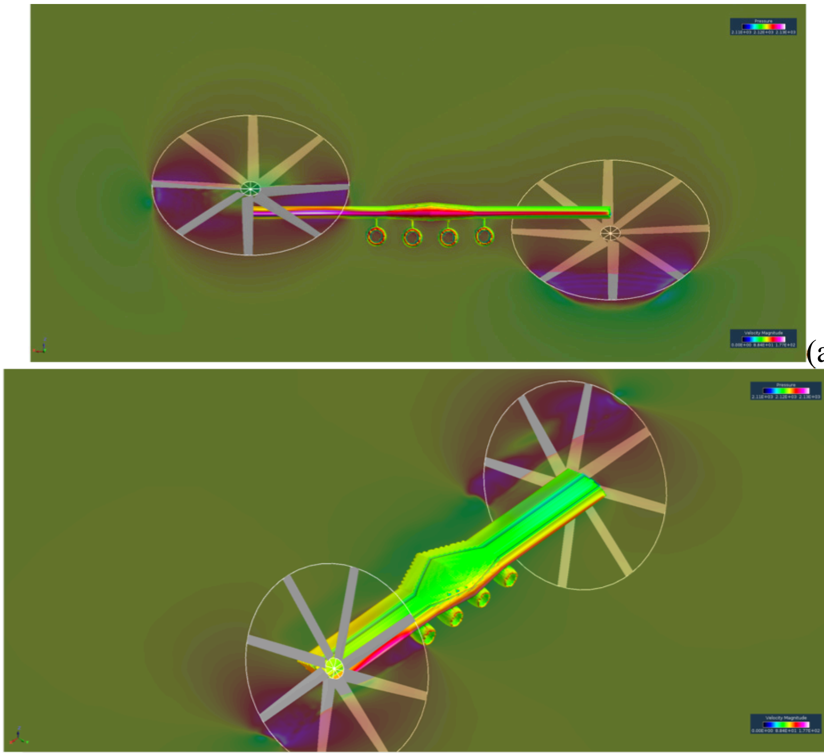
Figure 6. Hover in ground effect: (a) front view and (b) orthogonal view



(a)

(b)

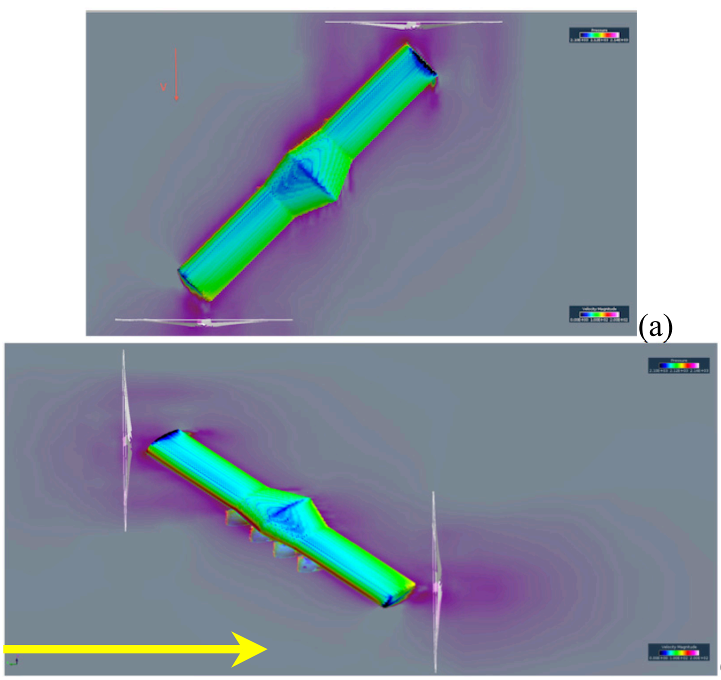
Figure 7. Low-speed air taxi in oriented as a tandem configuration: (a) rotor wake and (b) surface pressures



(a)

(b)

Figure 8. RotCFD predictions of TOW large manned vehicle in transition



(a)

(b)

Figure 9. RTOW forward flight cruise: (a) planform view and (b) orthogonal view

A manned TOW vehicle for commercial transport of passengers would by necessity be a very large aircraft so as to provide adequate cabin room for passengers in the interior of the flying wing cross-section. Unconventional passenger seating and cabin layouts might reduce the interior volume somewhat, but only to a limited extent. On the other hand, a TOW UAV configuration could be of much more modest dimensions, as it would not be significantly constrained by interior volume considerations. It would also be particularly amenable to use electric propulsion for such a vehicle.

Simplified aerodynamics models were also developed for both an isolated, short aspect-ratio wing at range of oblique sweep angles as well as the same wing with a tractor- and pusher- proprotor (as necessitated by the overall vehicle concept to avoid the rotor tip-path planes intersecting the wing when the wing is at an oblique swept angle). The wing aspect ratio is 3.5; the airfoil is a NACA 0024; the wing angle-of-attack is 4 Deg.; the wing tips are square/blunt-edged; LCTR2 rotors are modeled; the freestream velocity is 500 ft/s. Figure 10 presents a set of wing upper-surface pressure predictions of the isolated wing, for 10<λ<50 Deg. Figure 11 presents a similar set of wing upper-surface pressure predictions for the combined wing/rotor system, for 0<λ<30 Deg.

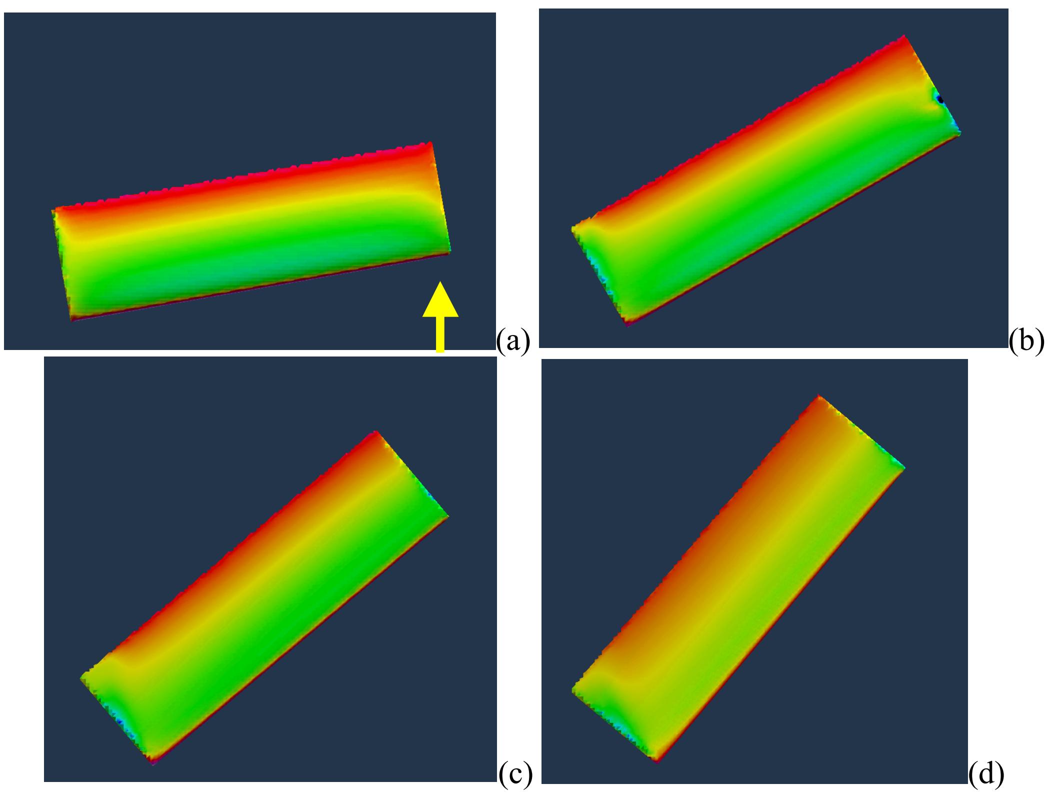
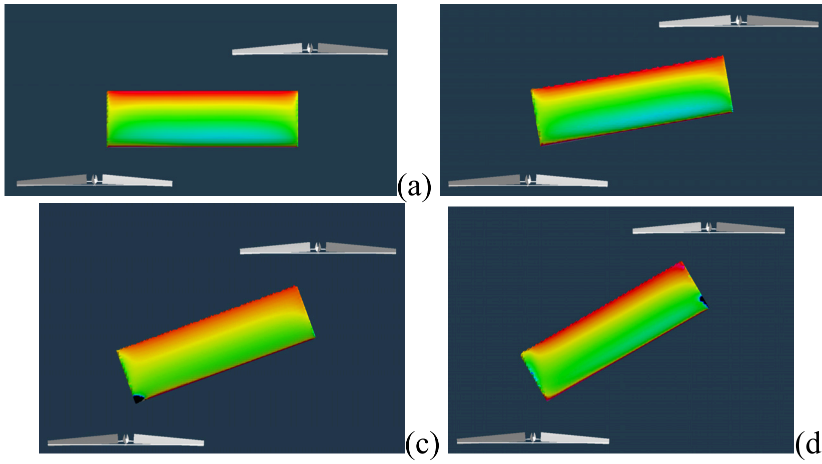


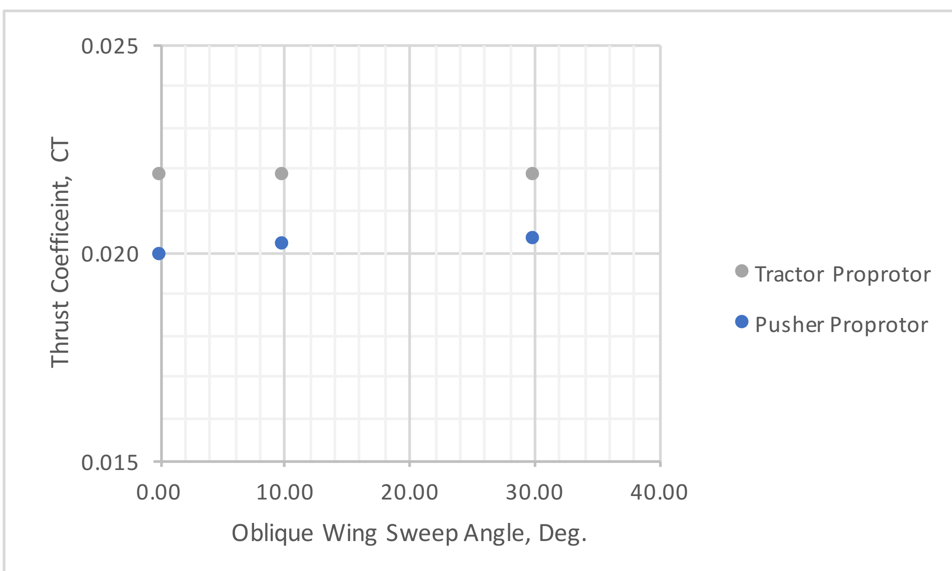
Figure 10. Upper-surface pressure predictions of the isolated wing: (a) λ=10 Deg.; (b) 30 Deg.; (c) 40 Deg.; (d) 50 Deg.



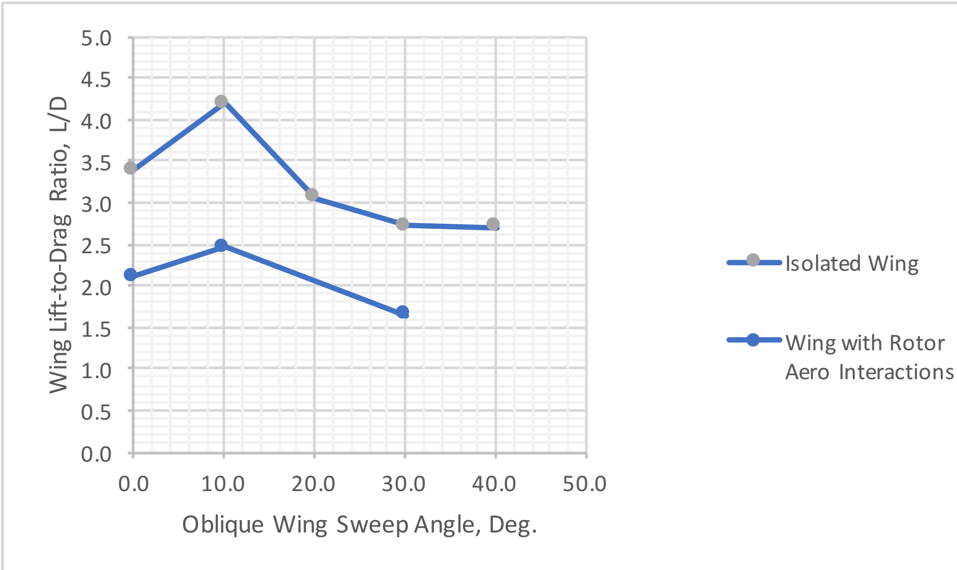
(a) (b) (c) (d)

Figure 11. Upper-surface pressure predictions for the combined wing/rotor system in cruise: (a) λ=0 Deg.; (b) 10 Deg.; (c) 20 Deg.; (d) 30 Deg.

Figure 12a-b presents the predicted results from the simplified cruise forward-flight aerodynamics model of a TOW vehicle. Figure 12a-b shows the influence of the wing oblique sweep angle on the wing L/D and on the tractor- and pusher- proprotor thrust coefficients.



(a)



(b)

Figure 12. Influence of the wing oblique sweep angle on cruise L/D

Flex

The underlying idea behind the Flex vehicle to migrate from previously proposed quad tiltrotor or quad tiltwing concepts with homogeneous or identical proprotors/propellers and, instead, consider a four-rotor-system (or potentially more) vehicle that employs heterogeneous rotors/proprotors/propellers that are tailored, in sets, to provide near-optimal performance at discrete operating conditions. The non-optimal rotor systems would be "throttled back" to some relatively benign/nonessential minimum-power/drag "rest state" when not critical to a particular operating condition/flight regime. Two configurations (Type-A and Type-B) are explicitly proposed in this paper, but alternative configurations could be readily defined – particularly if the vehicle was designed to carry more than four rotors.

The Flex Type-A configuration (Fig. 13) was provided as an illustration of an advanced vertical lift aerial vehicle in Ref. 11. It employs a pair of low-disk-load tractor-proprotors (primarily lifting-rotors for hover) and a pair of high-disk-load pusher proprotors (for efficient high-speed cruise propulsion). Both pairs of proprotors tilt.

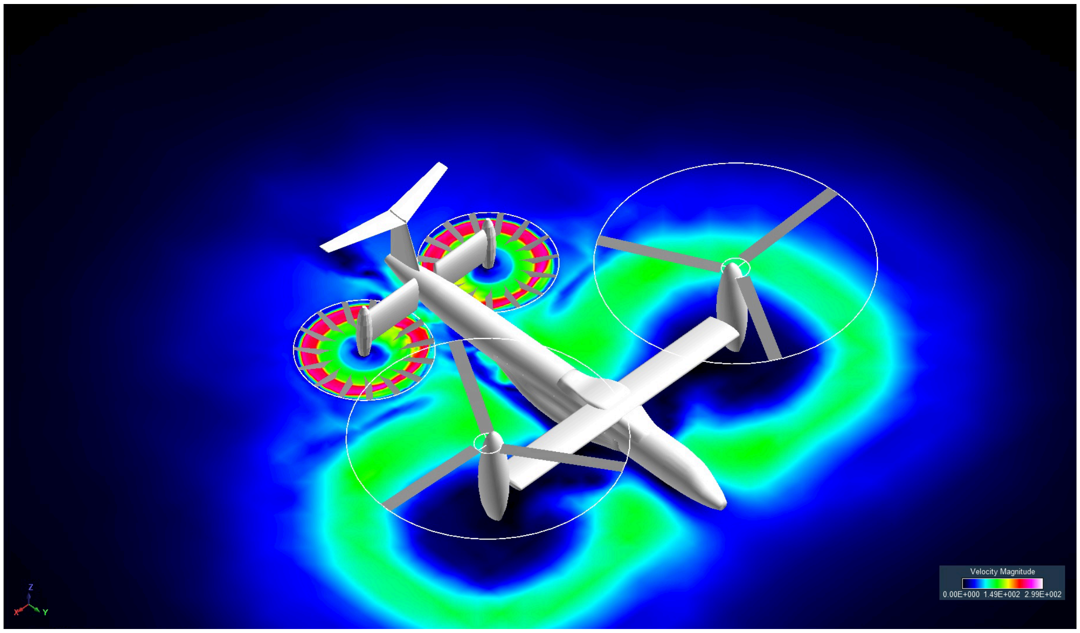


Figure 13. Flex Type-A vehicle

The Flex Type-B configuration (Fig. 14) notionally employs two pairs of proprotors, but instead of Type-A's one pair of pusher- and one pair of tractor-proprotors, both the lifting-rotors and the high-speed propulsors are tilting tractor-proprotors. Additionally, a canard (versus conventional tail-surfaces) is added to the concept so as improve the vehicle transition characteristics.

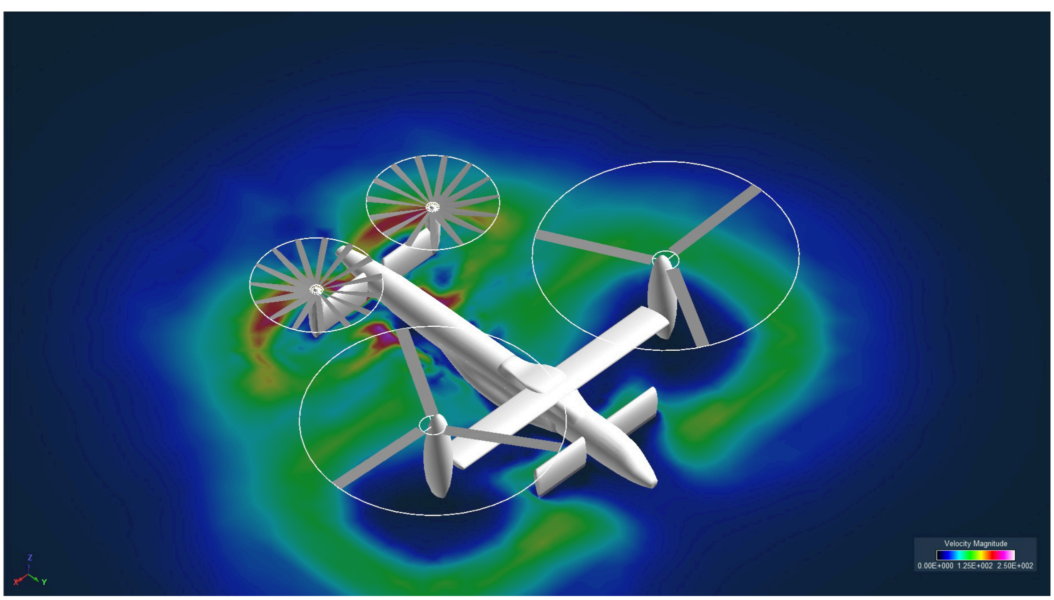


Figure 14. Flex Type-B vehicle

A key aspect of the FLEX configuration (in common for both Type-A and -B) is the lifting-rotors need to be untwisted (zero effective twist rate) – and possibly using symmetrical airfoils. This will slightly degrade the rotor performance for the lifting-rotors in hover. Figure 15 captures this reduction in the lifting-rotors' hover performance. The net increase in required torque coefficient for the untwisted rotor is most notable at higher thrust coefficient; for moderate thrust coefficients, though, the adverse impact of using untwisted rotors is modest.

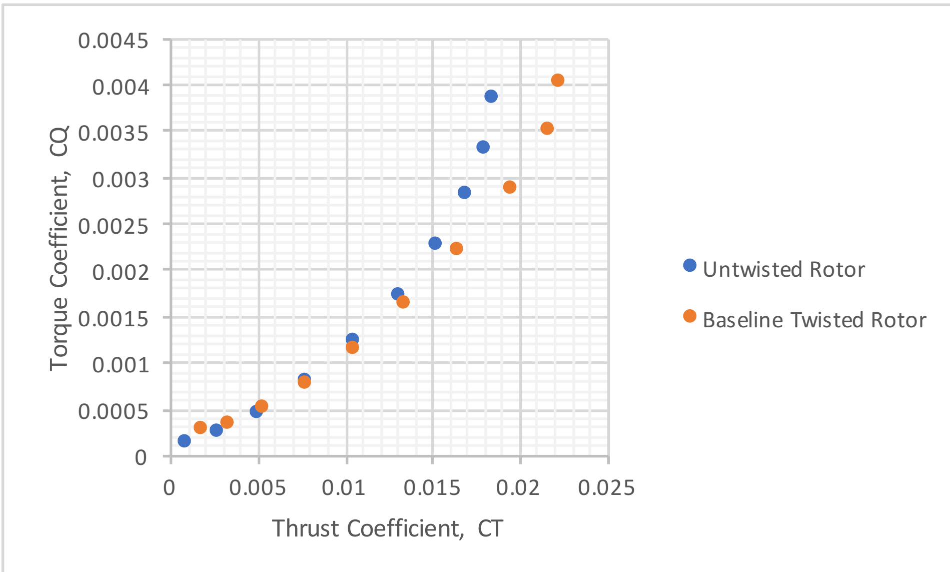


Figure 15. FLEX isolated "lifting rotor" hover performance

The relative proportion of the lifting-rotors' contribution (versus that of the cruise-optimized "propulsor" rotors/propellers) to the forward-flight propulsive force to maximize overall cruise efficiency and speed capability is an open question. Figure 16 presents results for the extreme operating condition of the "lifting rotors" trimmed to rotor collectives where the rotors providing zero thrust and therefore in the minimum delta power condition for these rotors when in high-speed cruise. Figure 17 provides estimates of the incremental effective-drag-to-lift ratio of these rotors spinning with zero thrust. In actuality, FLEX rotors would be trimmed to some intermediate thrust condition/contribution; e.g the forward rotor pair might provide ten-percent of the total propulsive thrust in high-speed cruise with the remaining ninety-percent coming from the aft pair of propulsor rotors.

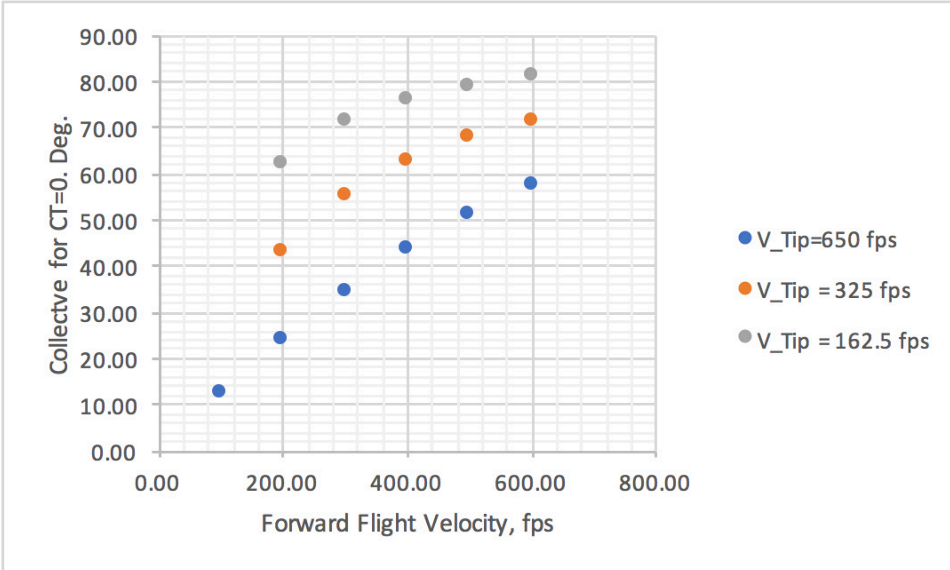


Figure 16. FLEX "lifting-rotor" zero-thrust collective trim condition for high-speed forward-flight

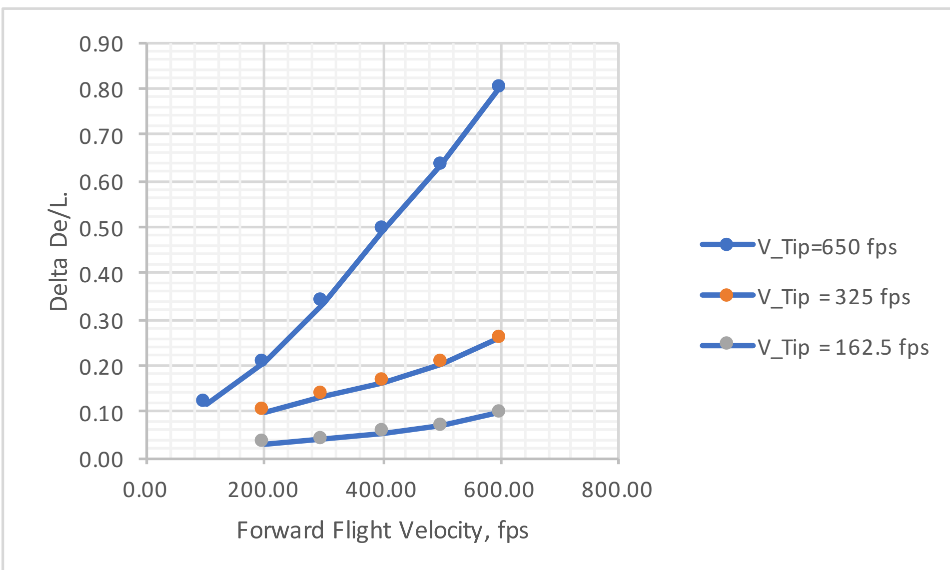


Figure 17. FLEX "lifting-rotor" delta-De/L effect on vehicle forward-flight performance as a consequence of the lifting-rotors being trimmed in the zero-thrust state

FLEX vehicles at very high speeds could notionally be configured into or operated at three or four lifting-rotor states: (1) blades stopped, folded, and stowed into a set of trailed proprotor blades (classic high-speed foldable/stowable tiltrotor configuration); (2) slowed and trimmed to low or zero thrust (current approach examined in this paper); (3) rotors stopped and weather-vanned; (4) rotors stopped and blades folded in-(disk-)plane into stationary, but lift-carrying, auxiliary wings.

Twin (Hull)

During the 1970s and 80's twin-hull fixed-wing aircraft were proposed as a potentially more fuel-efficient configuration than the single conventional tube-and-wing configuration. Additionally, in the mid- to late-1980's various joined-wing tiltrotor aircraft configurations were proposed to reduce overall wing thickness ratios while maintaining or improving whirl-flutter margins. Vehicle configurations are proposed in this paper that reflect a synthesis of these previously proposed concepts. This general configuration was also previously proposed in the 2000's for small rotary-wing UAVS (Ref. 9); the concept is proposed in this paper as being scalable from small UAVs to large manned aircraft. Two different configurations, Type-A (Fig. 18) and Type-B (Fig. 19), are proposed below. These are not exhaustive configurations as hybrid schemes might be proposed in which the forward proprotor might be a single rotor with the aft proprotors being coaxial; or, two sets of forward and aft coaxial proprotors might be proposed wherein the upper rotor for each set is larger in diameter than the lower rotor in each set. Further, both Type-A and -B configurations are presented as tandem-wing vehicles for the fixed-wing lift surfaces; it can be readily conceived that alternate wing planform geometries could be crafted, particularly as to minimize overall interactional aerodynamics effects of the lifting surfaces as well as to improve aggregate wing-assembly stiffness. Integration of wings and nacelles/pylons must to be accomplished such that spar continuity/integrity is preserved mid-span of the wings so as to ensure, in part, that mid-span-mounted rotors provide better wing loading than tip-mounted rotors. Additionally, it is assumed that the necessary turboshaft engines will not tilt and will be suspended from the wing or from engine mounts on the side of the vehicle hulls or their empennage. Cross-shafting will be an important consideration in the successful implementation of this set of concepts. This might also be another strong candidate to consider the relative trades of drive train mechanical complexity versus adoption of elements of hybrid electric propulsion.

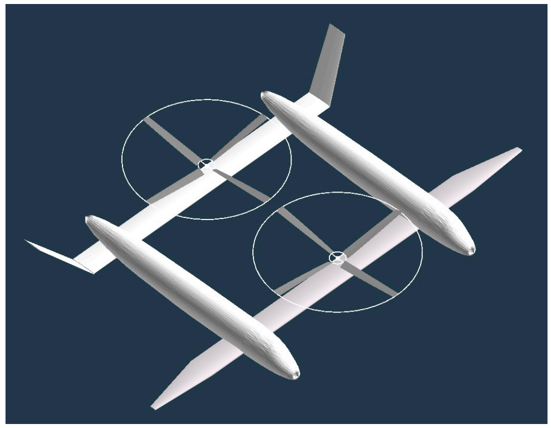


Figure 18. Twin Hull Type-A: single tiltrotor proprotor at mid-span of wings

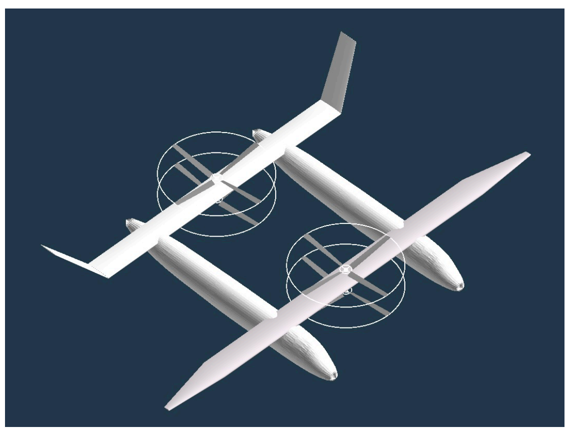


Figure 19. Twin Hull Type-B: coaxial tiltrotor proprotors at mid-span of wings

A simplified aerodynamics model was also developed for the Twin Hull vehicle configuration so as to parametrically investigate the influence of rotor spacing between the fuselage hulls on rotor thrust and vehicle download. A simple set of large fineness-ratio constant diameter (d_c=8 ft or d_c/R=0.25) cylinders were used to represent the fuselage hulls in this simplified aerodynamics model. This simplified aerodynamics model is for the Twin Hull Type-A configuration. Figure 20a-d is a set of predicted rotor wake velocity magnitude isosurfaces for a range of hull-to-hull spacing, $2.09 \leq b/R \leq 2.95$. Figure 21a-d is a corresponding set of predicted wing upper-surface pressures.

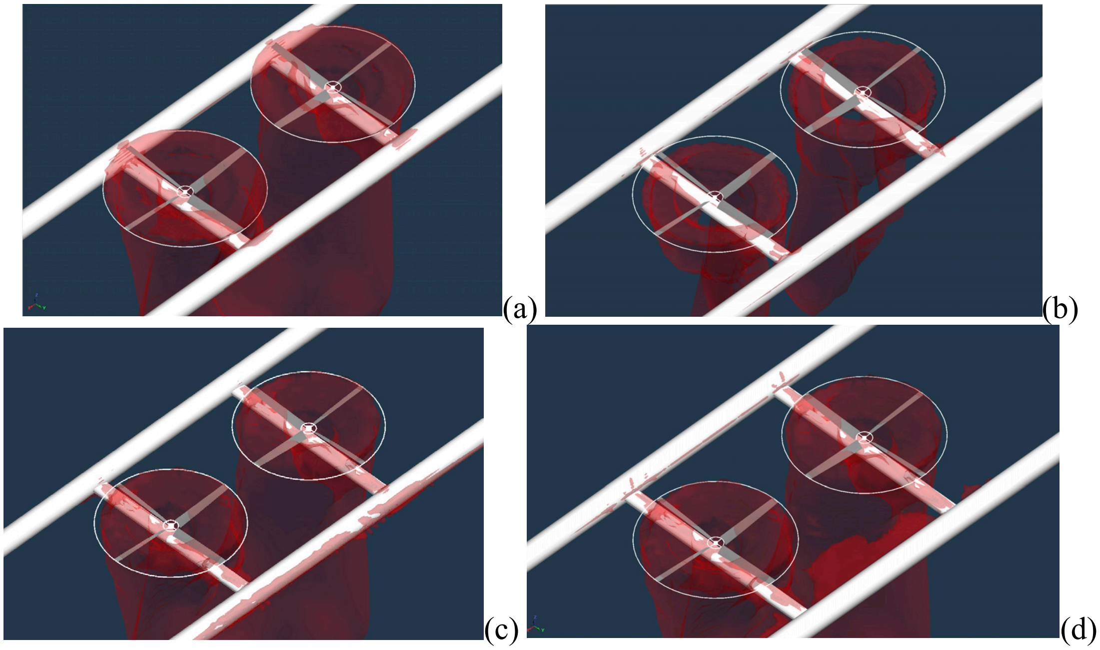


Figure 20. Rotor wake velocity magnitude isosurfaces: (a) b/R=2.09; (b) 2.46; (c) 2.71; (d) b/R=2.95

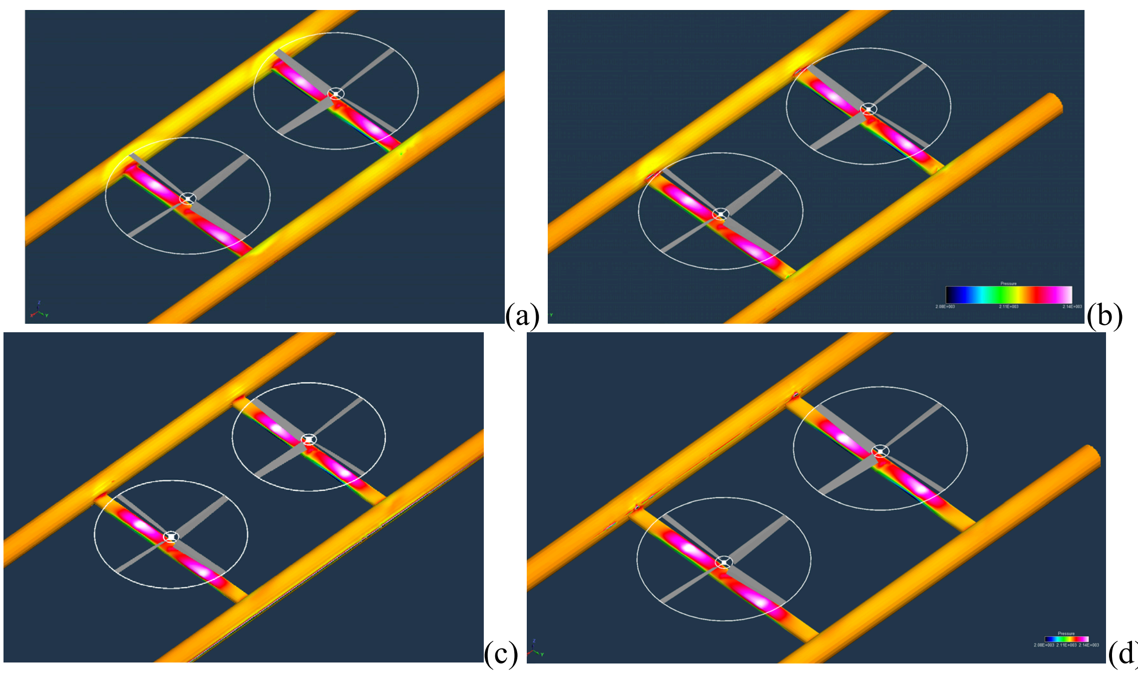


Figure 21. Wing upper-surface pressures: (a) b/R=2.09; (b) 2.46; (c) 2.71; (d) b/R=2.95

Figure 22 examines the influence of hull-to-hull spacing on the mean thrust coefficient (average between the two proprotors) and the total download to total thrust ratio during hover. The only significant conclusion from simplified aerodynamics model results is that hull-to-hull spacing does not appear to have to be significantly greater than b/R=2 to minimize vehicle download or to maximize the total thrust of the vehicle. From a design perspective, this initial result is a positive outcome, as larger span wings do not have to be incorporated into the vehicle design to minimize hover rotor/wing aerodynamic interactions. Finally, note that the wing download for the mid-span-mounted proprotors is nearly double that of comparable vehicle configurations wing-tip-mounted proprotors; this is not unexpected.

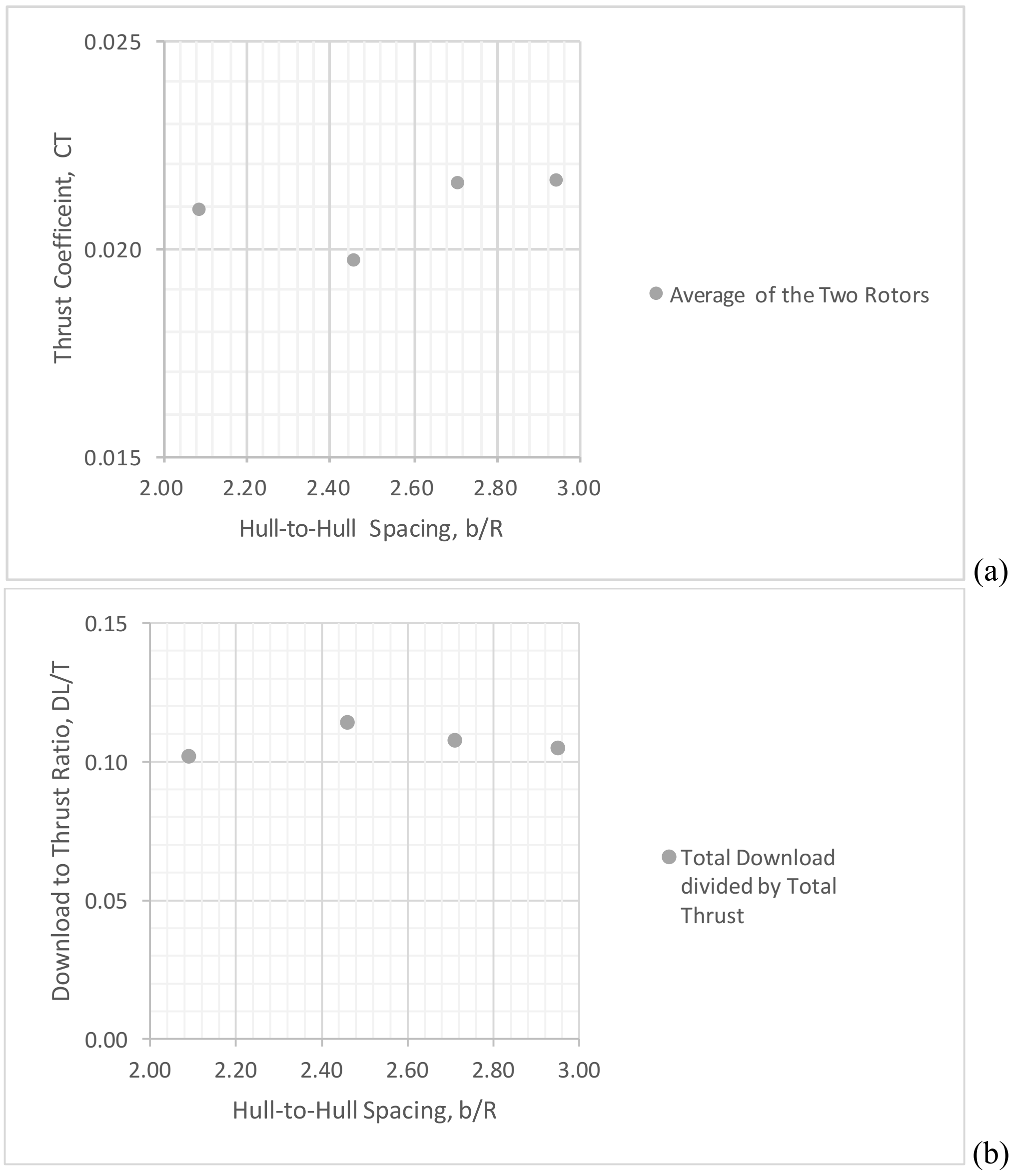
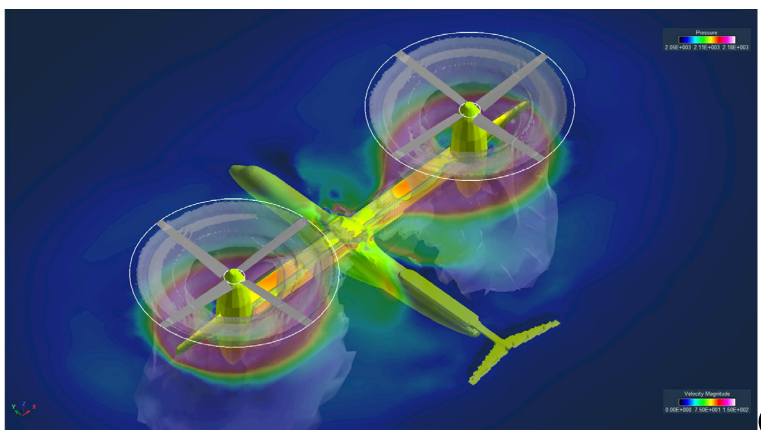


Figure 22. Influence of rotor spacing between the fuselage hulls on (a) rotor hover thrust and (b) vehicle download

Sweep

This concept would seek to explore whether or not extreme variable-geometry or morphing planform changes could have a substantial effort on vehicle aerodynamic performance between its hover and cruise states. Further, it explores if such extreme geometry changes could yield radically different dynamic stability (specifically whirl-flutter) behavior than the much more modest and fixed wing sweep angles used on current generation conventional tiltrotor aircraft. At this point, it is merely conjecture that variable sweep wings that could be forward-swept up to forty-five degrees or so might have a beneficial influence on whirl flutter, but it would be worthwhile from a design trade study perspective to explore this topic. Achieving this high degree of variable wing sweep would require some innovative thinking as to the mechanisms to actuate the wing sweep as well as means to counter large vehicle center-of-gravity (C.G.) shifts due to such large wing sweep changes in flight. Two notional approaches, Type-A and -B configurations, are presented. The Type-A configuration (Fig. 23) counterbalances the C.G. shift with an extendible tailboom. The Type-B configuration (Fig. 24-25) assumes that the whole wing assembly shifts longitudinally in opposition to the forward and backward sweeping of the wingtips.


(a)


(b)

Figure 23. Sweep Type-A Notional Vehicle: (a) orthogonal and (b) planform views

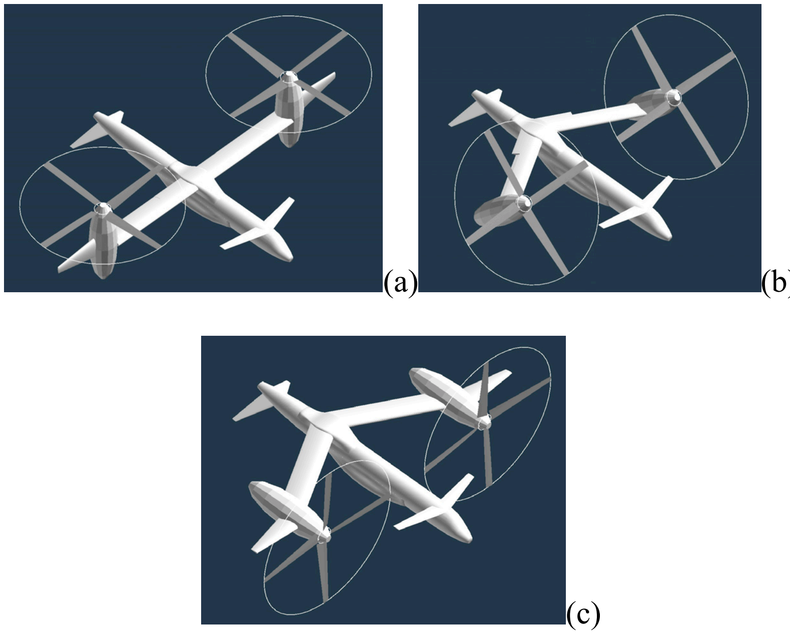


Figure 24. Sweep Type-B vehicle in (a) hover, (b) transition, and (c) cruise

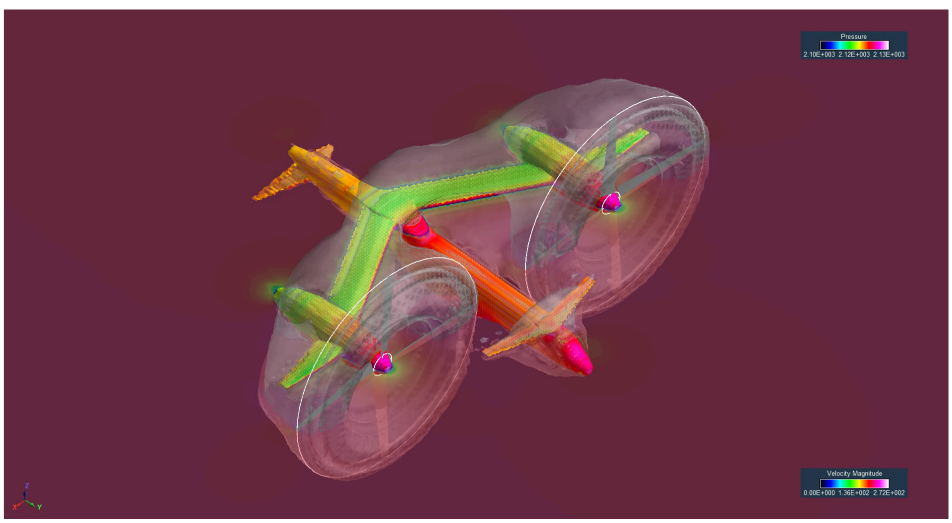


Figure 25. RotCFD forward flight prediction of Type-B variable sweep vehicle

A simplified aerodynamics model was also developed for the variable sweep vehicle configurations so as to parametrically investigate the influence of wing sweep on rotor thrust and vehicle download in hover. A large fineness-ratio constant diameter (d_c=8 ft or d_c/R=0.25) cylinder was used to represent the fuselage in this simplified aerodynamics model.

Figure 26a-d is a set of predicted wing upper-surface pressures for the wing sweep range of -45≤ λ ≤0.

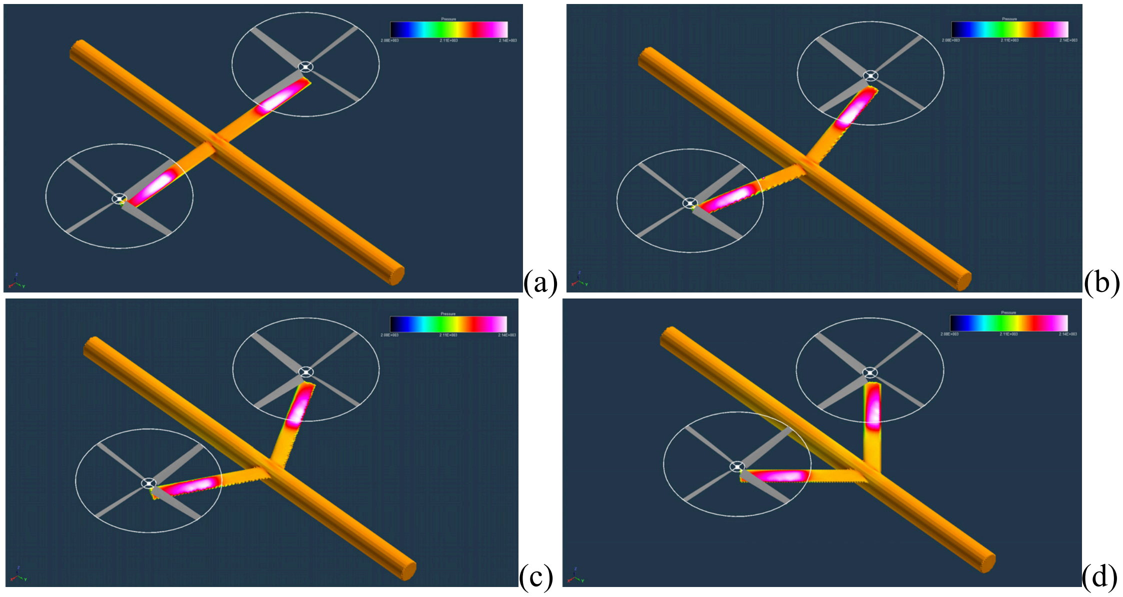
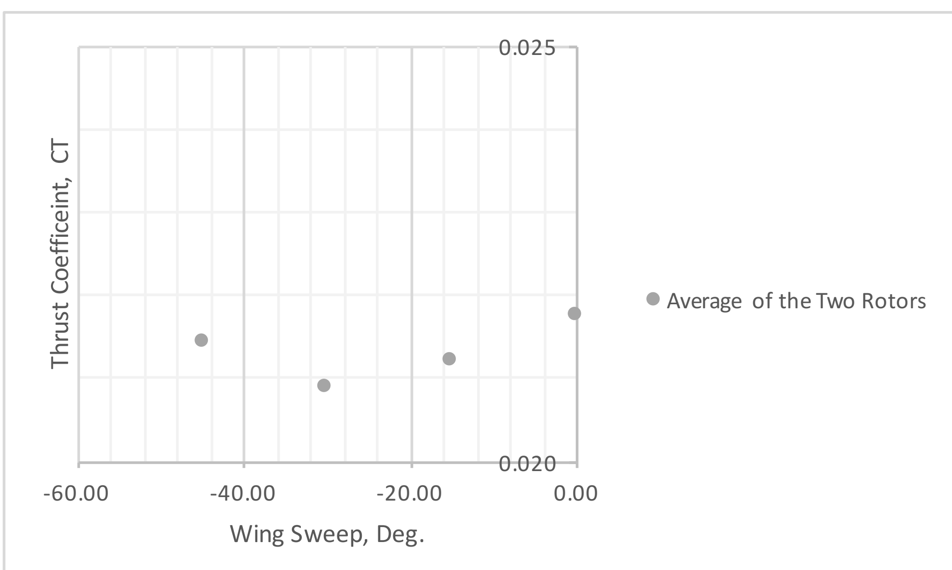
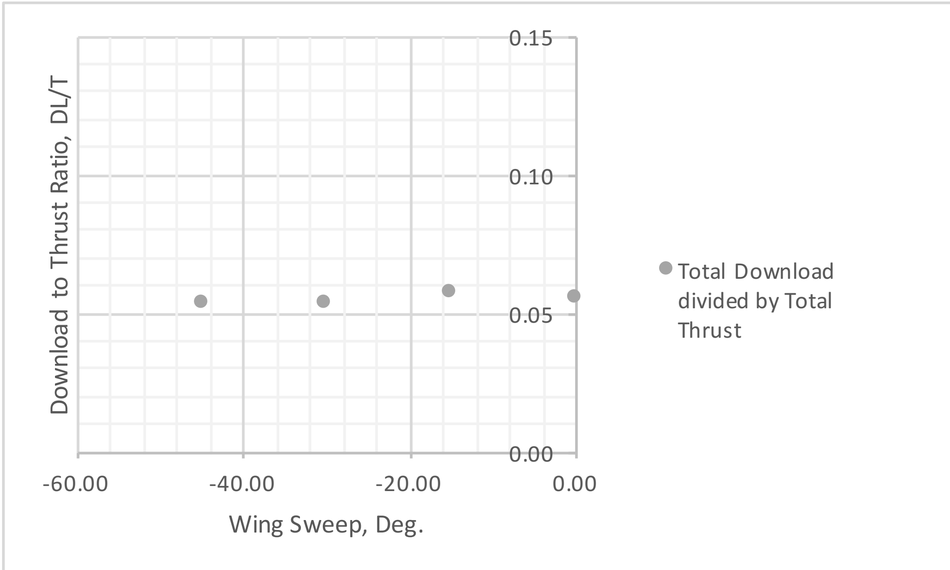


Figure 26. Wing upper-surface pressures for hover with different wing sweep angles: (a) λ = 0 Deg.; (b) -15 Deg.; (c) -30 Deg.; (d) λ = -45 Deg.

Figure 27 examines the influence of wing sweep on the mean thrust coefficient (average between the two proprotors) and the total download to total thrust ratio during hover using the simplified aerodynamics model. Wing sweep seems to have only a small effect on rotor thrust and download given these predictions.



(a)



(b)

Figure 27. Influence of wing sweep on (a) rotor hover thrust and (b) vehicle download

PIVOT

In the spirit of exploring the design boundaries of what plausibly constitutes a "tiltrotor aircraft", a final "tiltrotor" concept is presented: the PIVOT vehicle. This vehicle would be intended primarily as a UAV or a small manned aircraft. Its overall mission concept is consistent with a future world state in which global urbanization has reached the point that personal/public aerial transport within and around metroplexes – as well as large numbers of small VTOL/fixed-wing UAVs swarm through and about cityscapes – is the norm.

The PIVOT concept is intentionally very speculative in nature. This concept not only tilts its proprotors, but pivots/rolls as a whole; additionally, the cockpit/forward fuselage mechanically pivots in opposition to the overall wing/vehicle roll movement. There are two different types of PIVOT vehicle proposed depending on how the vehicle is intended to takeoff and land: 1. it is assumed that dedicated "skybridges" can be added to urban buildings such that the PIVOT could "dock" tailboom first into the façade of the building/skybridge (Fig. 28-29); 2. An alternate, more conventional, landing gear and tarmac arrangement is assumed (Fig. 30). The vehicle once achieving takeoff/hover flies in a similar manner as a coaxial helicopter for hover and low-speed flight. Because the vehicle center-of-gravity is vertically mid-span between the two rotors, the vehicle would have to have a very sophisticated stability augmentation system to avoid uncontrolled roll, pitch, and yaw motions. As forward speed is built up, through a combination of rotor shaft tilting in the roll direction or lateral cyclic pitch inputs, the vehicle begins to roll while at the same time increasing the wing angle-of-attack. Note that during this slow roll-over process, the vehicle sideslip is minimized or counterbalanced by the rotor thrust-vector resultant lateral inplane forces. At higher speeds and larger vehicle roll angles, while still in helicopter-mode, the proprotors begin to be tilted fore and aft (depending on whether the rotor was the upper or lower rotor in hover) and the conversion process begins. Finally, the roll maneuver is completed, the proprotor tilt transition/conversion is complete (Fig. 29). The vehicle wings are horizontal/level and the vehicle is in high-speed cruise airplane-mode (except, unlike conventional tiltrotor aircraft, one proprotor is a tractor and the other is a pusher proprotor).

Given the many degrees of freedom of the proprotor/nacelle tilt mechanisms, the inherent complexity of drive train components, and the overall complexity of flight modes, the PIVOT concept could likely be limited to hybrid electric propulsion.

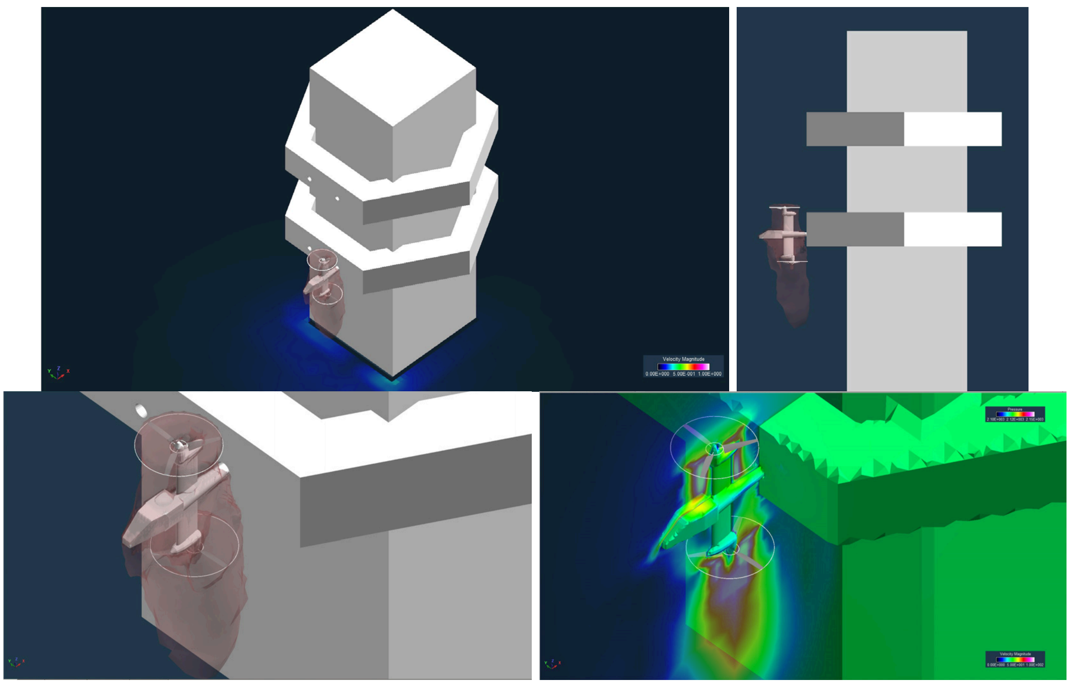


Figure 28. Urban canyon "aerie" perching on building

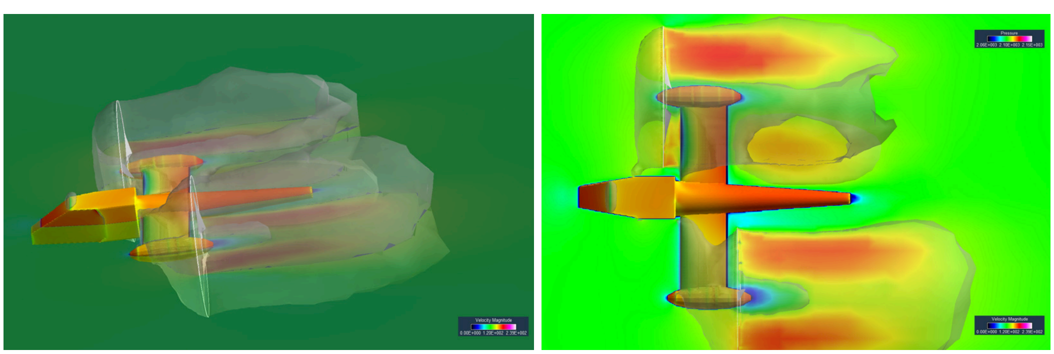


Figure 29. PIVOT in forward-flight cruise

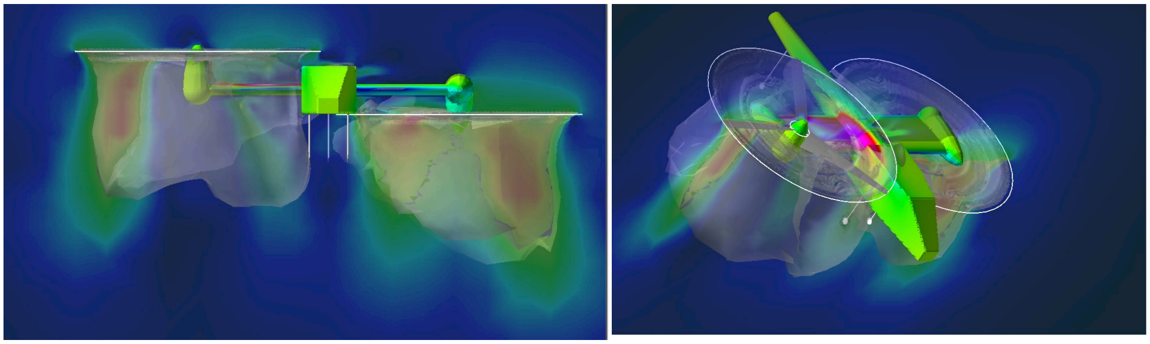


Figure 30. Takeoff from ground with (alternate) landing-gear (note additional degree of freedom with respect to proprotor/nacelle tilt)

Figures 31 and 32 are CFD static-thrust/hover predictions of a simplified aerodynamics model of PIVOT, wherein only a wing and two rotors (which roll relative to wing and not just tilt). Figure 31 is a set of velocity magnitude contour flow field predictions and Fig. 32 is a set of (lower) body surface pressures.

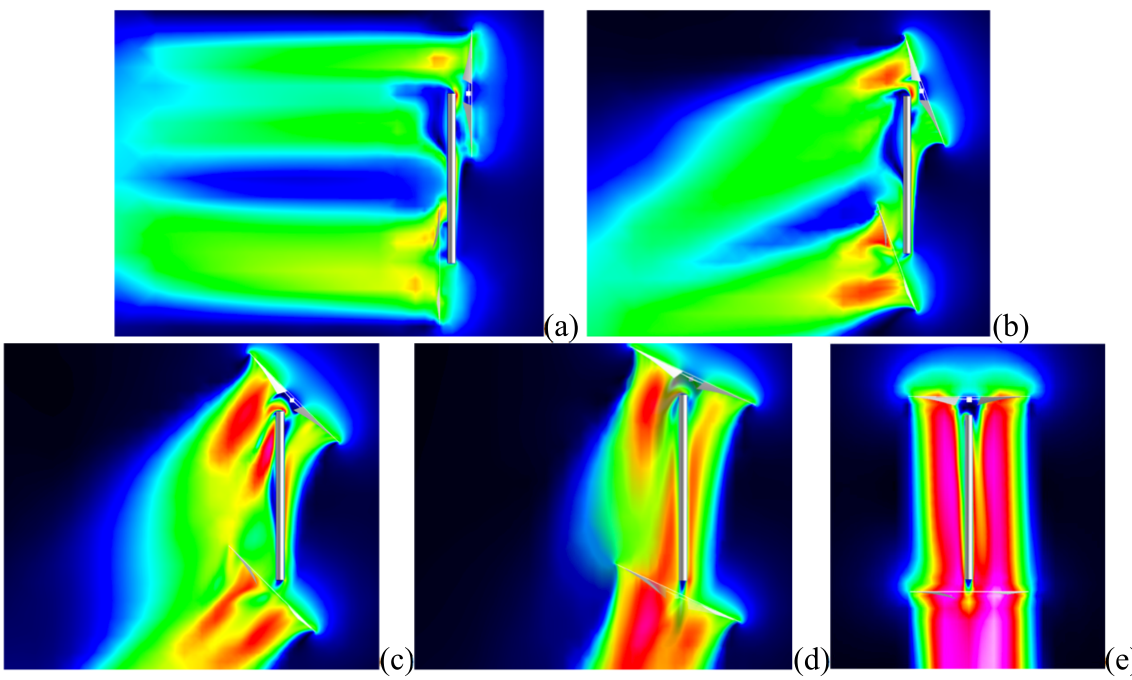
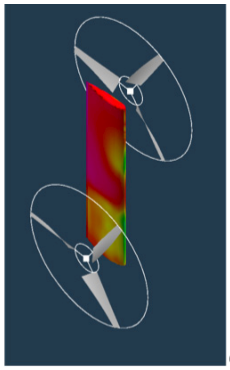
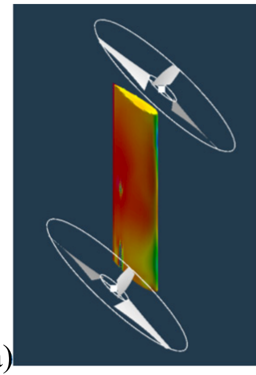


Figure 31. Velocity magnitude flow field predictions for simplified PIVOT model: (a) roll angle = 0 Deg.; (b) 20 Deg.; (c) 45 Deg.; (d) 65 Deg.; (e) roll angle = 90 Deg.


(a)


(b)

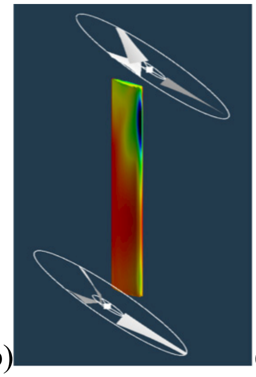
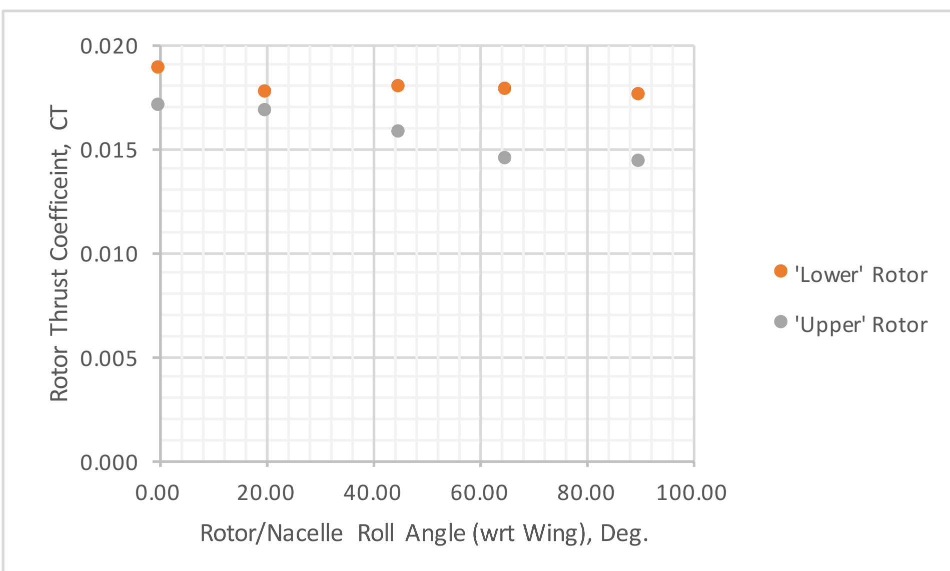
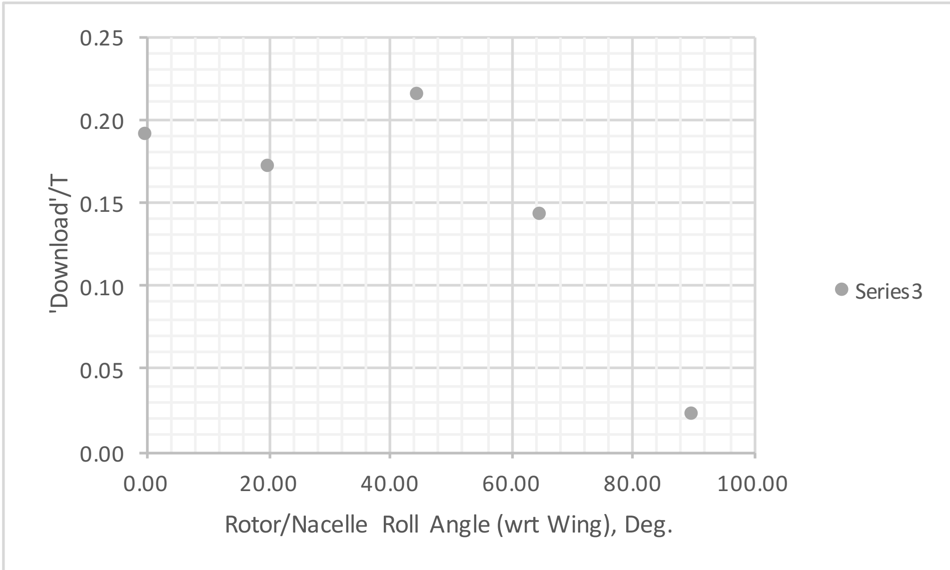

(c)

Figure 32. (Lower) body surface pressures for simplified PIVOT model: (a) roll angle = 0 Deg., (b) roll=20 Deg., and (c) roll=45 Deg.

The simplified PIVOT aerodynamics model was used to examine the influence of rotor roll angle (ninety deg. roll-angle when the rotor axes are parallel to the constant-chord wing leading-edge) on rotor static-thrust/hover thrust and wing download. These results are presented in Fig. 33a-b. The rotor thrust coefficient decreases with increasing rotor roll angle with respect to the wing because the wing effective "ground effect" diminishes with roll angle. Correspondingly, the wing download decreases with increasing rotor roll angle with respect to the wing because the projected wing area exposed to the rotors' wakes is reduced as roll angle is increased.



(a)



(b)

Figure 33. Influence of rotor roll angle on: (a) 'upper' and 'lower' rotor thrust and (b) wing download-to-total-thrust ratio

An Example of Something Like, But Not Quite, a Tiltrotor

A key condition for a tiltrotor aircraft is the requirement that the rotors tilt nearly ninety degrees in going from hover to cruise operation. A notional vehicle that meets many of the relaxed preconceptions about tiltrotor aircraft but does not meet the final airplane-mode cruise condition/requirement is discussed next.

The following notional vehicle design (Fig. 34), the Ames Urban Air Taxi (AUAT) is an intentional effort to combine the familiar with the exotic with respect to prior-art as to urban air mobility and "drone" configurations. This is also an attempt to build on several Ames capabilities: "Hopper" work; advanced vertical lift and UAV configuration conceptual design work; historical tiltrotor, oblique- and X-wing research; intelligent systems work; and expansion of UTM/ATM work. The rotors, though, do not tilt more than 30 degrees and, therefore, this aircraft is not part of the tiltrotor design trade space outlined in this paper. It is instead a homogeneous multirotor configuration in the context of Ref. 12.

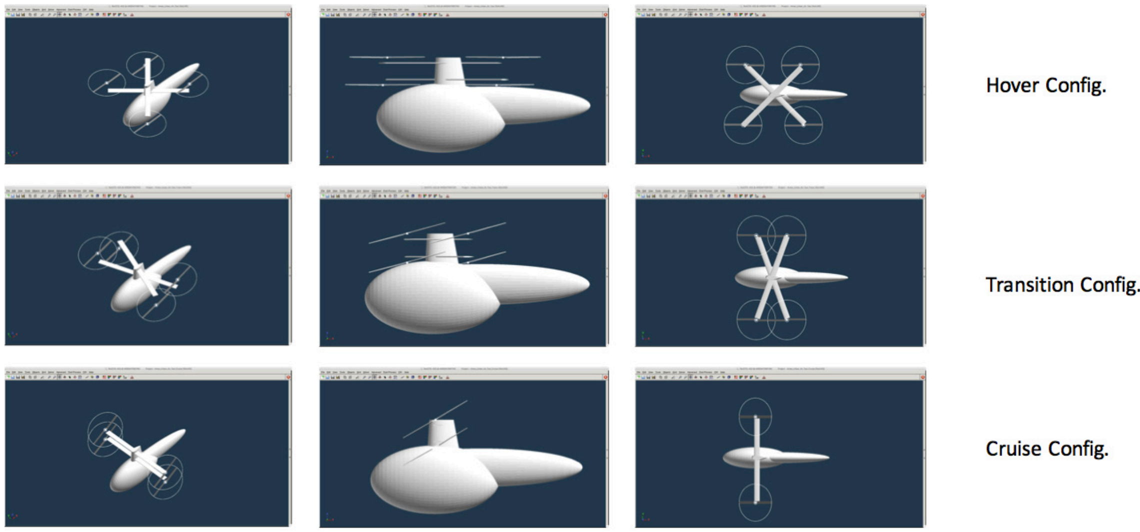


Figure 34. Ames Urban Air Taxi: not quite a tiltrotor aircraft

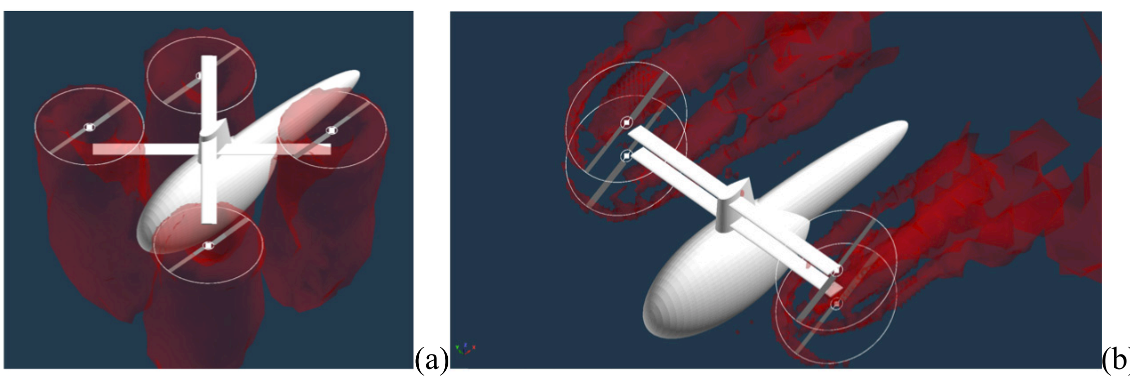


Figure 35. Initial CFD work on AUAT: (a) rotor wakes (velocity magnitude isosurface) in hover and (b) cruise (nondim. Q-criterion isosurface)

Future Work

This paper presents a high-level discussion of the potential greater design space of alternate tiltrotor aircraft configurations. It only presents notional concepts to merely illustrate the potentiality of radically reexamining the tiltrotor aircraft. Its goal is to present a vision of what might be possible in terms of future generations of tiltrotor aircraft and begin to give some inkling as to the new/emerging technologies to make these, and similar aircraft, concepts potentially feasible one day. A large body of work will be necessary to achieve that goal. Such work includes, in the near term, to go beyond the many design conjectures outlined in this initial paper to more solid foundational understanding of what is possible/plausible in terms of expectations for such vehicles (Fig. 36).

Figure 36. Test model development and experimental work in-progress

Acknowledgments

The author would like to acknowledge C.W. Acree, W. Johnson, and G.K. Yamauchi, all of NASA Ames Research Center, as to their extensive body of past work towards the development of NASA advanced rotorcraft reference designs, with particular recognition directed towards their efforts on the development of the Large Civil Tilt Rotor LCTR2 reference design.

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