Transitioning eVTOL Aircraft with Augmentative Cross-Modal Elements

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ABSTRACT

In the realm of transitioning eVTOL aircraft, hindrance may be placed on performance in each of the two flight modes due to the existence of apparatuses or devices intended wholly for the other mode. For example, the presence of wings will normally reduce hover endurance due to their weight, and the use of a plurality of exposed lift-propellers – for hover stability and control – can lower flight speed and range in airplane mode because of the excess drag. It would seem, then, that transitioning eVTOL aircraft are generally poor performers in any mode when compared to their dedicated, single-mode cousins. This paper explores another possibility, of substantial performance improvement when the devices or their use become elements augmenting performance in the other mode – or cross-modally. Through an example dual-propeller aircraft, several cross-modal elements – including phenomena like the fan-in-wing effect and the inverse of Custer's channel-wing effect – are identified and their merits expounded.

INTRODUCTION

Transitioning eVTOL aircraft have advantages over existing conventional aircraft in that they can take off vertically in a hover mode like a quad- or multi-copter drone – and are therefore suitable for urban environments and any that lack runways – but can also cruise for relatively long distances in an airplane mode. In such scenarios, having these combined abilities usually precludes competition from those conventional, single-mode aircraft. But transitioning aircraft operate with an inherent handicap; their performance in either mode is lessened by the existence of devices devoted to enabling the other mode. For example, the presence of wings and their associated weight will reduce hover endurance, and an excess of exposed lift-propellers that enable hover control will lower flight speed and range in airplane mode. This performance degradation, however, may be reduced – or even eliminated entirely – if transitioning eVTOL aircraft are treated not just as assemblages of conventional single-mode elements, but as unique environments offering new opportunities for improvement.

Convention and Focus

In this paper, such opportunities appear in the form of "cross-modal elements", devices and functions which exist or operate across the two modes though they are usually designed primarily for one of them. The term is preceded by the word "augmentative" if the element is intended – usually by redesign – to improve performance, or reduce its degradation, in the secondary mode.

In applying this approach, the focus here is on aircraft which transition via the forward tilting of some or all of their lift propellers through an angle of approximately 90 degrees. Additionally, the aircraft are not usually intended to loiter for long periods in hover mode but rather to briefly pass through it for taking off and landing. Conversely, there may be potential cross-modal elements associated with other transition means and flight profiles which are not included here. Nevertheless, it is possible that the principle of cross-modal augmentation is applicable across many eVTOL aircraft types.

Prior Work by Others

In the past, subsequent to the introduction of the first helicopters but prior to the advent of electric-powered propulsion, non-articulated VTOL rotorcraft were severely limited by hover-stability issues (e.g., Curtiss-Wright X-100) and by the cross-shafting and gear boxes needed between the lift propellers and prime mover(s) (e.g., Curtiss-Wright X-19). Most such aircraft never passed the experimental stage, but the era spawned a wealth of experimental data, and discoveries of phenomena like the *fan-in-wing effect* (Ref, 1, p. 255), the *radial-lift principle* (Ref. 2), and *Custer's channel-wing effect* (Ref. 3).

Present

In recent years the electrification of flight has ubiquitously enabled VTOL – now referred to commonly as eVTOL – with over 800 aircraft configurations listed presently (Ref. 4). Distributed powered lift, i.e., the use of multiple motors and propellers, has solved the hover stability and control problem of un-articulated rotorcraft, and has eliminated the need for cross-shafting, enabling as well simple transitioning between hover and airplane modes. A representative aircraft in this realm, situated in the frontlines of the quest for certification and commercial application, is the 6-propeller Joby S4 shown in Figure 1.

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Figure 1. Joby S4 transitioning eVTOL aircraft at take off (top) and in forward flight.

Need

Though present-day transitioning eVTOL aircraft are intended to serve a segment of the aviation market that no other existing genre can satisfy, there is still much room for improvement within the genre. Enabled by an almost unlimited supply of powered, distributed lift, these first generation aircraft employ conventional, discrete wings along with the plethora of propellers – a collection of devices borrowed directly from single-mode aircraft. That approach has worked, but to advance further and maximize performance, what is needed is a holistic approach, the recognition that the dual-mode genre offers an opportunity to discover and implement a set of performance-improving devices unique to it. Only then will the genre properly serve its intended market. The following sections will describe what is likely only a small portion of such devices.

BACKGROUND: DESIGN CONSTRAINTS

The intent here is not to extoll one particular aircraft design, but it is important to note that the cross-modal elements to be demonstrated are not random nor part of a system but resulted from one solution to a design problem: how to incorporate a dual-propeller platform into a transitioning eVTOL aircraft. In this particular case the elements were *enabling* in their primary modes and only afterwards augmentative cross-modally through design adjustment. Background details on how this solution evolved can be found in Refs. 5 and 6, but rather than now skipping directly to the cross-modal elements, some discussion about the aircraft is warranted to provide context. Ironically, it begins with the most important cross-modal elements.

Two Propellers: Efficient Airplane Flight from Active Tilting in Hover

By definition, the propellers are the main cross-modal elements in the genre of transitioning aircraft employing their tilting. Propellers provide vertical lift at take off and in hover, and the propulsive force in forward flight. Considering them or their treatment to be augmentative as well would then seem a misnomer, but this is not necessarily correct.

In terms of energy efficiency, the number of propellers on a conventional, non-VTOL airplane should be as few as possible, which – ignoring the single-prop scenario for our purposes here – is two, assuming of course that the engines or motors can be made large enough. A greater number of propellers and associated nacelles will naturally incur higher losses. The problem in the transitioning eVTOL application, however, is that more than two propellers have seemingly been required for stability, control and redundancy in hover.

But it is in fact possible to hover with only two propellers, through a technique called *active tilting*, which involves use of the propellers' gyroscopic, momentum-wheel, and drag-torque moments. Established more than a decade ago (e.g., Refs. 7, 8, 9) in conjunction with the advent of electric powered aircraft, active tilting is especially applicable to the transitioning aircraft genre since in it the propellers already tilt. Additionally, by generating the same non-atmospheric, inertial control-elements used to rotate and orient vehicles in space, the aircraft can be potentially impervious to wind gusts. As a refresher, active tilting will be discussed in more detail in a later section, but for now it is sufficient to say that it enables hovering with two propellers and so increases energy efficiency in airplane mode – and therefore is an augmentative cross-modal element.

Aircraft Brief Description

The object aircraft of this study, shown in Figure 2, is a roughly 1/5-sized foam and carbon-tube model of a dual-propeller personal transport nicknamed 'Twister'. Though freed of size constraints, it retains the wrap-around canard and half-ducts (formerly referred to as duct-wings) born of its predecessor's need for wing-surface area in the extremely tight footprint restrictions of the GoFly challenge of 2017-2023 (Ref. 6). Both surfaces are the principal cross-modal

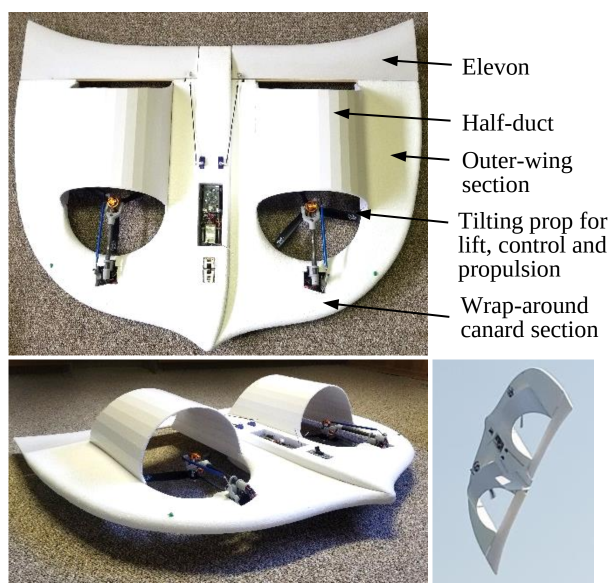


Figure 2. Transitioning eVTOL 'Twister' model.

elements – after the propellers – and both also serve to protect the pilot, passengers and ground personnel from the rotating propellers.

Removal of the GoFly size restrictions, including span-wise, has allowed extension of the wing beyond the half-ducts, thereby creating an outer-wing section (Figure 1). This and the removal of the longitudinal length limit have permitted the installation of elevons considerably downstream from the propellers and away from adverse prop-wash during transition. The resulting aircraft planform is now essentially that of a delta-wing, whose aerodynamic center in airplane mode can be made to coincide with the lift line through the propeller (and aircraft mass) centers in hover, thereby achieving balance in both modes.

Specifications for the Twister model are listed in Table 1. Further details and discussion regarding its propeller tilting for transition and hover control – including a recap of the hover control-moment equation in pitch – and flight testing status follow the section on cross-modal elements.

Table 1. Twister-Model Specifications.

Characteristic	
Wingspan	43.5 in (110.5 cm)
Length	36.0 in (91.4 cm)
Propellers	10 in (25 cm) dia, 3-blade, CW & CCW, nylon, cut from 13x8 (33x20 cm) stock Master Airscrew
Motors (2)	Turnigy D2830/11 1000kV
Speed Controls (2)	Turnigy Plush 18A, 2S-4S, 5V BEC
Tilt Servos (2)	Hitec HS-85MG, 0.16 sec/60^0 42 oz-in (3 kg-cm) @ 4.8V
Battery	3-4S (11.1-14.8V), 2200mAh, 20C, LiPoly
Flight Controller	Arduino APM 1280 w/ IMU
Radio Control	Spektrum DX8 transmitter, AR8010T receiver
Flying weight	3.0 lb (1.36 kg)

CROSS-MODAL ELEMENTS AND THEIR AUGMENTATIVE FUNCTIONS

Referencing Table 2, several of the Twister aircraft's more passive elements which serve multiple functions and across its two flight modes are described in the following.

Wrap-Around Canard in Hover: Fan-in-Wing Effect

(Table 2, row (a)). The canard serves primarily as a conventional wing, providing lift during forward flight of the aircraft. But, with its close proximity to the propeller accentuated further by its wrap-around shape, it can also provide substantial lift in hover due to the fan-in-wing effect. In it, ambient air above the canard surface is drawn into the propeller, lowering the air pressure to below ambient and thereby creating lift on the canard, in effect adding to the vertical thrust of the propeller. Test-rig studies of the effect on wings completely surrounding the propellers have shown such thrust increases to be a large fraction of the original propeller thrust (Ref. 1, p. 255). Though the canard on Twister-like aircraft only partly surrounds the propellers, the effect can still be considerable. Hover testing of the 11 lb (5 kg), 1/3-scale GoFly model (Ref. 6) showed an effective thrust increase of 0.5 lb (0.23 kg) – measured by noting the shift in center of lift from the prop centers (and assuming that the half-ducts had little or no effect).

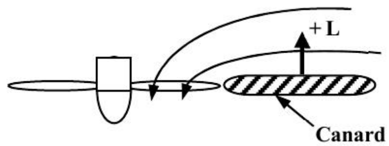
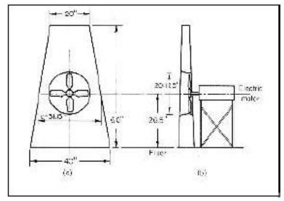
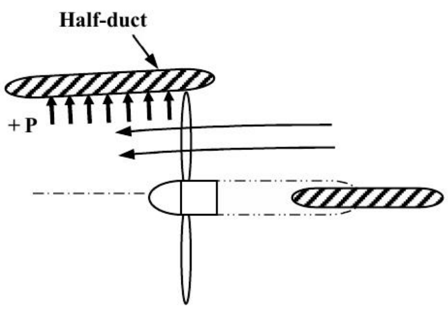
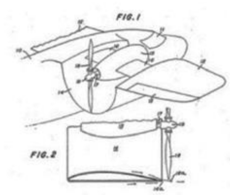
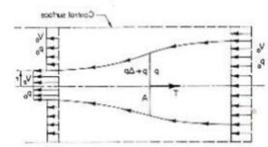
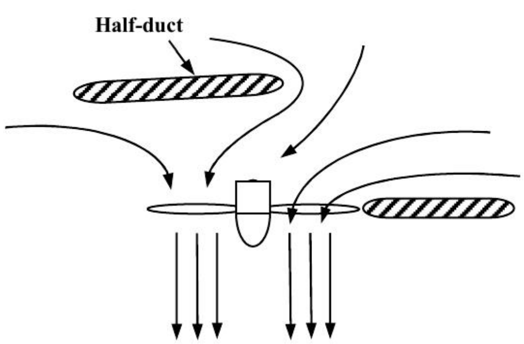
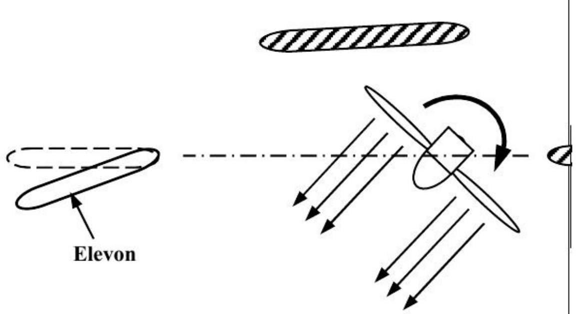
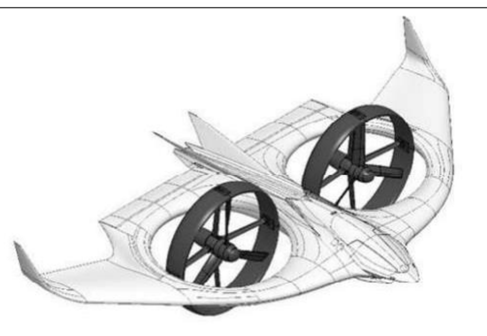
Half-Ducts in Airplane Mode: Inverse Custer Effect

(Table 2, row (b)). While the half-duct serves as both a vertical fin for directional stability and a conventional lifting surface, its semi-circular shape and tight proximity to the propeller provides an additional lift element. From classical streamtube analysis, there exists a region of high pressure behind the rotating propeller, and it manifests itself as additional lift on the half-duct. This is the inverse of the Custer channel-wing effect (Ref. Custer patent), where the vertical propeller plane is located at the trailing edge of the channel-wing; it draws in air at all forward speeds and reduces air pressure from ambient along the channel, thereby creating additional lift on the wing. Though an enabling device, it is not yet known how the half-duct affects overall airplane performance compared to a conventional wing.

Half-Ducts in Hover: Avoiding Downwash Impingement

(Table 2, row (c)). To use only two laterally displaced propellers in a transitioning aircraft creates a dilemma in that they and straight airplane wings will interfere with each other without extra provision. Especially acute is the vertical thrust lost from direct wing impingement by the downwash of relatively small propellers. Not really an option in the eVTOL domain, tiltrotors such as the V-22 Osprey and AW609 Leonardo mitigate the impingement (or masking) effect with wing planforms being a small fraction of the rotor disk areas. The common eVTOL solution is to use multiple propellers, with a portion of them located in front of and others behind the otherwise-conventional wing. Some of these aircraft designs, however – as shown in Table 2, row (c) – recognize that wings above propellers are not as detrimental to vertical thrust as those below, and have overlapped the rear propellers accordingly. The Twister takes this a step further, necessarily increasing the overlap between the half-duct and propellers substantially. But in the large, low-pressure field above a propeller, it is possible that direct impingement, flow separation, and any losses associated with the half-duct are minimal. This appeared to be the case during hover testing of the Twister's GoFly predecessor (Ref. 6). It is further possible that, with their proper design, the half-ducts can even augment vertical lift in hover mode.

Table 2. Augmentative Functions of Cross-Modal Elements in Twister-like Aircraft

Element	Augmentative Function	Reference or Comparison
(a) Canard in Hover	**CANARD'S FAN-IN-WING EFFECT**  Augments lift in hover.	 Fan-in-wing study cited by McCormick (Ref. 1, p. 255)  Hover testing of author's GoFly aircraft (Ref. 6)
(b) Half-Duct in Airplane Mode	**HALF-DUCT'S INVERSE CUSTER EFFECT**  Increased stream-tube pressure behind propeller adds to lift produced by half-duct in airplane mode.	 Custer's Channel Wing with propeller at trailing edge for lift augmentation at low flight speeds.  From classic streamtube analysis: Reduced air pressure in front of propeller and increased pressure behind. From McCormick (Ref. 1, p. 74).
(c) Half-Duct in Hover	**PROPWASH IMPINGEMENT AVOIDANCE/ LIFT AUGMENTATION**  Staggered half-duct's offset above propeller allows inflow without impingement or separation during hover.	 Direct impingement of rotor downwash on wings of AW609: Acceptable with large diameter rotors.  Under-wing lift-propellers in eVTOL vectored thrust aircraft (2021 Ohio Advanced Air Mobility Showcase).
(d) Elevon During Transition	**AVOIDING IMPINGEMENT DURING TRANSITION**  Elevon is sufficiently downstream from propeller to avoid adverse flow impingement during transition.	 Impinging rotor efflux on Augusta-Westland Project Zero aircraft during transition.

Elevons: Avoiding Impingement During Transition

(Table 2, row (d)). The aircraft's elevons are sufficiently rearward of the propellers to avoid adverse impingement on them during transition. Moreover, they can be angled without stalling to effect pitch and roll control of the aircraft during transition and at any tilt angle of the propellers.

HOVER CONTROL AND TRANSITION OF TWISTER MODEL

For attitude control in hover mode, dual-propeller, active-tilting aircraft employ the propellers as inertial systems comprised of momentum wheels and control moment gyroscopes – in addition to their atmospheric thrust vectoring and differential thrusting. The following subsections will describe both aspects of this control, along with a brief introduction to transition tilting. One key development of the Twister aircraft over its GoFly predecessor is that each propeller's hover pitch-control and transition tilting, though occurring in different directions, are now accomplished by a single servo-mechanism.

Hover Pitch Control

Pitch control of the Twister aircraft in hover is achieved via *oblique* active tilting of its two counter-rotating propellers. In it the high (mass moment of) inertia propellers impart gyroscopic and drag-torque control-moments about the aircraft pitch axis – together with conventional thrust vectoring – guided by the aircraft's onboard flight controller and IMU (Inertial Measurement Unit). The gyroscopic moment arises from the lateral component of the tilting and provides the dynamic or damping control-element necessary for a stable system, missing in eVTOL aircraft attempting to utilize only longitudinal tilting for aircraft pitch control.

Using a schematic representation of the aircraft, Figure 3 shows how symmetric hover-control tilting of the propellers, represented as angle γ (from the aircraft vertical) – about oblique axes swept forward by angle Λ from the lateral axis – generates the aircraft net pitch-control moment M_C. It is a function of the propellers' thrusts T (and height h of the tilt axes above the aircraft mass center), their drag-torques Q, and gyroscopic moments $I_R\omega\gamma'$, where I_R is the propeller mass-moment of inertia about its spin axis, and ω is its rotational speed. Moment $I_R\omega\gamma'$ is always perpendicular to the propeller's spin and tilt axes. In equation form, for small tilt angles γ, the pitch-control moment M_C acting on the aircraft due to the propellers being symmetrically and simultaneously tilted about their respective oblique axes is obtained from

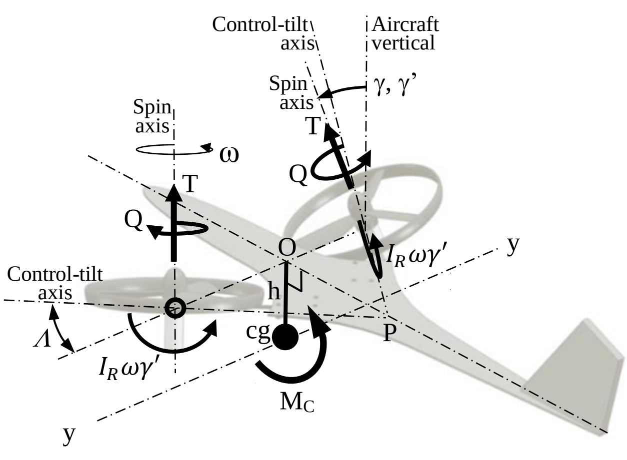


Figure 3. Oblique tilting generates pitching moment M_C.

$$\frac{1}{2}M_C = (I_R\omega \cdot sin\Lambda)\gamma' + (hTcos\Lambda + Qsin\Lambda)\gamma$$

Gyroscopic moment — Thrust-vector moment — Torque-vector moment

which shows that the aircraft can be controlled and stable in pitch even if its mass center is level with the propellers' tilt axes (h = 0). It is also evident that the gyroscopic and drag-torque portions of the moment disappear for purely longitudinal tilting ($\Lambda = 0$). It should be noted, however, that the equation does not include the propeller pod inertias resisting the tilting, which are required, of course, for a full equation of motion in aircraft pitch.

Hover Roll and Yaw Control: Dynamic Enhancement from Cross-Coupling

If the dual propellers were massless, then hover would require only a static protocol of yaw being simply controlled by *differential* tilting, and roll controlled by differential propeller speeds and hence thrusts. In practice, however, with propellers of non-zero masses – or more accurately, mass-moment of inertias I_R – a beneficial coupling exists between roll and yaw which is exemplified in the following pair of scenarios:

1. Differential tilting of the propellers longitudinally – or by the longitudinal component of oblique tilting – causes the aircraft to first roll, not yaw, due to the gyroscopic rolling moments generated by the tilt rate. If only yaw was intended, then in compensation the flight controller's sensor-actuator must speed one propeller up and slow the other down to change the thrusts and keep the aircraft level. But in doing so the prop-motors will have immediately imparted a net inertial torque on the aircraft, enhancing the originally intended yaw by dynamical (momentum-wheel) means. It is evident from this that increasing the gain of the roll sensor-actuator will improve the yaw response, which has been observed in practice (Ref. 7).
2. Similarly, a differential speed change to intentionally roll the aircraft will in fact cause it to yaw first, since the speed change is again a dynamic, momentum-wheel effect. To correct this, the propellers are immediately directed to differentially tilt, producing a gyroscopic rolling moment which precedes and dynamically enhances the originally intended roll's static protocol of changing thrust.

It should be possible to devise new, dynamic protocols which proactively utilize inertial effects rather than just reactively, thereby making aircraft responses even faster.

Transition

Turning the transition-control knob on the Twister's radio transmitter fully clockwise causes the tilt-servo arms, prop-motors and attached propellers to become tilted forward longitudinally 90 degrees for locked operation in airplane mode (Figure 4).

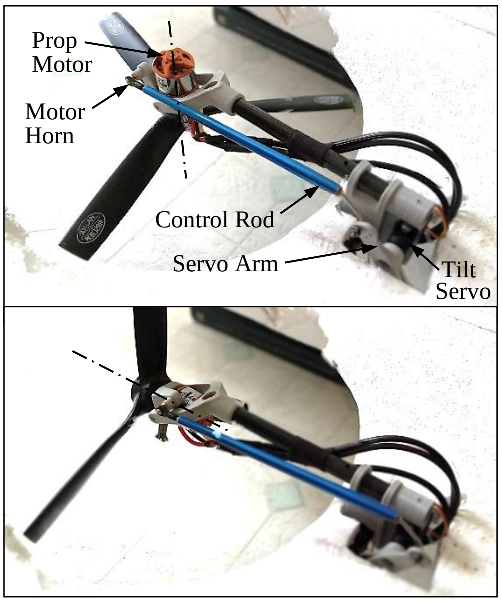


Figure 4. *Top*: RH propeller shown horizontal in hover mode. *Bottom*: Tilted forward 90 deg. in airplane mode.

Oblique pitch-control tilting in hover – commanded by the pilot's elevator stick – essentially morphs into longitudinal transition tilting (Figure 5) with the same servo via the pilot's control knob and a proprietary mechanism not visible in Figure 4. In this way, transition begins with stabilized hover-mode forward motion already in place.

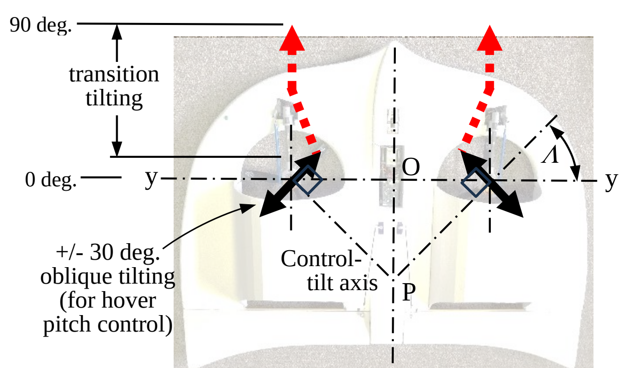


Figure 5. Propeller tilting for hover control and transitioning in Twister model.

The yaw- and pitch-control servo throws are linearly phased out with rotation of the transition knob, and the control of differential prop-motor speeds is linearly transferred from roll inputs to yaw inputs. The elevons, remaining active throughout the flight envelope, become the sole means of roll and pitch control in airplane mode.

TWISTER FLIGHT TEST STATUS

With the GoFly model successfully demonstrating the hovering ability of half-duct aircraft (Table 2, row (a) and Ref. 6), focus for the Twister model has been on its flying well in airplane mode. Hand launched, it is currently flying full circuits in a 300 x 300 ft (100 x 100 m) field and landing in tall grass. With testing in this realm nearly complete, the next focus will be on transitioning to and from airplane mode. Subsequently, a more thorough theoretical analysis of this aircraft type in all its aspects, CFD (computational fluid dynamics) simulations, and wind tunnel testing are all highly desirable prior to and in conjunction with building and flying a full-scale aircraft.

CONCLUSIONS

It has been shown that hover-mode- and airplane-mode-enabling flight elements can be selected and designed for the purpose of augmenting performance in the other mode, that is, cross-modally. At this point, however, only the benefits of the wrap-around canard's fan-in-wing effect have been measured. The half-duct, by closely enveloping the propeller and incurring the inverse Custer channel-wing effect, can theoretically increase lift in airplane mode It is not known, however, if it improves overall airplane-mode performance nor if it augments vertical lift in hover mode.

Active tilting is shown to not only enable the use of just two propellers in hovering eVTOL aircraft, but to impart inertial control moments seen previously only in spacecraft. Not only are propellers the main cross-modal elements in transitioning eVTOL aircraft, these merits – together with the argument that, in terms of energy efficiency, the ideal number of propellers for any aircraft in airplane mode is two – show that their treatment can be augmentative as well. This justifies the use of exotic but transition-enabling flight elements like half-ducts and curved canards, and the search for and development of their cross-modal augmentative capabilities.

If they prove to be beneficial and not just enabling here, the resulting augmentative cross-modal elements – and the approach of employing them and others like them – may then be useful in other aircraft configurations and applications, in place of disparate and conventional flight elements borrowed from existing single-mode aircraft.

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