Urban Aerial Mobility Networks using Amphibious Vertical Takeoff and Landing Vehicles

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This study considers novel urban aerial mobility (UAM) networks that address some of the key operator and community acceptance challenges inherent in proposed UAM operations. This paper seeks to examine three possible approaches to improve operator and community acceptance – specifically targeting cost, safety, and noise. First, the conceptual design space will be examined for VTOL amphibious vehicle technologies, including the implications of on-water versus in-flight time/speed. Second, the implications of minimizing community over-flights by flying over-water will be examined. Third, the implications of the partial use of on-water, or near-shore/littoral, vertiports on UAM network performance will be examined. This study considers an alternate design trade space for urban aerial mobility systems. A large number of cities in the United States are located near or surround large bodies of water. Many of these same cities are considered to be candidates for metropolitan aerial transportation systems so as to moderate the impact of urban ground-transportation congestion. This paper will expand discussion and study of notional amphibious VTOL vehicles. There is nothing particularly new with regards to helicopters with amphibious takeoff and landing capability. For example, light rotorcraft have been outfitted with pontoons since the 1950s. Larger utility helicopters – used for carrying offshore oil-rig crew – have been designed, with varying degrees of success, to emergency land in rough waters in case of onboard mechanical system failures. The unique difference for the proposed amphibious UAM vehicles, as compared to these earlier amphibious rotorcraft, is that water operation is the norm rather than the exception and that, further, the water-born operation (and design) of such vehicles can be optimized to yield significant economic and operational benefits over solely UAM land-based stations and operations. Various different amphibious UAM networks will be discussed. A first-order set of analyses – employing novel mission metrics – is presented in this paper that will examine the operational performance of these amphibious networks. In particular, amphibious operations might address critical safety and community acceptance issues. An examination of the aerodynamic and hydrodynamic characteristics of amphibious VTOL UAM vehicles will be presented in this paper. One possible conceptual design for an amphibious UAM vehicle is a hybrid synchropter/hydroplane vehicle. As interest in urban aerial mobility grows, it is worthwhile to consider whether or not amphibious vertical takeoff and landing vehicles can play an important role in providing such mobility.

NOMENCLATURE

AOA	=	Angle of attack, Deg.
CONOPS	=	Concept of operations
C	=	Circuituity, $C = (d_A - d_M)/d_M$
DNL	=	Day-night sound level, dB
d	=	Total distance traveled during mission, km (or nm)
d_A	=	Actual distance traveled, as used in the circuituity estimate, $d_A \equiv d$
d_M	=	Minimum, straight line, point-to-point distance that could ideally be traveled inflight

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d_{WT}	=	Distance traveled while on the water, km (or nm)
eVTOL	=	Electric (propulsion) vertical takeoff and landing aircraft
E	=	Mission energy required
E_F	=	Energy required if mission was completed with flight only
FOD	=	Foreign object debris
P_F	=	Power required during cruise while inflight
P_{WT}	=	Power required during cruise while on water
s	=	Relative community noise sensitivity of amphibious flights versus direct over-land flights, nondim.
S	=	Wetted surface area, ft^2
UAM	=	Urban air mobility; aka urban aerial mobility
VTOL	=	Vertical takeoff and landing aircraft
V, V_F	=	Vehicle inflight cruise speed, ft/s (or knots)
V_{WT}	=	Vehicle cruise velocity while on the water, ft/s (or knots)
β	=	Ratio of 'annoyed' community members, as per some DNL noise threshold, for amphibious flights versus solely over-land flights
ε	=	Weight equation interpolation metric, nondim.
φ	=	Mission performance metric wherein time versus energy savings can be assessed

INTRODUCTION

The Skimmer project was conceived as an exercise in considering an alternate design trade space for metropolitan aerial transportation systems. A large number of cities in the United States are located near or surround large bodies of water. Many of these same cities are considered to be candidates for metropolitan aerial transportation systems (Refs. 1-3) so as to moderate the impact of urban ground-transportation congestion. Though the bulk of the study in Ref. 1 (and, generally, throughout the whole of ongoing UAM research) assumed that the vertiport stations in the metropolitan aerial transportation systems, aka Hopper networks, see Refs. 1-3, were sited on city property on the land, a very brief discussion was given to the possibility of water/shore-based stations employing amphibious rotorcraft. This current work will expand discussion and study of the use of these notional amphibious rotorcraft "Skimmers." These vehicles and their associated water/shore-based vertiport networks will be partly discussed in the context of the littoral environs of Seattle, i.e. the large body of water known as the Puget Sound.

There is nothing particularly new with regards to helicopters with amphibious takeoff and landing capability. For example, a number of light rotorcraft have been outfitted with pontoons for since the 1950s. Larger utility helicopters – used for carrying offshore oil-rig crew – have been designed with varying degrees of success to emergency land in rough waters in case of helicopter onboard mechanical system failures. The unique difference for the proposed "skimmers" as compared to these earlier amphibious rotorcraft is that water operation is the norm rather than the exception and that, further, the water-born operation (and design) of such vehicles can be optimized to yield significant economic and operational benefits over solely UAM land-based stations and operations.

There is already a modest state-run ferry network in the Puget Sound. This is addition to private watercraft throughout the Sound servicing small communities on the shorelines of the Sound as well as the many small and large islands within its expanse. "Floating island" and shore-based vertiport stations can be expected to be co-located with the ferry stations and small and large marinas and piers located throughout the immediate littoral environs of Seattle and its neighboring communities.

Some representative notional amphibious vehicle networks are shown in Figs. 1-3. This would include a coastline following network, an offshore vertiport or transit station network, and a waterways crossing network. Other networks are viable as well. Additionally, another focus of this paper is the design considerations of the amphibious vehicles. In particular, a multi-modal amphibious vehicles that is hybrid synchropter and hydroplane, Figs. 4-5.

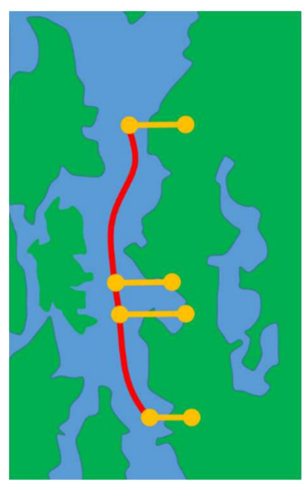


Figure 1. Skimmer Network 1 – Coastline Following

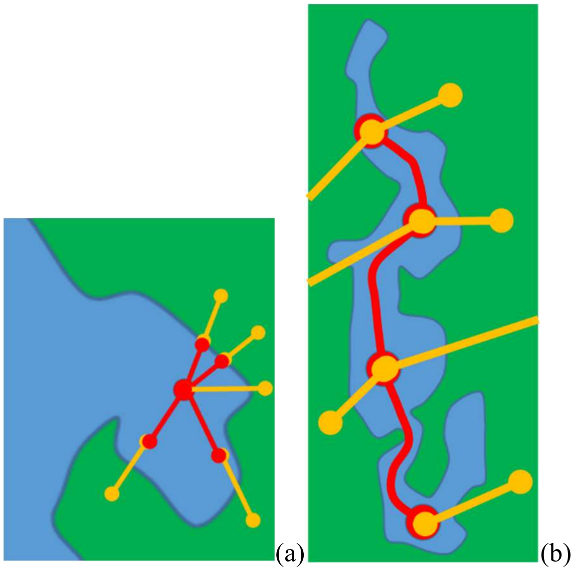


Figure 2. Network 2 – Offshore Vertiport/Waterway Transit Stations: (a) bay-centric and (b) lake-centric

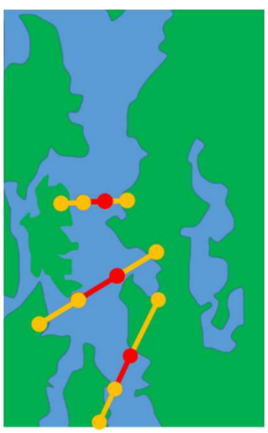


Figure 3. Network 3 – Waterway Crossings

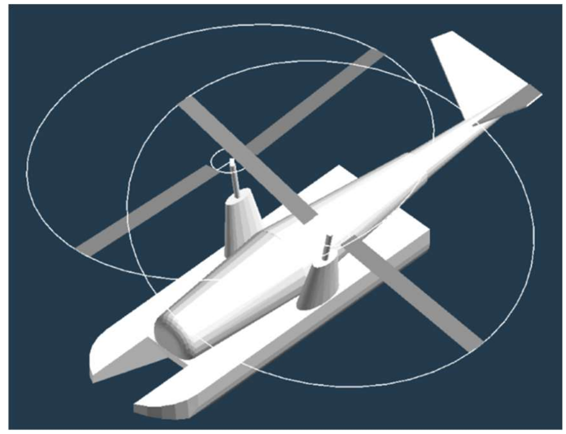


Figure 4. A notional Skimmer conceptual design

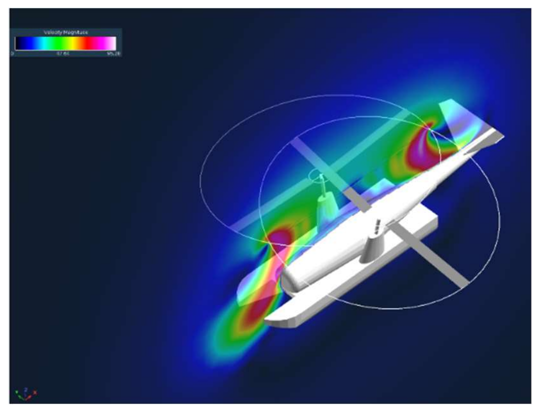
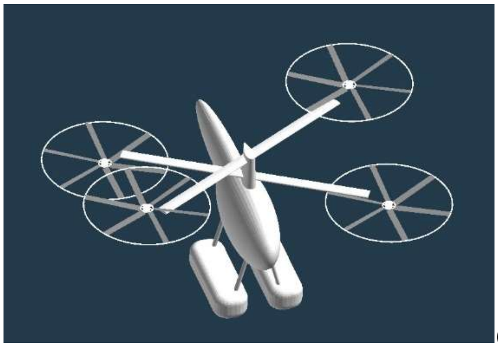


Figure 5. Skimmer: Amphibious ("synchropter" helicopter) rotorcraft

DESCRIPTION OF AN AMPHIBIOUS OR WATER-BASED AERIAL VEHICLE TRANSPORTATION SYSTEM

There is a large design trade space for amphibious UAM vehicles that can be considered by researchers and aircraft developers. This is just one potential emerging aviation market; others include the emerging markets of uninhabited aerial vehicles (e.g. Refs. 5-6). Some of these notional vehicles can be seen in Fig. 6a-e. Many other vehicle concepts could also be suggested.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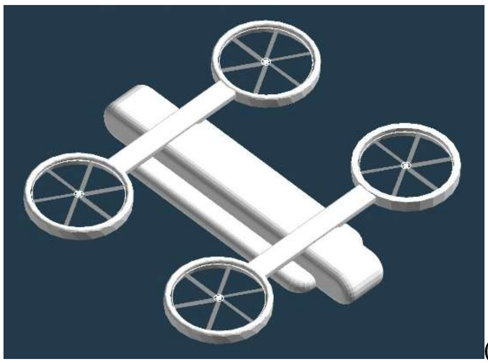
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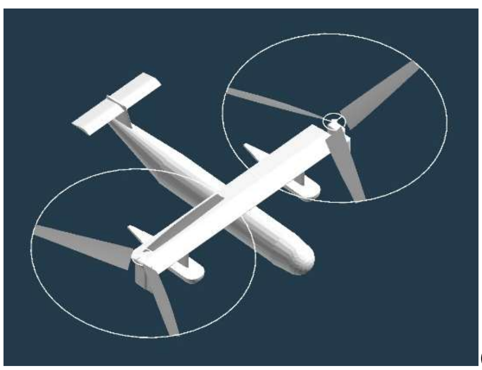
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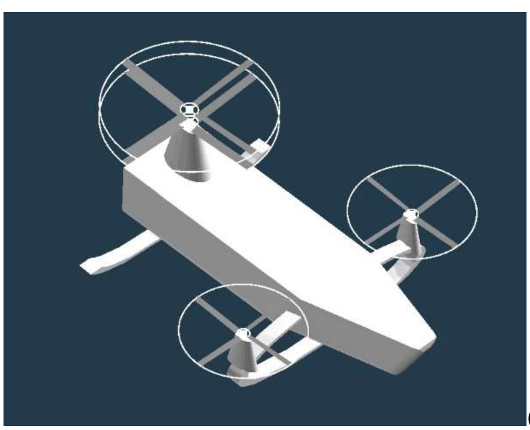

(d)

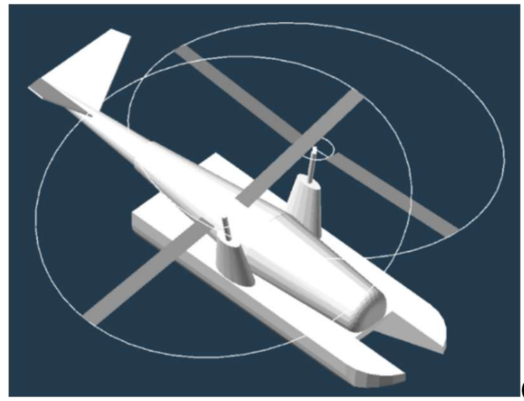
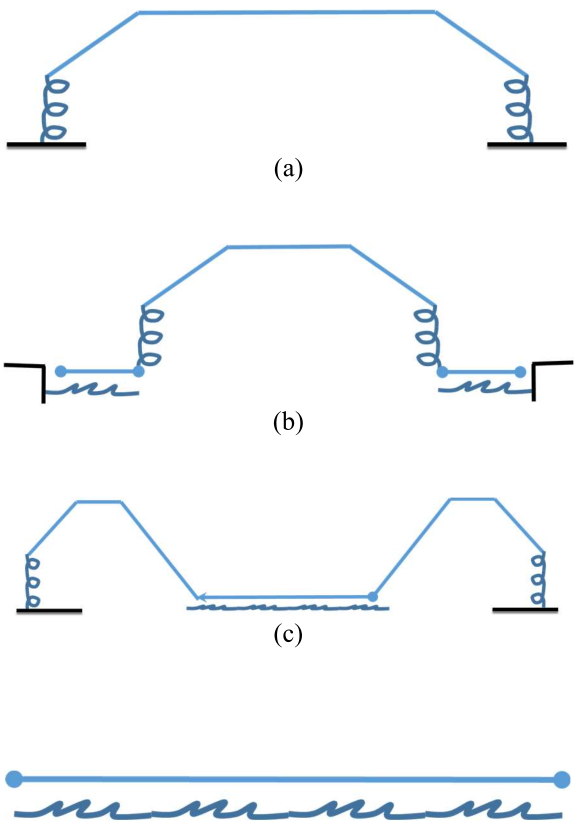

(e)

Figure 6. Design trade space for UAM vehicle/network operations over/on water: (a) vehicles that land or takeoff on piers, stationary water rigs, or "floating island" vertiports (Ref. 4); (b) vehicles that vertically land and takeoff on the water with pontoons, floats, or buoyant hulls; (c) vehicles that perform short runs of water taxiing or on-water forward acceleration/deceleration during takeoff and landing; (d) vehicles designed to have sustained periods of on-water cruise operation through hull buoyancy or hydroplaning; (e) hydroplane

Takeoff and landing (during both standard and emergency operations) will be require unique safety considerations for amphibious UAM vehicles. Water contamination and electrical shorting of electric propulsion systems, including large, high-power batteries, could potentially be a critical hazard. Additionally, FOD could also be a critical hazard during takeoff and landing on open water. If significant water taxiing or hydroplaning of the vehicle is also a key aspect of the vehicle design and CONOPS then FOD becomes even more of a crucial issue to consider. The likely existence of such debris, including logs, free-floating kelp, even marine animals and sea/water birds need to be factored into the vehicle structural design so as to reinforce hulls/fuselages and rotor/propeller-systems to minimize potential impact damage. Additionally, specially tailored forward-looking sensors to scan the sea/water surface and the immediate sea/air interface may well need to be developed. On-demand "hopping" midway during "skimming" hydroplaning/water taxiing might be required to "hop" (temporarily take low-level flight) over large FOD in the water might be required and factored into the vehicle design and CONOPS model.

Figure 7a-d illustrates four general types of skimmer mission profiles. These general mission profiles are consistent with the amphibious networks of Figs. 1-3. Each of these general mission profile reflects a different mix – and duration thereof – of VTOL, in-flight, on-water mission segments. The mission profiles range from solely VTOL and aerial in-flight mission segments to a solely on-water mission segments, with two in-between air/water mission profiles.



(a)

(b)

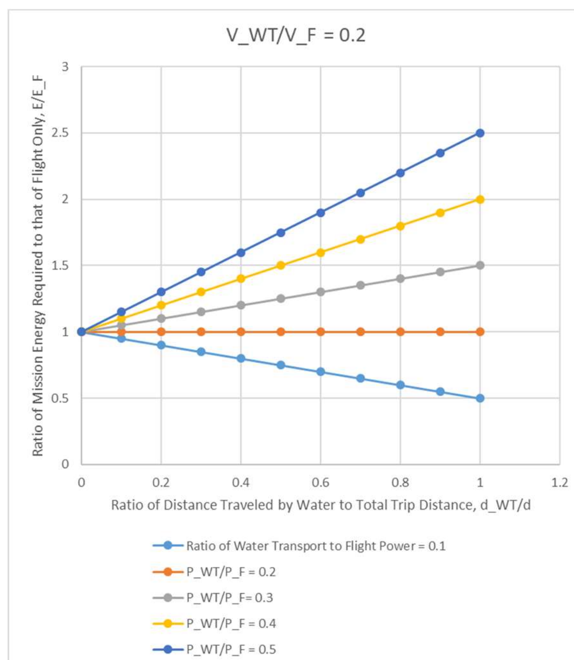
(c)

(d)

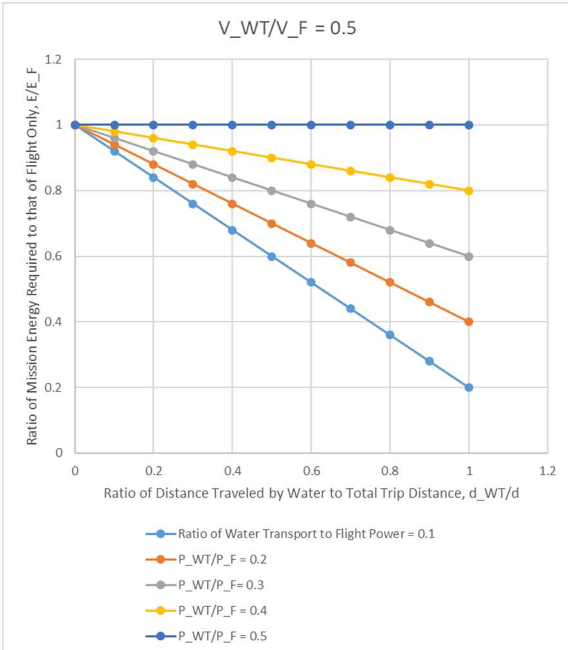
Figure 7. Four general mission profiles: (a) flight only, (b) flight with short/slow water taxiing, (c) flight with long-distance/high-speed surface water transport, and (d) water transport only

FIRST-ORDER AMPHIBIOUS VEHICLE MISSION PERFORMANCE ANALYSIS

One of the key considerations in potentially adopting amphibious vehicle networks is whether or not there can be reasonable compromise between the net speed of a trip (and, therefore, passenger time savings) and the required energy expenditure for that trip. Networks that are solely comprised of aerial inflight trips will doubt be faster than trips that incorporate amphibious operations (with on-water mission segments). However, such networks with only aerial operations will be very energy intensive, especially if they are highly dependent on VTOL operations. Networks with amphibious networks with significant on-water mission segments (especially if such on-water operations can be optimized for in-water speed and performance) could yield significant energy savings with modest compromises in trip travel time. Figure 8a-b illustrates some mission performance trends for a spectrum of vehicle capabilities that encompass the range of missions shown in Fig. 7a-d. Figure 8a is the energy expenditure trends – for a number of different ratios of on-water versus in-flight power, P_{WT}/P_F – for a relative ratio of on-water versus in-flight cruise speed of $V_{WT}/V_F = 0.2$. Figure 8b is a similar set of energy expenditure trends for a relative on-water versus infight speed ratio of $V_{WT}/V_F = 0.5$. The key observation from these overall trends is that there are clear design advantages, in terms of energy expenditure, if amphibious vehicle can be developed that are both fast and efficient on the water as well as in the air.



(a)



(b)

Figure 8. General performance trends: (a) mission energy as a function of flight leg segment fraction and (b) mission energy relative to missions with flight only

Figure 8 is derived from the simple first-order analysis based on Eq. 1.

$$\frac{E}{E_F} = 1 + \left[\left(\frac{P_{WT}}{P_F}\right)\left(\frac{V}{V_{WT}}\right) - 1\right]\left(\frac{d_{WT}}{d}\right) \tag{1}$$

Mission profiles with leg segments with water transport, in addition to flight, are viable from a mission performance perspective in terms of mission energy required if the following inequality relationship holds.

$$\left(\frac{P_{WT}}{P_F}\right)\left(\frac{V}{V_{WT}}\right) < 1 \tag{2}$$

Figure 9 illustrates, in a general sense, the ratio of mission time required versus time required for flight only missions. UAM is all about saving time; therefore, reducing mission time for skimmer type operations, relative to flying only, will be a key design consideration in skimmer vehicle and network development.

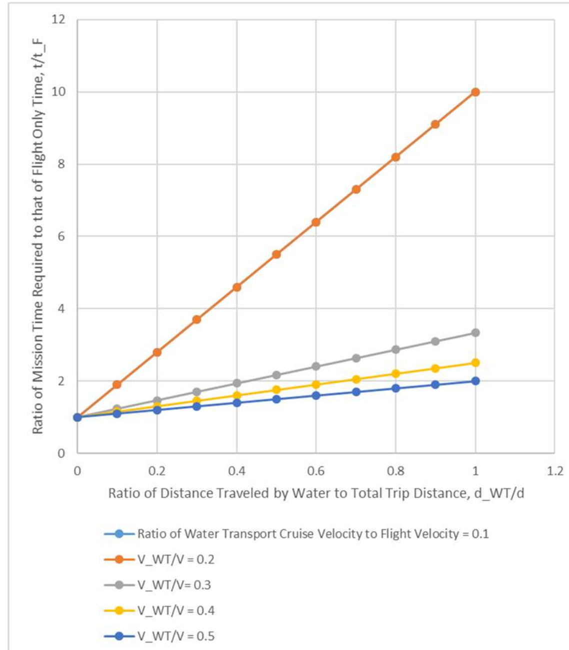


Figure 9. General mission time required trends

The Fig. 9 results are based on the simple, first-order analysis inherent in Eq. 3.

$$\frac{t}{t_F} = 1 + \left[\left(\frac{V}{V_{WT}}\right) - 1\right]\left(\frac{d_{WT}}{d}\right) \tag{3}$$

Equation 3 further acknowledges that skimmer missions will take longer than flight only missions unless – and unlikely feasible – the following holds

$$\left(\frac{V}{V_{WT}}\right) < 1 \tag{4}$$

Accordingly, minimizing mission time requires maximizing on water cruise speeds, relative to inflight cruise speed. This is consistent with the examining of hydroplane, hydrofoil, and perhaps hovercraft propulsion for the water transport legs of the overall skimmer mission. This is, in part, why a hybrid synchropter-hydroplane vehicle, such as seen in Fig. 4 will be examined in more detail in this paper. Additionally, on-water mission leg-segment distances should be kept to a minimum distance relative to the distance covered inflight, subject to other constraints or objectives such as improving community acceptance through reduced overflight noise and emissions and improved perception of safety.

An aggregate performance metric can be devised wherein the tradeoffs between time-expended versus energy-expended can be explored. Equation 5 captures this proposed metric, φ; the resulting expression incorporates Eqs. 1 and 2.

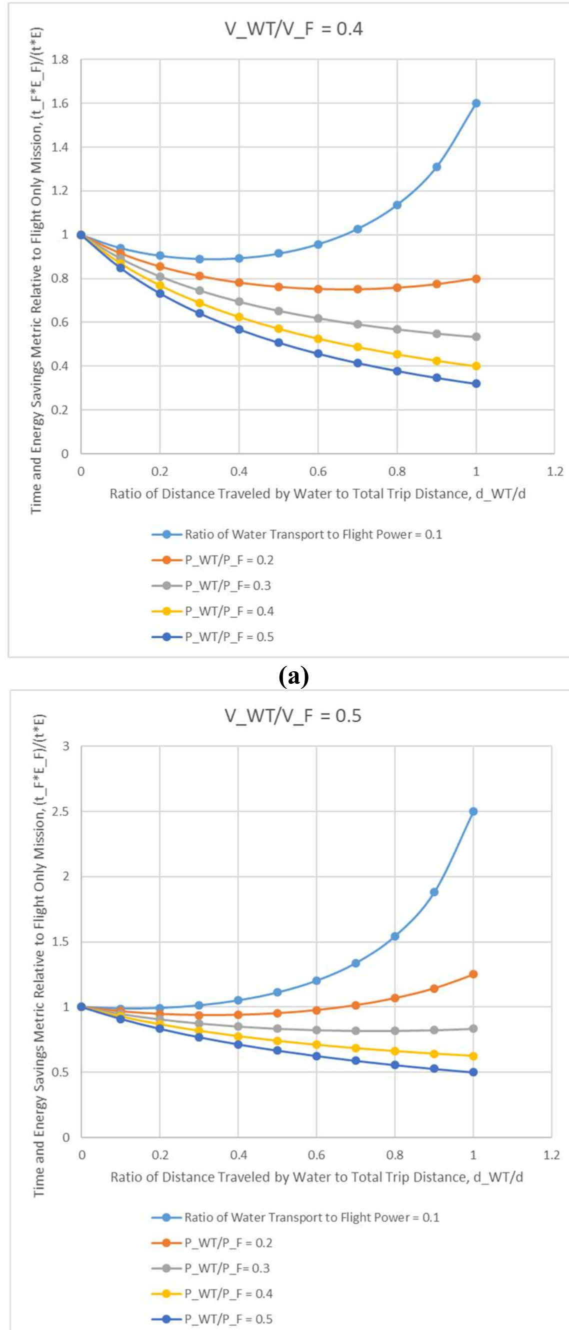
$$\varphi = \frac{t_F E_F}{tE} = \left\{1 + \left[\left(1 + \frac{P_{WT}}{P_F}\right)\left(\frac{V}{V_{WT}}\right) - 2\right]\left(\frac{d_{WT}}{d}\right) + \left[1 - \left[1 + \frac{P_{WT}}{P_F}\right]\left(\frac{V}{V_{WT}}\right) + \left(\frac{P_{WT}}{P_F}\right)\left(\frac{V}{V_{WT}}\right)^2\right]\left(\frac{d_{WT}}{d}\right)^2\right\}^{-1} \quad (5)$$

This implies that in order to result in $\varphi \geq 1$, to be more productive from a time and energy savings perspective, the following inequality constraint needs to be satisfied:

$$\left(1 + \frac{P_{WT}}{P_F}\right)\left(\frac{V}{V_{WT}}\right) + \left[1 - \left[1 + \frac{P_{WT}}{P_F}\right]\left(\frac{V}{V_{WT}}\right) + \left(\frac{P_{WT}}{P_F}\right)\left(\frac{V}{V_{WT}}\right)^2\right]\left(\frac{d_{WT}}{d}\right) \leq 2 \quad (6)$$

In order to maximize the time and energy savings provided by a skimmer vehicle with a mission combining both wind transport and flight, it is necessary to be as fast and as efficient on water as possible. And, further, if water transport can be sufficiently fast and efficient, then the on-water mission leg-segment should be of a long as distance as possible given the specific mission profile being performed.

The larger the value of φ, the better from a mission performance perspective; i.e. either time is saved, or energy, or both, to complete a mission relative to a flight only mission. When $\varphi = 1$ then the mission is equivalent in performance to a flight only mission. Figure 10 illustrates some of the general trends derived from Eq. 5.



(b)

Figure 10. Combined Time and Energy Savings φ Metric: (a) relative water speed to flight speed of 0.4 and (b) relative water to flight speed of 0.5

Having the flexibility to trade-off the amount of travel distance covered inflight versus on-water also addresses some of the concerns inherent to attempting to provide all-weather capability for UAM vehicles and networks. With the skimmer concept, inflight time/distance can be reduced with bad weather and increased to on-water surface operations.

AMPHIBIOUS VEHICLE NOVEL DESIGN CHALLENGES

Work to fully explore the amphibious urban aerial mobility design trade space will require the development of novel weight equations that merges conventional rotorcraft weight estimation with that of marine vehicle weight estimate methodologies. One approach is to develop ad hoc interpolation functions between a rotorcraft sized to the inflight mission and a watercraft, of a given type, sized to the on- or over-water portion of the mission. There are well-developed weight equation estimation methodologies for both rotary-wing aerial vehicles (e.g. Ref. 7) and marine vehicles (e.g. Ref. 8), respectively. There is very little discussion in the literature for weight estimation methodologies for amphibious aerial vehicles.

The ad hoc approach suggested for weight estimation assumes a weighted composite of certain subsystem weights as incremental increases above that of the aerial vehicle estimate stemming from the marine vehicle estimates. These incremental increases can be incorporated in aircraft/rotorcraft sizing codes as a prescribed delta mission equipment package (ΔW_{MEP}). The main areas of added weight as to providing for amphibious vehicle capability to a rotorcraft is anticipated to be on the weight of the vehicle fuselage or hull, the weight of the propulsion system so as provide for both aerial and on-water mobility, and the weight of the auxiliary systems to provide for dual modes of operation in terms of guidance, navigation, and control.

$$W_{Fus} = W_{Fus_{Rotorcraft}} + \varepsilon_{Fus} W_{Fus_{Watercraft}}$$

$$W_{Prop} = W_{Prop_{Rotorcraft}} + \varepsilon_{Prop} W_{Prop_{Watercraft}}$$

$$W_{Aux} = W_{Aux_{Rotorcraft}} + \varepsilon_{Aux} W_{Aux_{Watercraft}}$$

(7a-c)

$$\Delta W_{MEP_{Fus}} = \varepsilon_{Fus} W_{Fus_{Watercraft}}$$

$$\Delta W_{MEP_{Prop}} = \varepsilon_{Prop} W_{Prop_{Watercraft}}$$

$$\Delta W_{MEP_{Aux}} = \varepsilon_{Aux} W_{Aux_{Watercraft}}$$

(8a-c)

$$\Delta W_{MEP} \approx \Delta W_{MEP_{Fus}} + \Delta W_{MEP_{Prop}} + \Delta W_{MEP_{Aux}}$$

(9)

The above analysis is predicated on the development or usage of weight equation interpolation functions, ε. These interpolation functions range from $0 \leq \varepsilon \leq 1$. Future work will have to be performed arrive at a rigorous methodology to define values for ε_{Fus}, ε_{Prop}, and ε_{Aux}.

Ultimately, a more rigorous and generalized approach(es) must be defined to estimated amphibious vehicle weights for conceptual and preliminary design.

Note that the proposed amphibious network might be more compatible with regional transportation versus a localized single-metropolis urban system. Accordingly, such a system might be more compatible with hybrid-electric propulsion versus all-electric.

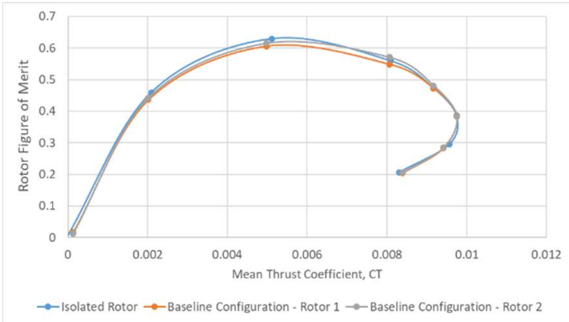
IN-FLIGHT VEHICLE AEROPERFORMANCE STUDIES

The focus of the following in-flight aeroperformance analysis is on the synchropter-hydroplane hybrid vehicle. This aeroperformance analysis is primarily based on the mid-fidelity computational fluid dynamics code, RotCFD, Ref. 9.

There are two fundamental issues related to hybrid, multi-modal vehicles. First, it is always a concern that providing multi-modal capability in a vehicle may result in too large of compromises in aerodynamic performance (and hydrodynamic performance, in this particular case) for each mode of operation. Second, there is always a concern in providing such multi-modality why accepting too much vehicle weight growth.

Hover Analysis

Figure 11 is a prediction of figure of merit as a function of thrust coefficient and rotor collective for both an isolated rotor and the two synchropter rotors (designated rotor 1 and 2) with a relative cant angle of twenty degrees.



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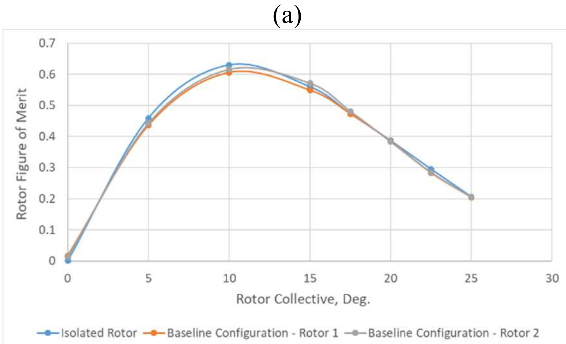


(b)

Figure 11. Figure of Merit as a function of (a) thrust coefficient and (b) collective (Coll. = 20 Deg. and Cant Angle = 20 Deg.)

Figure 12 presents fuselage download trend with thrust shows overall high download values. There is a thrust dependency of the download ratio whereby mid-range thrust coefficients show the lowest download values. Accordingly, there is an opportunity during subsequent vehicle design to reduce them.

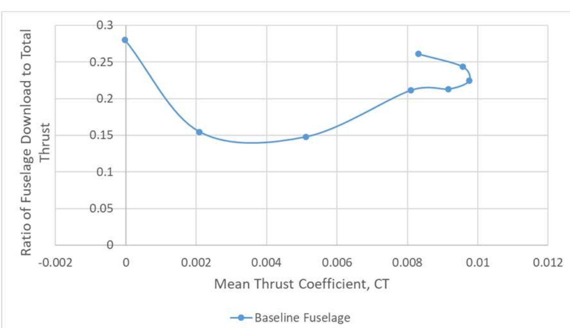


Figure 12. Ratio of Fuselage Download to Total Thrust (Coll. = 20 Deg. and Cant Angle = 20 Deg.)

Figure 13 shows the hover performance for two synchropter rotors (no fuselage, rotors only) as a function of rotor relative cant angles at one rotor-to-rotor spacing.

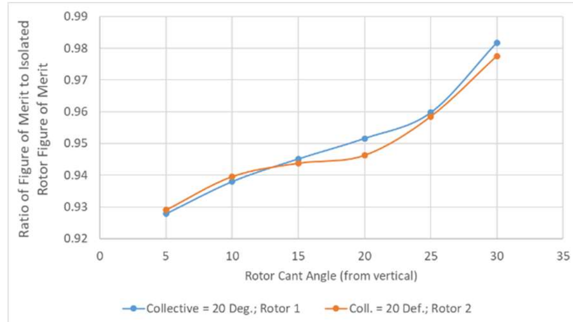


Figure 13. Ratio of hover figure of merit to isolated rotor figure of merit as a function of rotor cant (rotor axis angle with respect to vertical axis)

Figure 14 shows the hover performance of these synchropter rotors (no fuselage, rotors only) as a function of rotor-to-rotor spacing, for a fixed cant angle of twenty degrees.

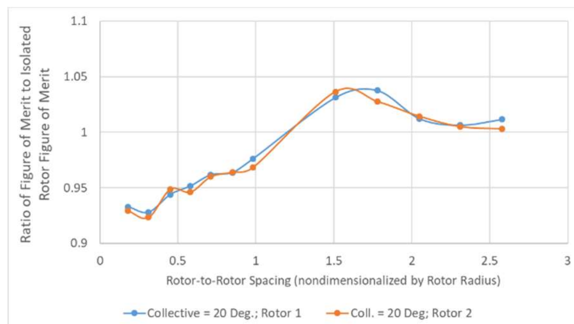
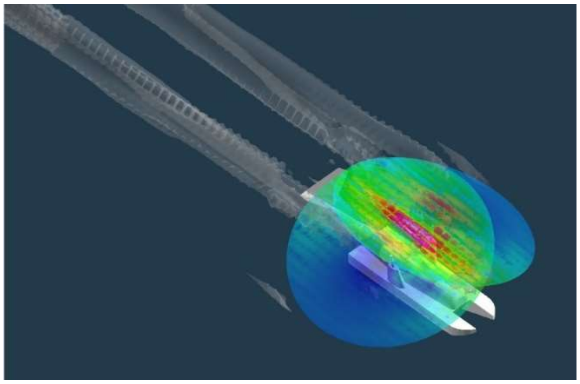


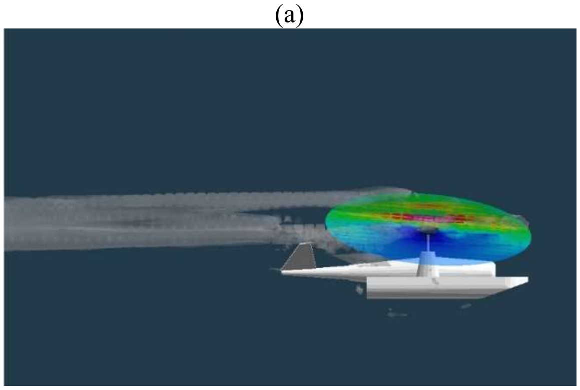
Figure 14. Ratio of hover figure of merit to isolated rotor figure of merit as a function of rotor-to-rotor spacing

Forward-Flight Performance

RotCFD results, e.g. Fig. 15, were generated for the synchropter-hydroplane hybrid vehicle notional conceptual design for forward flight speeds ranging from 50 to 350 ft/s (30-208 knots). The rotor(s) modeled in this study is a generic two-bladed, constant chord (c/R = 0.1), linear twist rate (θ_{tw} = -10) set of blades using NACA 0012 airfoils. The rotors are spun at tip speeds of V_{Tip} = 600 ft/s. The overall geometry is consistent with the CAD and rotor models displayed in Figs. 4-5.



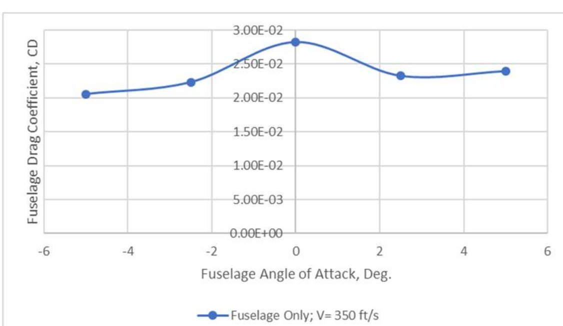
(a)



(b)

Figure 15. (Collective = 20 Deg., Cant Angle = 20 Deg., Tip Path Tilt = 5 Deg. nosedown, and V = 350 fps)

Figure 16a-b presents the fuselage-only lift and drag coefficients (using vehicle wetted surface area for both coefficients) as a function of angle of attack at a representative (maximum) forward flight velocity of 350 ft/s. These results were obtained for relatively coarse grids using the 'realizable κ-ε' turbulence model.



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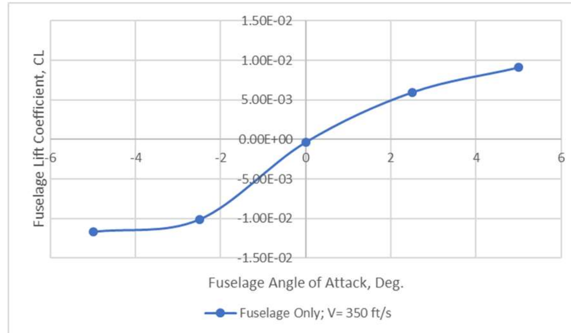
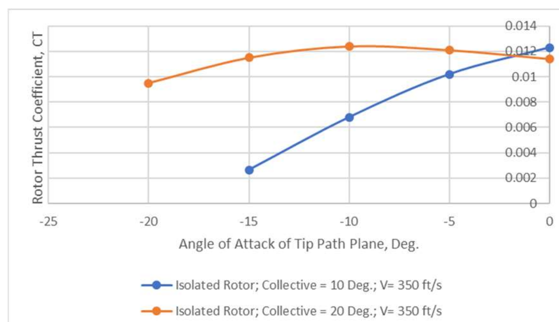


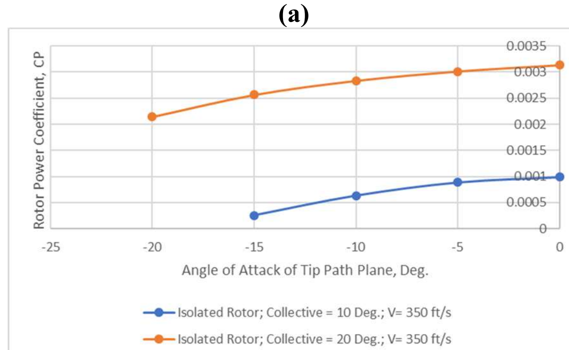
(b)

Figure 16. Fuselage-Only Aerodynamic Characteristics as a function of angle of attack: (a) drag coefficient and (b) lift coefficient

All the following rotor forward-flight aeroperformance preliminary results are for nontrimmed-cyclic (i.e. fixed-pitch) rotors. Figure 17a-b shows the forward-flight aeroperformance results for an isolated rotor. Further, for the large majority of the results presented in this paper, the starboard (on the right) rotors are rotating counterclockwise.



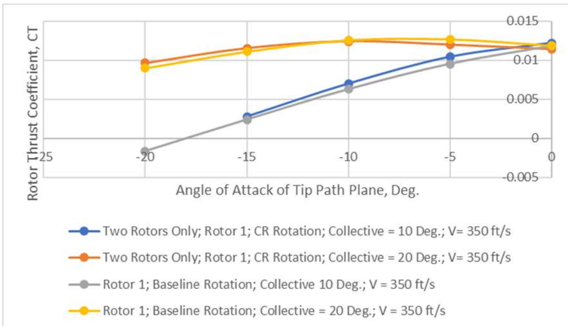
(a)



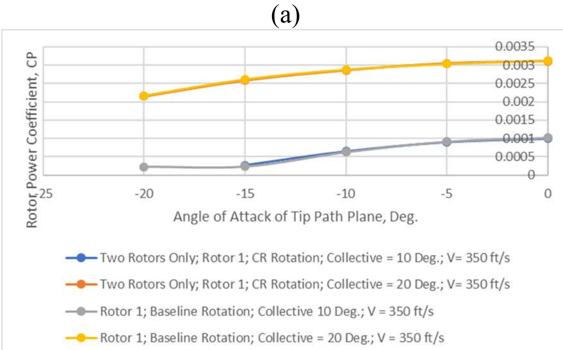
(b)

Figure 17. Isolated rotor forward flight aeroperformance trends as a function of rotor tip path plane angle of attack: (a) CT and (b) CP

One of the key questions for any side-by-side rotor, including synchropter rotors, is whether the direction of rotation of rotors influences the performance of the rotors. In this particular case, Fig. 18a-b, the direction of rotation does not seem to significantly affect rotor performance for two synchropter rotors with twenty degrees cant and a rotor-to-rotor spacing of 0.58R.



(a)



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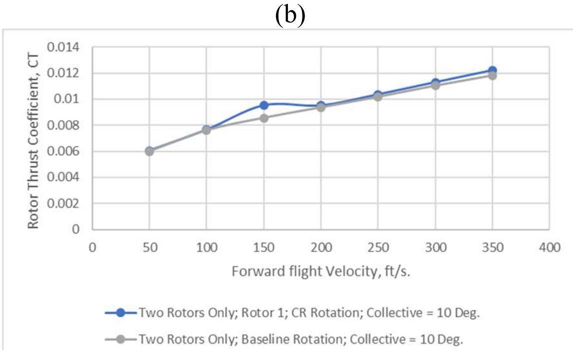

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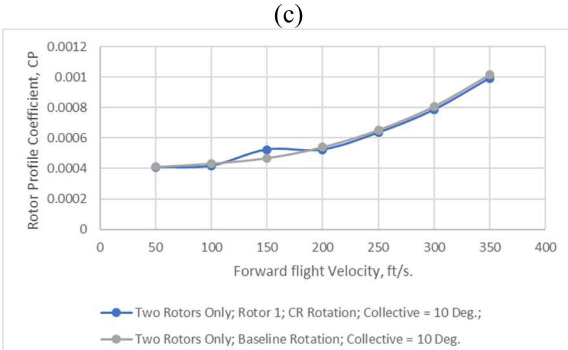


(d)

Figure 18. Rotor trends as affected by rotor direction of rotation

The following figures, Figs. 19-26, show the complete vehicle rotor and fuselage characteristics as a function of forward flight velocity, fuselage angle of attack, and rotor collectives. Figure 19-20 are RotCFD predictions of rotor thrust and power coefficients, for both rotors, as a function of forward-flight velocity and the fuselage of angle-of-attack (for rotor collective of ten degrees). Figure 21-22 are predictions of the fuselage lift and drag coefficients (based on wetted surface area) as a function of forward-flight speed and fuselage angle of attack. The rotors angle of plane rotation is five degrees nose-down relative to the fuselage longitudinal axis.

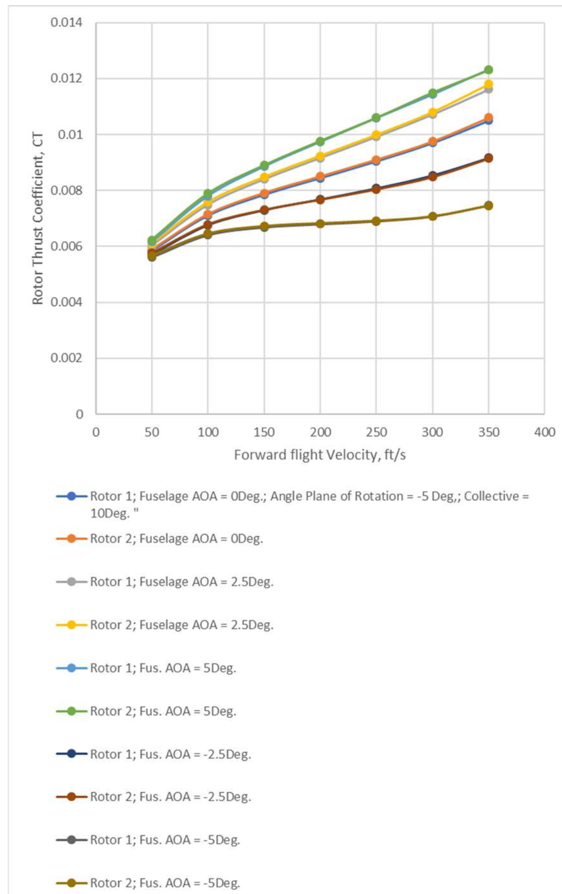


Figure 19. Complete vehicle out-of-ground-effect (free flight) thrust coefficient trends (collective = 10 Deg.; fixed-pitch or non-trimmed-cyclic)

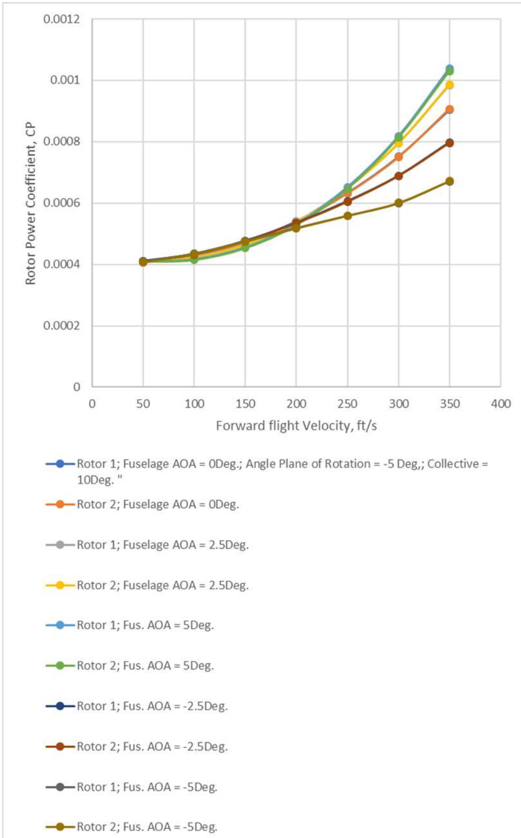


Figure 20. Complete vehicle out-of-ground-effect (free flight) power coefficient trends (collective = 10 Deg.; fixed-pitch or non-trimmed-cyclic)

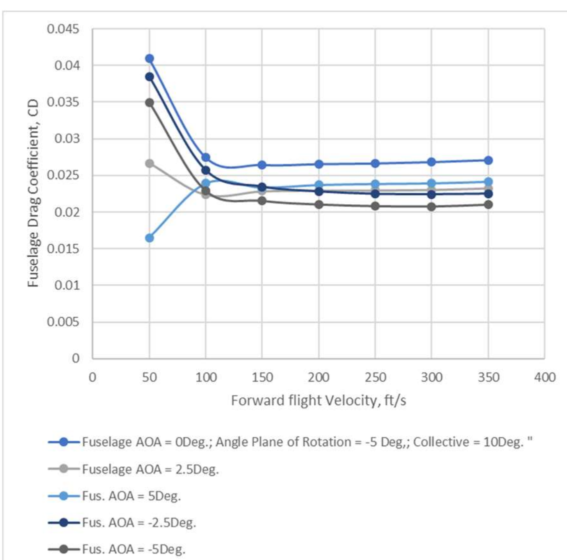


Figure 21. Complete vehicle free flight fuselage drag coefficient trends (collective = 10 Deg.; fixed-pitch or non-trimmed-cyclic)

Figure 22 clearly shows the effect of rotor wake downwash on the vehicle download (negative lift) for the lower vehicle speeds. At higher speeds the rotor downwash no longer impinges on the vehicle fuselage and download becomes negligible.

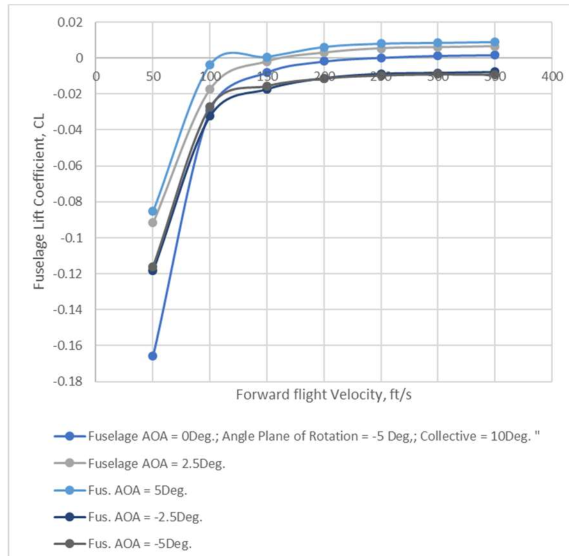


Figure 22. Complete vehicle free flight fuselage lift coefficient trends (collective = 10 Deg.; fixed-pitch or non-trimmed-cyclic)

Figures 23-26 are a set of results for the free flight complete vehicle aeroperformance trends for rotor collective settings of twenty degrees. Figures 23 and 24 are RotCFD rotor performance results, thrust and power coefficients, as a function of forward-flight velocitu. Figures 25 and 26 are the RotCFD computational fluid dynamics for the lift and drag coefficients (based on wetted surface area) of the vehicle fuselage as a function of forward-flight velocity. All results in Figs. 23-26 are presented in terms of sets of fuselage angle-of-attack curves. The rotor planes of rotation is five degrees nose-down relative to the fuselage longitudinal axis. The fuselage lift and drag coefficients as a function of forward-flight velocity again, just as the ten degrees collective results, clearly show the influence of the rotor wake impingement at the lower forward-flight velocities. Again, these CFD results are based on fairly coarse gridding and will have to be confirmed in future work, as the vehicle design geometry is refined/matured.

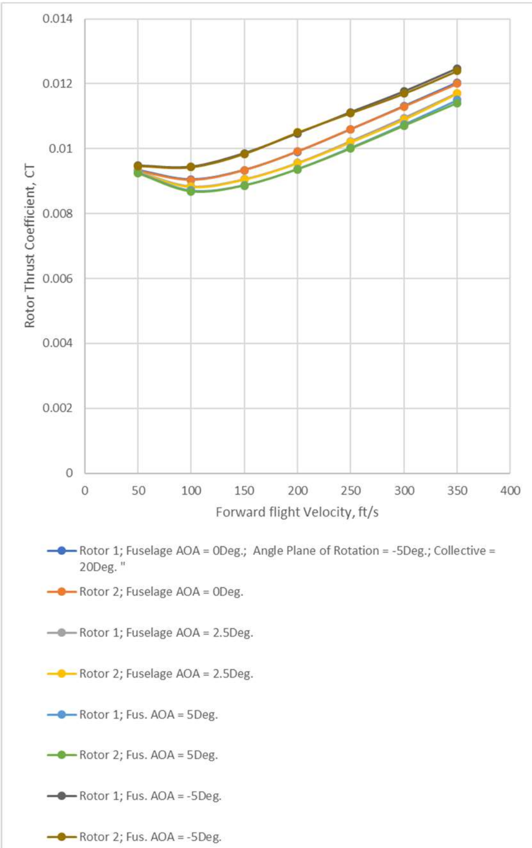


Figure 23. Complete vehicle out-of-ground-effect (free flight) power coefficient trends (collective = 20 Deg.; fixed-pitch or non-trimmed-cyclic)

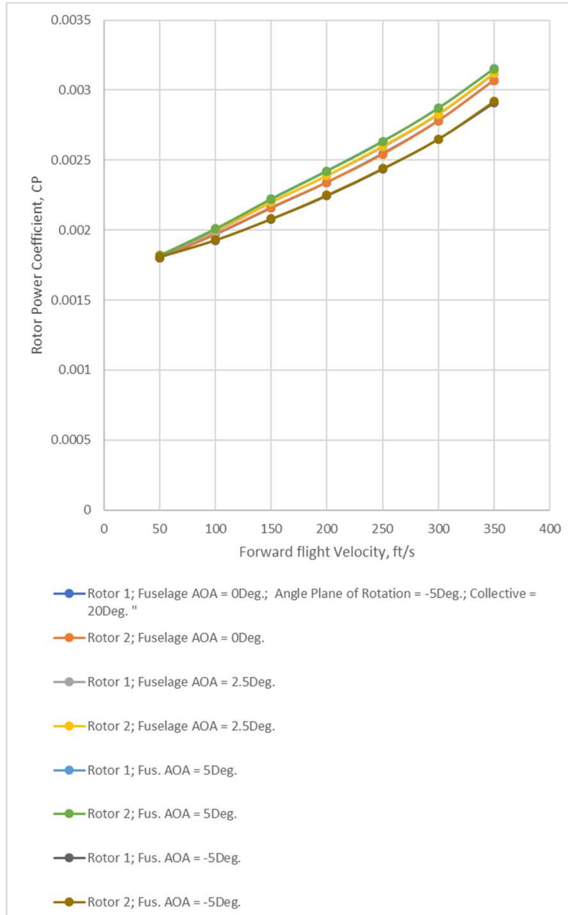


Figure 24. Complete vehicle out-of-ground-effect (free flight) power coefficient trends (collective = 20 Deg.; fixed-pitch or non-trimmed-cyclic)

The rotor results are for a relatively generic two-bladed rotor. The most unique aspect of these results is that they encompass any small fuselage-on-rotor and rotor-on-rotor (for the synchropter rotor configuration) interactional aerodynamics. Figures 23 and 24 can be compared to Fig. 19-20 and Fig. 18c-d to get insights into the fuselage-on-rotor interference effects.

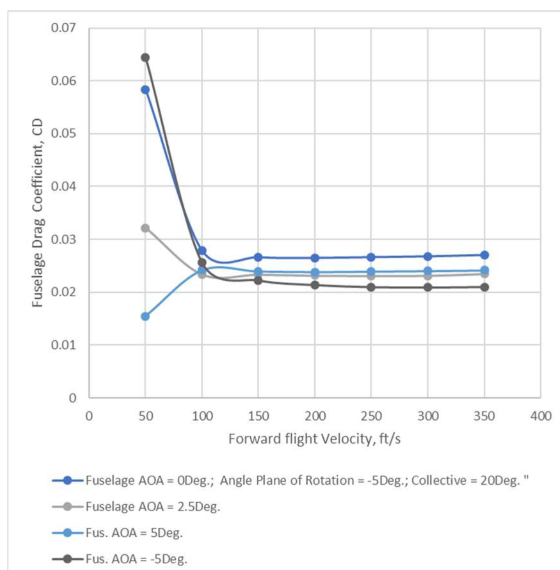


Figure 25. Complete vehicle free flight fuselage drag coefficient trends (collective = 20 Deg.; fixed-pitch or non-trimmed-cyclic)

At higher collectives, the rotor wake impingement lasts longer and the download magnitude is greater than at the lower collectives.

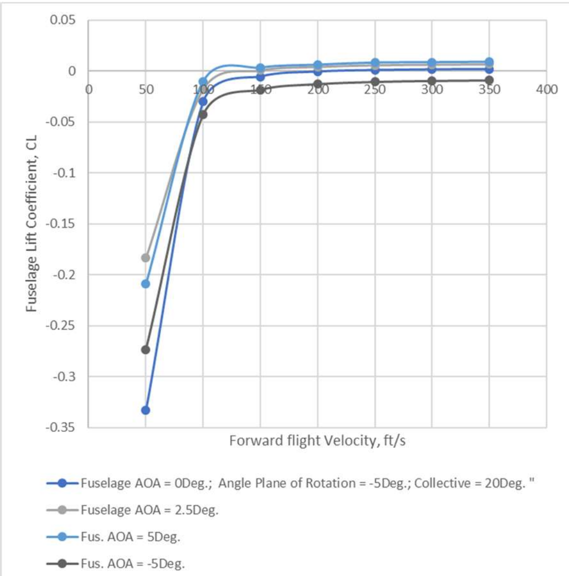


Figure 26. Complete vehicle free flight fuselage lift coefficient trends (collective = 20 Deg.; fixed-pitch or non-trimmed-cyclic)

As noted previously the success of a multi-modal vehicle is not contingent on its performance during one mode of operation but needs to consider all modes of operation. The following discussion examines the performance implications of this notional vehicle configuration during on-water transit.

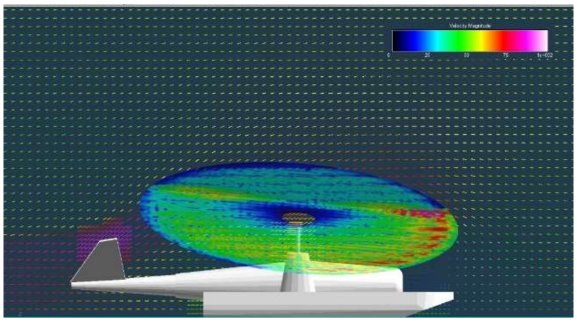
ON-WATER TRANSIT HYDRODYNAMIC PERFORMANCE

It is important to acknowledge that a considerable amount of future work needs to address some open foundational aerodynamic and hydrodynamic performance questions for amphibious vehicles such as suggested in this paper. Largely unexplored in this paper, and left to future work, is how to best balance, or even optimize, the aerodynamic and hydrodynamic performance of such amphibious vehicles across the whole mission, including all on- or over-water and in-flight mission segments; e.g. Figs. 27-28.

The principal focus of this paper is to focus on hydroplane-type hulls for two reasons: first, because of their low-drag form factor on water (due to use of hydroplaning versus buoyancy) high speeds of water taxiing might be achieved, and, second, the wing-like hydroplane hull shape might also yield low-drag and beneficial lift in flight. The downside of using a hydroplane hull is that the resulting download in hover and low-speed flight might be quite high; additional the large waterline surface area of a hydroplane-type hull might negate the possibility of purely vertical takeoff due to the large inherent water surface tension with respect to the hull.

Water taxiing, or on-water cruise operation, can be effected by either rotor-assisted forward propulsion or independently through use of marine-screws or water-jets, or perhaps some optimal hybrid combination thereof. The amount of time cruising on the water, versus flying through the air, is a tradeoff between time and performance in the form of expended energy. Cruising on the water reduces the required energy but increases the total time. Correspondingly, there is the next, more detailed, level of analysis whereby the relative efficiency tradeoffs of one type of waterborne propulsion (marine screws or water-jets) against another type (rotor-assisted propulsion) can be performed. This propulsor (momentum imposed in the water or momentum imposed in the air) combination tradeoff will be a function of water/sea-state conditions, the magnitude and type of FOD on the water, and the required waterborne cruise speed. Slower waterborne cruise speeds under rougher water conditions with high levels of FOD in the water will tend to dictate to use primarily marine-screws or water-jets. Faster waterborne cruise speeds will potentially demand rotor-assisted propulsion. And in between speeds may require a combination of propulsion modes with time-varying propulsive-force load factors for the various propulsors working in combination. Finally, the relative speed and duration of the waterborne cruise will also have design implications as to amphibious hull type for the vehicles. Slower speeds and shorter times on the water will tend to dictate primarily buoyant hulls with larger displacements whereas faster speed and longer times on the water will tend to emphasize hydroplaning hulls (or even hydrofoils).

As can be readily seen in the above discussion, there is a very large design space to consider for notional amphibious UAM vehicles. This work will be necessity have to be very selective in its consideration of the potential design space to arrive at a tractable initial exploration of this application domain.



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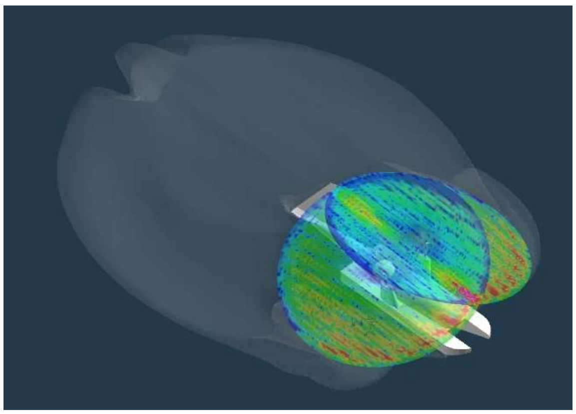
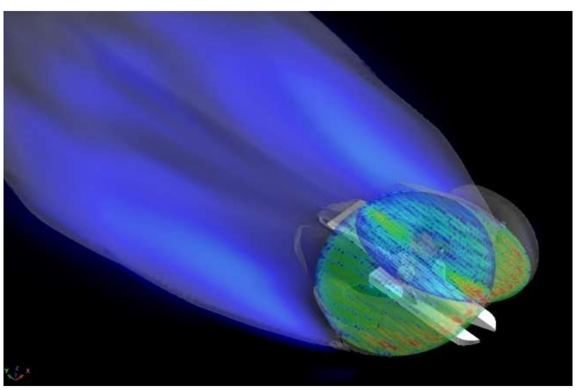


(b)

Figure 27. Water taxiing: ratio of hull draft with respect to rotor radius, d/R = 0.05; V=50 ft/s; rotor shaft angle = 5 Deg. nose-down; rotor collective = 10 Deg.; fuselage AOA = 0 Deg.



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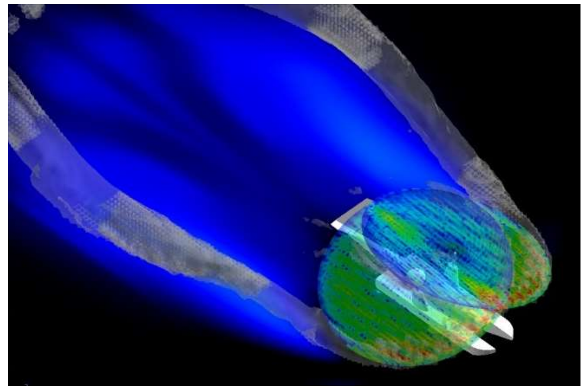
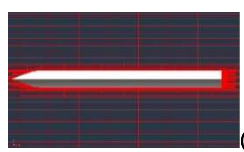


(b)

Figure 28. Water taxiing: hull draft/R = 0.025 (rotor shaft angle = 5 Deg. nose-down; rotor collective = 10 Deg.; fuselage AOA = 0 Deg.): (a) V=50 ft/s isosurface; (b) V=50 ft/s and nondim. Q-criterion isosurfaces

The hydrodynamic resistance of the submerged hull can also be estimated for the skin friction and the pressure drag contributions by the mid-fidelity CFD code, RotCFD. The wave generating and wave breaking contributions cannot be estimated by this tool, as it cannot accurately model the air-sea interfaces. These wave resistance contributions need to be estimated separately by other analysis methods.

Figure 29 illustrates the two gridding approaches taken to estimate the hydrodynamic drag (the skin friction and pressure drag contributions) and (water-planning) lift of the submerged portion of the synchropter-hydroplane vehicle hull.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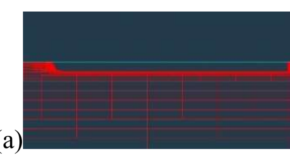
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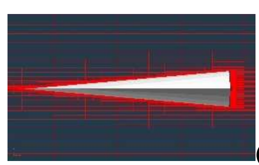
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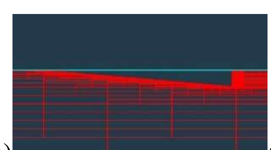
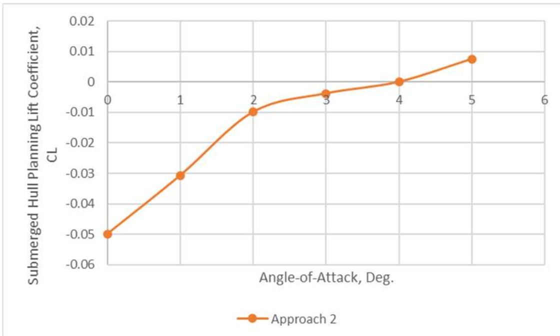
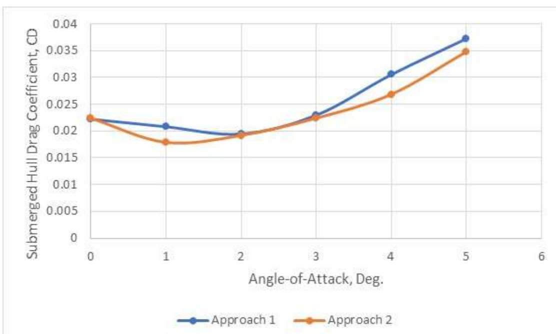

(d)

Figure 29. Hydrodynamic modeling of the submerged portion of the synchropter-hydroplane hybrid vehicle hull: (a) AOA = 0 Deg., approach 1; (b) AOA = 0 Deg., approach 2; () AOA = 5 Deg., approach 1; (d) AOA = 5 Deg., approach 2

Given these two grid modeling approaches, the planning lift and drag of the submerged hull as a function of the vehicle angle-of-attack is predicted and shown in Fig. 30a-b.



(a)



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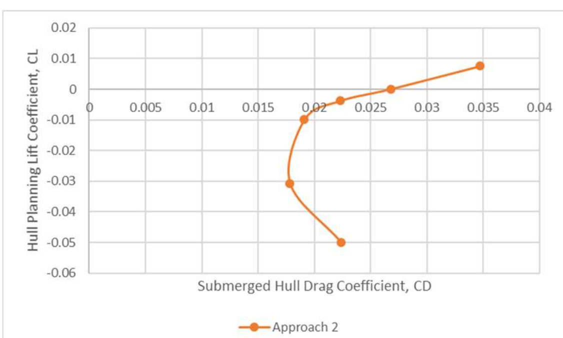
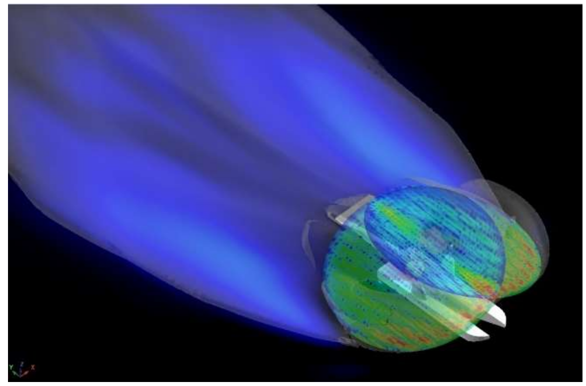


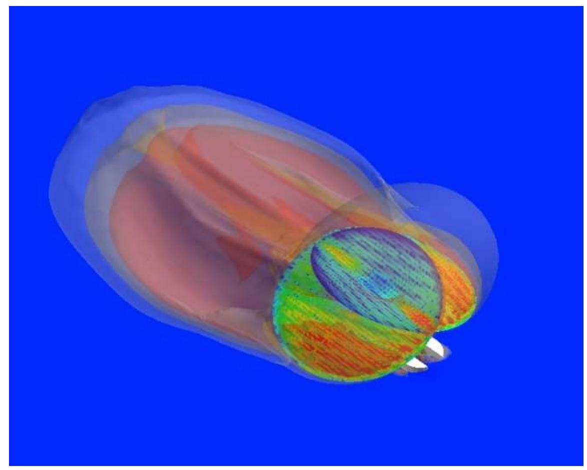
(c)

Figure 30. Submerged portion of hull (draft/R=0.043) predicted hydrodynamic characteristics: (a) planning lift vs. angle of attack (AOA), (b) drag vs. AOA, and (c) lift vs. drag

The vehicle performance during on-water transit, and/or water taxiing, is the sum of both the aerodynamic performance of the portion of the vehicle above water (e.g. Fig. 31) and the hydrodynamic performance for the portion of the vehicle submerged under the water.



(a)



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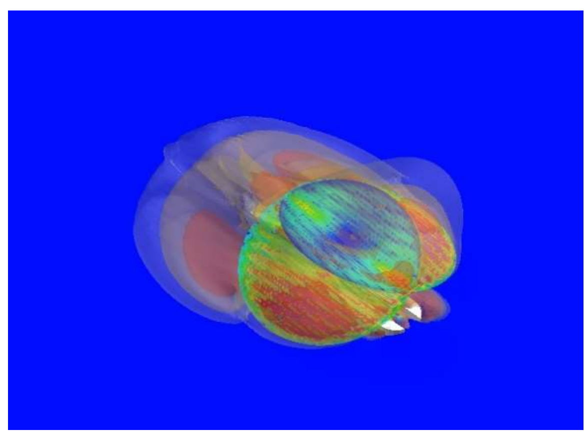
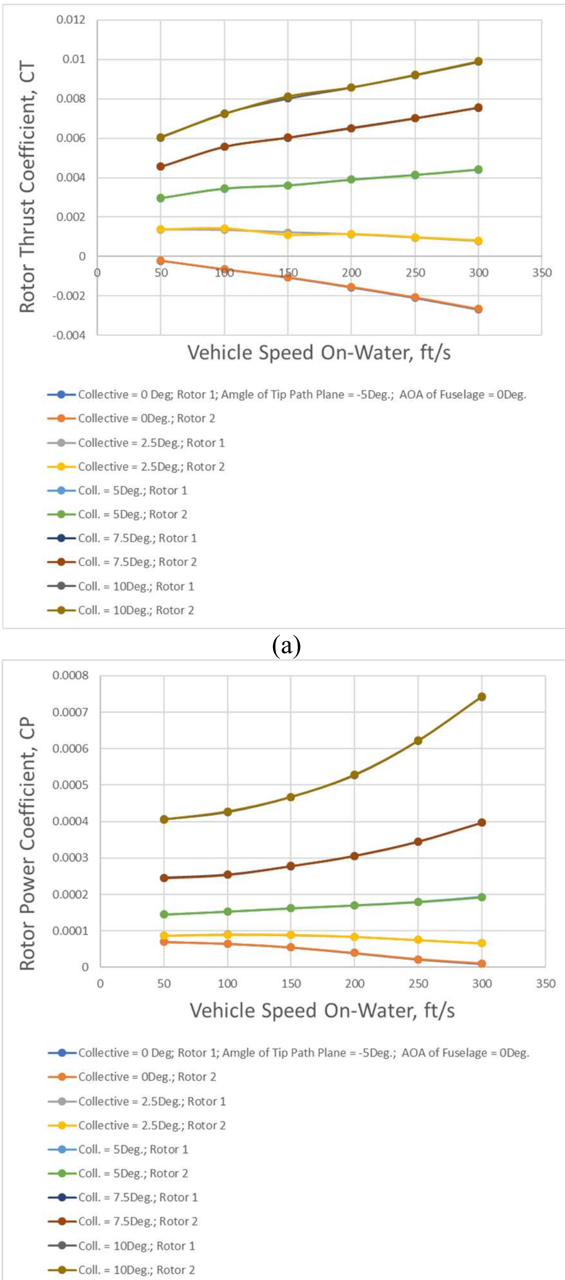


(c)

Figure 31. Water taxiing (draft/R = 0.025; angle of plane of rotation = 5 Deg. nose-down; rotor collective = 10 Deg.; fuselage AOA = 0 Deg.): (a) V=50 ft/s isosurface; (b) V=100 ft/s isosurface; (c) V=150 ft/s isosurface

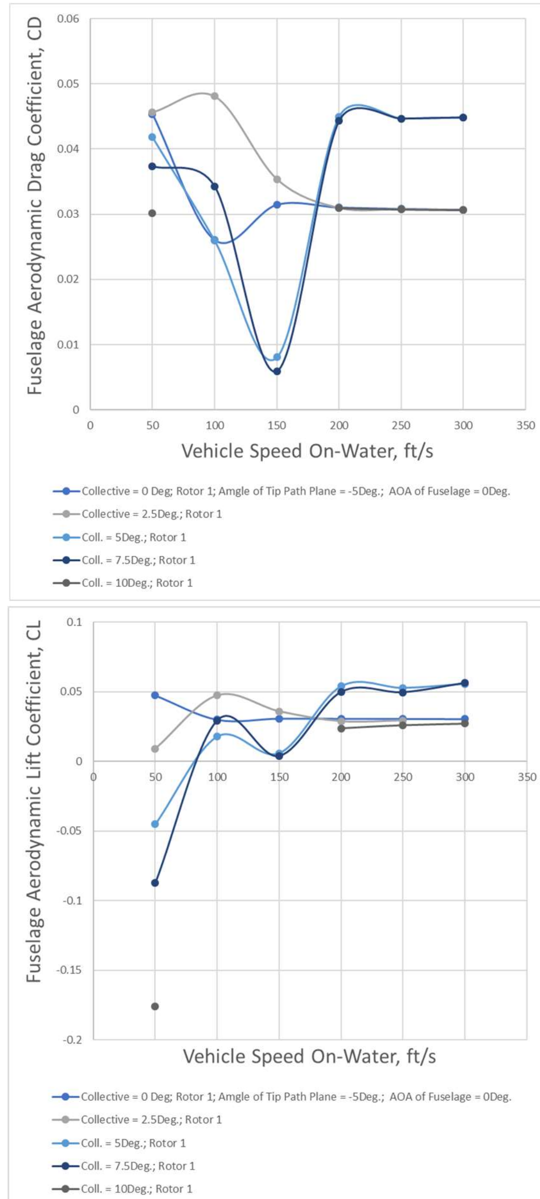
Figures 32 illustrates the aerodynamic contributions of the vehicle during in ground effect on-water transit of the amphibious synchropter and hydroplane vehicle. The nondimensionalized draft of the vehicle is draft/R = 0.043. A variety of rotor collectives are studied. The optimum collective (or, in fact, whether, the rotors should be spun at all during water transit) still needs to be examined in the context of the relative water-based propulsion versus the air-based propulsion.



(b)

Figure 32. CT and CP as a function of vehicle forward-flight velocity: (a) CT and (b) CT

Figure 33 is the complementary set of predictions of the vehicle aerodynamic lift and drag during the vehicle on-water transit.



(b)

Figure 33. On-water transit aerodynamic contributions as a function of vehicle speed: (a) CD and (b) CL

FIRST-ORDER AMPHIBIOUS VEHICLE NETWORK ANALYSIS

Urban aerial mobility vehicles and networks will have to be responsive to many stakeholders: potential passengers/consumers, the general public, commercial operators and network service providers, aircraft manufacturers, and local, state, and federal governmental bodies. Each stakeholder will have a voice and vote on the success and failure of UAM networks. In many cases, there are competing interests between these stakeholders. Accordingly, system architecture development, and system analysis of those architectures' performance, will depend on novel metrics – many of which may be unique to this problem.

If one considers the generic example networks shown earlier in Figs. 1-3, there are two observations that can be quickly made. First, skimmer type networks will entail a greater degree of circuitity than networks employing flying VTOL vehicles only.[1] And, second, skimmer networks might need to be capable of greater ranges than competing more city-centric UAM or eVTOL concepts; in fact, the longer ranges may necessitate thinking of skimmers falling somewhere between urban and regional transportation.[2]

A simple first-order analysis will now be performed examining, first, the factors inherent in circuitity for the three generic skimmer networks introduced earlier. Second, time and savings metric, φ, estimated initially through Eqs. 5-6, will be extended to account for circuitity. Finally, initial results from the time and energy savings analysis will be presented in figures below.

Consider Network 1 generically introduced earlier in Fig. 1; Network 1 is identified as a coastline following network. A series of on-shore vertiports that are situated up and down a coastline, located inland by small distances. The inflight distance covered by the skimmer is relatively small compared to the on-water distance covered by the vehicle during water transport. It is implied, though not absolutely required, that network 1 would support skimmer vehicles that could VTOL or STOL directly onto the waterway and would not necessarily require offshore vertiport stations.

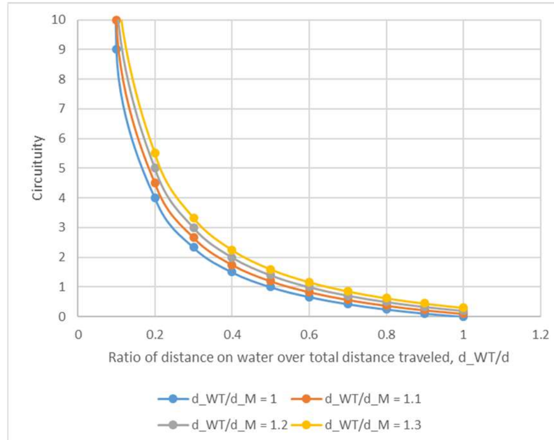


Figure 34. Skimmer Network 1 circuitity as a function of ratio of distance on water versus total distance traveled for various different

The above figure, Fig. 34, is derived from the simple expression

$$C = \left(\frac{d}{d_{WT}}\right)\chi - 1$$

$$\chi \equiv \left(\frac{d_{WT}}{d_M}\right) \quad (10)$$

Where a series of curves are defined for various prescribed values for the parameter χ, the relative amount of travel on-water versus the total trip distance. When $\chi = 1$ the on water travel is in a point-to-point straight line; when $\chi > 1$ then the water travel is following the coastline in a curved or nonlinear path. Figure 34 merely emphasizes that the water travel should be as straightline as possible and that vertiports should be close to the shore (but not too close to shore as to negate the necessity for flight leg segments) so as to minimize circuitity of the overall mission transit profile, At its most extreme, $d_{WT}/d \to 0$, it suggests that if the amount of on-water travel is too small, and the circuitity too high, then water travel is likely no longer reasonable and only point-to-point flight to a destination should be performed.

[1] Increased circuitity will, though, further erode the time and savings metric, φ, as compared to flight only transport because flight ideally could be point-to-point (if vertiport siting on land, within the cityscape, were not an issue), whereas even if the offshore vertiports and/or waterway lanes were very close to the shoreline there would still be some inherent circuitity above that for point-to-point overflights.

[2] Increased range would tend to reduce circuitity and make the flight and water transport more point-to-point like.

Consider Network 2 generically introduced earlier in Fig. 2; Network 2 is identified as one enabled by set of offshore vertiport/waterway transit stations. There are two types of Network 2's identified: a bay-centric and a lake-centric network. Figure 2 focuses on the bay-centric network. It is assumed that the bayshore is approximately described by a circular arc. Further, it can be assumed for the purposes of this analysis that onshore vertiports, within the cityscape, are approximately the same offset distance from the shoreline. Therefore, $d \approx constant$ and $d_{WT} \approx constant$. Therefore, circuitity, under these conditions is only secondarily influenced by the ratio d_{WT}/d. Instead, the primary influence on circuitity for Network 2 is the minimum point-to-point straightline distance between origin and destination vertiports, or d_M or, nondimensionally, d_M/d; refer to Fig. 35.

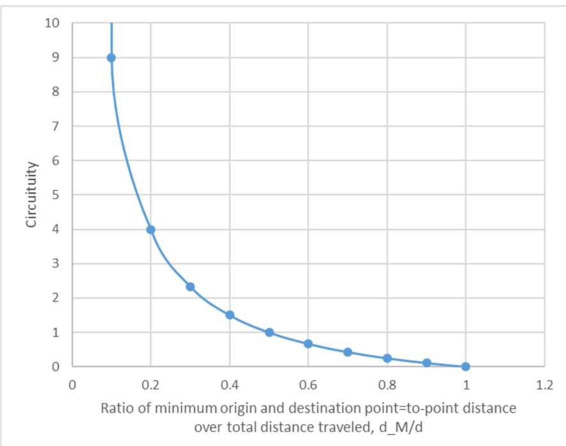


Figure 35. Skimmer Network 2 circuitity as a function of

Consider Network 3 generically introduced earlier in Fig. 3; Network 3 is identified as network focused on waterway crossings from one onshore region to another removed onshore region enabled by a combination of flight and on-water mission leg segments. In this network it is envisioned that there are no offshore vertiports and that the skimmer vehicles would be capable of VTOL and STOL on/off the water. Additionally, it is assumed that the flight profile trajectory is approximately point-to-point straight line or linear. Therefore circuitity should be relatively small for this general type of network system.

Taking circuitity into account, the following holds

$$\varphi = \frac{t_F E_F}{tE} = \left\{1 + \left[\left(1+\frac{P_{WT}}{P_F}\right)\left(\frac{V}{V_{WT}}\right) - 2\right]\left(\frac{d_{WT}}{d}\right) + \left[1 - \left[1+\frac{P_{WT}}{P_F}\right]\left(\frac{V}{V_{WT}}\right) + \left(\frac{P_{WT}}{P_F}\right)\left(\frac{V}{V_{WT}}\right)^2\right]\left(\frac{d_{WT}}{d}\right)^2\right\}^{-1} \quad (11a)$$

This implies that in order to result in $\varphi \geq 1$, to be more productive from a time and energy savings perspective that the following inequality constraint needs to be satisfied:

$$\left(1+\frac{P_{WT}}{P_F}\right)\left(\frac{V}{V_{WT}}\right) + \left[1 - \left[1+\frac{P_{WT}}{P_F}\right]\left(\frac{V}{V_{WT}}\right) + \left(\frac{P_{WT}}{P_F}\right)\left(\frac{V}{V_{WT}}\right)^2\right]\left(\frac{d_{WT}}{d}\right) \leq 2 \quad (11b)$$

Urban aerial mobility vehicles and networks will have to be responsive to many stakeholders: potential passengers/consumers, the general public, commercial operators and network service providers, aircraft manufacturers, and local, state, and federal governmental bodies. Each stakeholder will have a voice and vote on the success and failure of UAM networks. In many cases, there are competing interests between these stakeholders. Accordingly, system architecture development, and system analysis of those architectures' performance, will depend on novel metrics – many of which may be novel to this problem. One key metric is identifying the impact of UAM flights on community noise annoyance. Noise is one of the key challenges of developing successful UAM networks. A key argument for considering amphibious vehicles and networks for UAM applications is the potentiality for significant community noise reductions and, therefore, improved community acceptance. Some of the noise issues can be addressed as a part of the vehicle design. But a significant portion of the noise challenge will have to be addressed at the network architecture design and operational levels.

A simple first-order analysis is now suggested for getting a general sense of the relative noise abatement/mitigation of varying the portion of the vehicle trips conducted on- or over-water versus the flights solely over land. The parameter β is the ratio of 'annoyed' community members, as per some DNL noise threshold, for amphibious flights versus solely over-land flights.

$$\beta = 1 - (1 - sC)\left(\frac{d_{WT}}{d}\right) \tag{12a}$$

The above equation would further suggest that community noise annoyance is reduced with amphibious operations if the following inequality were abided by

$$C < 1/s \tag{12b}$$

In short, it is suggested that amphibious flights can reduce community noise annoyance, if the portion of the flights over land and the flights over water (or on-water transit) are overflights/transit over lower population density or less noise sensitive urban areas, i.e. low values of the noise sensitivity parameter, s. This holds to the point, though, that trip circuituity becomes so large (nearly doubling the trip travel distance) that noise annoyance reductions are negated. Figure 36 illustrates this suggested relationship.

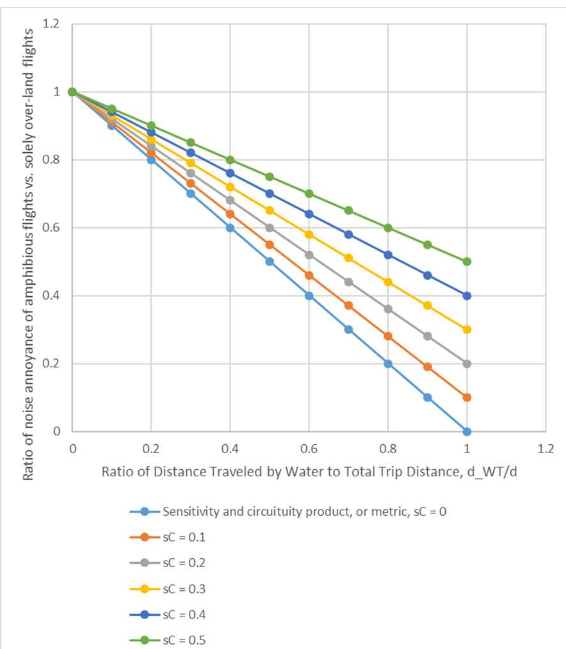


Figure 36. The ratio of 'annoyed' community members with amphibious flights relative to solely over-land flights

Another key argument for amphibious vehicles and networks is the potentiality for enhanced community safety for such a transportation network. Finally, vertiport siting and community economic enhancement might also result for the implementation of amphibious vehicle networks.

There many considerations that would need to be addressed for a practical skimmer network. There are challenges with respect to high-speed water transport. There are concerns about collision with surface debris, large marine animals, and even collision with small watercraft and large ships. There also be concerns regarding ship wakes and natural waves impacting safe high-speed cruising on water. Accordingly, there are sense and avoid and traffic management issues even while on the water. Offshore vertiport stations, if not carefully sited could impede waterway traffic and, in turn, create unacceptable congestion of shipping.

On the other hand, as discussed in Ref. 1 for vertiport stations in general but nonetheless still applicable to skimmer network offshore stations, such vertiport stations could have a significant economic development impact on the local economies of the urban centers near which they were sited. Further, if these vertiport stations become as much as destination as the final destination of the public traveling via skimmer vehicles and networks then there is likely an additional positive economic impact.

FUTURE WORK

The immediate follow-on work being performed on this topic has focused mostly on more detailed aeroperformance consideration of some of the alternate hybrid amphibious vehicles discussed briefly at the beginning of this paper. There is very large design space that could be considered by the rotorcraft research community. Clearly, in the case of the notional hybrid synchropter-hydroplane vehicle, aerodynamic refinements need to be made to vehicle configuration; for example, the predicted hover download and the vehicle drag in forward-flight need to be reduced to arrive at an aerodynamically efficient vehicle. Accompanying that aerodynamic and hydrodynamic work will be detailed weight estimation methodology development to allow fully realized vehicle sizing analyses and trade studies. Additionally, airspace management researchers are encouraged to consider more detailed assessments of amphibious vehicle networks as to potentially meeting the perceived societal benefits of urban aerial mobility transportation systems. New flight control, collision avoidance sensor (both in-flight and on- or over-water), and guidance and navigation challenges will need to be tackled by researchers.

Finally, though the focus of this paper has been on metropolitan or regional aerial transportation systems, this new amphibious VTOL aerial vehicle design space could also have significant substantial implications for future Coast Guard and U.S. Navy littoral missions.

CONCLUDING REMARKS

Many of the world's metropolitan centers lie near or along waterways. As interest in urban aerial mobility grows, it is worthwhile to consider whether or not amphibious vertical takeoff and landing vehicles can play an important role in providing such mobility. In particular, amphibious operations, including overflight over water for a significant fraction of the total flight time, might address critical safety and community acceptance issues.

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