Elevators in autogyro propeller wake enable low-speed pitch control

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Abstract

Purpose – High autogyro accident rates prompted experimental investigation of this type of aircraft's low-speed pitch characteristics. Pitch control is typically derived from main rotor tip-path-plane adjustment. Thus, autogyro designers often omit horizontal tails and pitch control surfaces. The purpose of this paper is to enable autogyro low-speed pitch control by intentionally placing elevators in the propeller wake.

Design/methodology/approach – Wind tunnel tests were conducted on a 1:10 scale teetering rotor autogyro model. The model included a horizontal tail with elevators placed in the propeller wake. Straight-and-level flight conditions were estimated via a scaling scheme based on the main rotor diameter. At minimum flight speed, the pitching moment induced by 30° elevator deflection was measured. This process was repeated for a range of elevator positions behind the centre of the pitching rotation.

Findings – When placed in an autogyro propeller wake, deflected elevators induce significant pitching moments. If the elevator is shadowed from free stream flow by the autogyro cowling, the pitching moment remains unchanged regardless of the distance between elevators and centre of pitch rotation. However, if the elevator is immersed in the freestream, the pitching moment increases via deflection of both propeller wake and freestream flow.

Research limitations/implications – Kinematic similarity ensures ratios between propeller wake, wind speed, and main rotor flows are representative of full scale. Without flow visualization, main-rotor-diameter-based scaling does not ensure kinematic similarity. Results are therefore qualitative.

Practical implications – Elevators mounted in autogyro propeller wake are worthy of inclusion on all autogyros for pitch control at low speed.

Originality/value – Improved low-speed pitch control arising from elevators mounted in autogyro propeller wake could potentially reduce accidents.

Keywords Propeller-driven aircraft, Flight dynamics

Paper type Research paper

Introduction

This paper is motivated by an autogyro design hypothesis: tail-mounted elevators intentionally located in the propeller wake can provide meaningful low-speed pitch control through thrust deflection. Horizontal tails and pitch control surfaces are often omitted in autogyro design because pitch control is enabled by adjusting the main rotor tip-path-plane. Nonetheless, the pitch stability benefit of large horizontal tails on autogyros of conventional configuration has been reported (Coton *et al.*, 1998). However, intentionally adding elevators that enable thrust deflection for pitch control is a new autogyro design concept that could enable a pilot to ease safely out of a high rotor tip-path-plane attack angle flight situation without loss of altitude.

The autogyro is an aircraft whose lifting mechanism is an unpowered rotor. Although similar in appearance to a helicopter rotor, the autogyro's main rotor operates by a different aerodynamic principle (i.e. autorotation), and it inclines rearward with respect to the flight direction under normal conditions (Glauert, 1927). As no power is transmitted from the airframe to the main rotor, a torque-balancing tail rotor, familiar in most helicopters, is not necessary. A powered propeller, aligned in the flight direction, provides propulsive thrust. Owing to the dominance of fixed-wing aircraft and helicopters in commercial, recreational, and military aviation, published experimental autogyro research is sparse. Nonetheless, a robust recreational autogyro aviation community has developed in the UK. Despite the autogyro's robust and safe flight stability against stall situations, this aircraft type has incurred a particularly high accident rate as compared to other sport aircraft (Houston, 1998). Accidents tend to arise especially from nose-down pitching movements in low-speed forward flight, motivating research to identify autogyro design improvements enabling safer recovery from this precarious flight regime.

Theory and background

The autogyro's flight envelope allows it to achieve very low ground speed. When the aircraft is in straight and level flight at reduced speed, the main rotor tip-path-plane tilts far backwards to maintain air flow through the rotor and provide lift. As the rotor tip-path-plane inclines further backwards, the rotor drag contribution increases. Propeller thrust must be increased to maintain lower straight and level speed. Minimum steady flight speed is achieved when additional engine power available to overcome the increasing main rotor drag is exhausted.

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The schematic-free body diagram (Figure 1(a)) presents the criteria for steady, straight, and level flight of an autogyro with its main rotor at high angle of attack, Θ, with respect to direction of flight. This condition occurs when the sum of forces acting on the aircraft balance in the horizontal and vertical directions and the moments about the aircraft's centre of gravity sum to zero. These statements are represented mathematically via equations (1)-(3):

$$\sum F_X = 0 = T_p - (D + D_r) \quad (1)$$

$$\sum F_Y = 0 = (L_p + L_r + L_f) - W \quad (2)$$

$$\sum M_{cg,z} = 0 \quad (3)$$

In equations (1) and (2), F_X and F_Y are forces in the horizontal and vertical directions, respectively, T_p is the horizontal component of propeller thrust, D is autogyro parasitic drag, D_r is the main rotor induced drag. L_p is the vertical component of propeller thrust, L_r is the main rotor lift, L_f is the lift induced by the fuselage, and W is the all-up-weight of the autogyro. In equation (3), $M_{cg,z}$ is the pitching moment induced about the aircraft's centre of gravity.

Meeting these conditions at high rotor tip-path-plane angle of attack may cause the autogyro to become trapped in the low-speed regime which may lead to a crash. For example, a pilot attempting to induce an autogyro out of the low-speed regime might try to increase speed by tilting the rotor tip-path-plane forward to drop the nose. This manoeuvre, typical for accelerating a fixed-wing aircraft, causes the main rotor tip-path-plane to become more aligned with the onset flow. Lower air flow through the main rotor disk decays main rotor rotation speed, reducing lift. Simultaneously, reduced airframe attack angle drops the propeller's vertical thrust component. The forces in equation (2) no longer sum to zero; L_r and L_p shrink in magnitude while other parameters remain fixed, inducing a net gravitational force toward the ground. The aircraft must descend to again achieve straight and level flight, and if this manoeuvre is performed with inadequate elevation, a crash can occur.

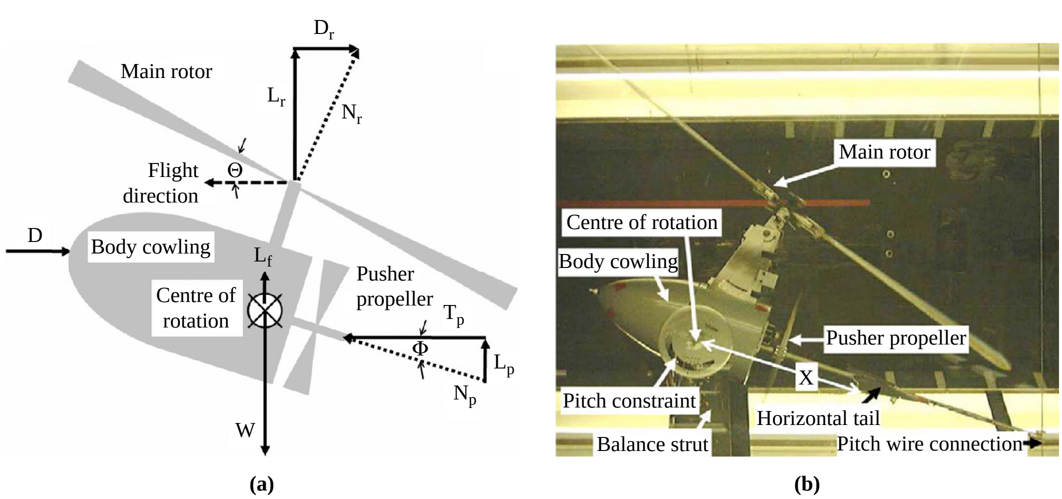
At minimum straight-and-level flight speed, the pilot has exhausted nose-up pitch rotation. However, an outside perturbation such as a wind gust could pitch the aircraft further nose-up. If the gust increases up-flow through the rotor, rotational speed and lift are increased. When equilibrium returns, the engine cannot provide enough forward velocity to drive adequate airflow through the main rotor to maintain straight and level flight. The forces in equation (2) no longer sum to zero; L_r is too small for equilibrium, inducing a net downward force due to gravity. With sufficient altitude, the autogyro descends, and recovers level flight via increased air flow through the rotor disk. A fixed wing aircraft in a similar situation at high angle of attack would stall as flow separation from the wings reduced lift. Since the rotor of an autogyro is always rotating while in flight, it cannot technically stall as some lift is always being produced. However, should the minimum-speed nose-up pitching perturbation occur for an autogyro without sufficient altitude to restore rotor lift adequate to balance weight, the aircraft will crash.

Intentionally placing tail-mounted elevators in the propeller wake to vector the thrust allows the pilot to control the angle of attack of the main rotor tip path plane (Θ) independently of the autogyro body angle of attack (Φ) at low speed. Independent body angle control enables the pilot to ease the autogyro out of the low-speed flight regime in which the aircraft might otherwise become trapped by changing the direction of propeller thrust without changing the attack angle of the main rotor tip path plane. Using propeller thrust vectoring elevator control surfaces, the autogyro body could gently be pitched nose down while the main rotor tip-path-plane angle of attack remains unchanged. This manoeuvre would simultaneously increase airspeed (increasing rotor lift) while reducing the vertical propeller thrust component. In equation (2), equilibrium is preserved as L_r increases while L_p decreases generating no net downward force; therefore, a crash is averted.

Given the potential benefit of the proposed thrust-vectoring elevator improvement, a critical design question is how far behind the propeller (and the CR in pitch) to place the elevator to maximize low-speed pitch control. At least, three competing parameters impact optimal placement:

1 the lever arm distance between the centre of rotation (CR) and elevators;
2 the spatial momentum density in the flow downstream of the propeller; and
3 elevator proximity to the autogyro cowling wake.

Figure 1 Autogyro schematic (a) showing forces acting on the aircraft in straight-and-level flight. For comparison, an image of the autogyro wind tunnel model and (b) operating at its lowest straight-and-level flight speed



As will be shown in the discussion, elevator cowling wake proximity is important because it determines whether the elevator is exposed to free stream flow induced by the autogyro's forward velocity. When the elevator is close enough to be in the cowling wake (and therefore shadowed from the surrounding flow) only the lever arm and propeller wake momentum density are important to pitching moment generation. Not considered herein are details of the complex interactions between the main rotor and pusher propeller.

Experimental apparatus

Experimental data were obtained using a working 1:10 scale autogyro model at the University of Bristol's 7 × 5 ft. wind tunnel. The model, pictured in Figure 1(b), was not intended to be representative of an existing aircraft, but rather to embody the principal elements of any autogyro and be adaptable to many different flight situations. A shaft ran through the model, allowing it to pitch about a CR, mimicking rotation about a centre of gravity that would occur in a real aircraft. While the model had capacity to pitch nose-up and nose-down about its CR, it could not yaw or roll. A pitch constraint prevented the model from damaging itself by over pitching. A long rod protruding from the tail was pinned to the wind tunnel's pitch wire to control body incidence. Upon the tail rod, a pair of strain gauges was fixed, top and bottom, to provide pitching moment data. As is typical for helicopter wind tunnel tests, the model was mounted upside-down between two struts from the wind tunnel's force balance. Note that Figure 1b has been rotated 180° to orient the model as an autogyro in normal flight would appear to provide clearer comparison to the schematic in Figure 1(a) and the equations for straight-and-level flight. Since the autogyro body position was static in all tests, orientation with respect to gravity did not impact results. To eliminate balance strut and pitch constraint aerodynamic effects from the measurements, their lift and drag versus wind tunnel speed were measured without the autogyro model, and these values were accounted for in later measurements.

The model's main rotor was a two-bladed teetering rotor 95 cm in diameter. Mounted atop the airframe, the spindle of the main rotor could be actively tilted by a servo from 0° rearward through a 20° inclination with respect to the model. This function replicated a pilot's main rotor pitch control. The model had no facility for adjusting individual blade pitch during flight. Tilting the rotor increased the incidence of the advancing blade with respect to the retreating one. These cyclic incidences reached maximum and minimum values when the blades were perpendicular to the flow. The 90° phase lag characteristic of rotor systems caused the blades to fly highest over the nose and lowest over the tail. The resulting effect was an increase in the main rotor tip-path-plane angle of attack. Others have published numerical autogyro flight dynamics studies simulating performance via computer models based on wind tunnel data from an airframe absent a main rotor (Thomson and Houston, 2008). An important contribution of the current paper is to report experimental autogyro wind tunnel results where a main rotor was used, and the lift it generated established the flight conditions for data collection.

A horizontal stabilizer with servo-controlled elevators was attached to the rear of the model. As shown in Figure 1(b), the stabilizer could slide from a location nearly abutting the propeller to a distance about 300 mm behind the CR (about 150 mm away from the propeller). This flexible design allowed elevator pitching moment effectiveness measurement with respect to X, where X is the distance between the CR and the leading edge of the horizontal stabilizer (X is shown in Figure 1(b)). The thrust-line was initially aligned with the CR, but as described in the results, it was adjusted below the CR (away from the main rotor) in the second round of experiments to clear the cowling wake at lower X-value. A complete description of the model's capabilities and features is outlined elsewhere (Traum and Carter, 2005).

Methods

Owing to the density of motors and sensor equipment inside the autogyro body, the model was heavier and the airframe larger than would be expected for a functional autogyro with a similar main rotor size. It was therefore unrealistic to model straight and level flight by balancing the model's actual weight against main rotor lift. It was also impossible to use the model's actual drag to balance propeller thrust. A scaling scheme, broadly applicable to all rotorcraft wind tunnel models, was applied to estimate straight-and-level flight conditions.

Estimations of typical main rotor loading and aircraft drag were developed from a survey of performance data for 32 conventional sport-class autogyros from major manufacturers. Data were obtained from manufacturer specifications listed by the Popular Rotorcraft Association (www.pra.org). These values were applied to the model according to the scaled ratio of model main rotor diameter to the main rotor diameter of each autogyro on the survey. Without flow visualization, main-rotor-diameter-based scaling did not ensure kinematic similarity. So, while elevator-induced pitch moments measured experimentally here will be qualitatively replicated in a full-scale aircraft, these moments will not necessarily scale up with main rotor diameter. The survey yielded a requirement that the model generate 6.87 N of lift to simulate straight and level flight. To calibrate drag, a lift-to-drag ratio of about 3:1 was derived from maximum flight speed and engine power data for the real aircraft.

For steady-level flight, lift remains constant regardless of the airspeed, but drag decreases with decreasing airspeed. So lift-to-drag ratio increases as airspeed is reduced. Thus, a lift-to-drag ratio of 6:1 was used, which is justified because the lift-to-drag ratios obtained from the real autogyros were for maximum speed; doubling this number for low speed was conservative. For example, the quotient of lowest speed to maximum speed lift-to-drag ratios for the Benson gyrocopter (http://bensengyrocopter.com/) is only 1.05.

Lift and thrust on the model were measured using the wind tunnel's balance system. Before the experiment, the lowest wind tunnel speed at which the model could attain steady, level flight (6:1 lift-to-thrust ratio) was established. With the tunnel running at this speed, the experiment proceeded in four steps. First, the body angle of incidence was set at the highest attainable value of 19°. Second, the minimum straight and level flight speed of the model was achieved using an iterative process whereby the propeller thrust was adjusted until the lift-to-thrust ratio was 6:1. Then main rotor tip-path plane was trimmed until the measured pitching moment zeroed. Then the propeller thrust was again adjusted for a lift-to-thrust ratio of 6:1, and the process was repeated until no further adjustments were needed to achieve zero pitching moment and a 6:1 lift-to-thrust ratio.

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This condition was established with the horizontal stabilizer positioned as close to the CR as possible (179 mm behind the CR) and the elevator at neutral position. Third, the elevator was set to its maximum nose-down deflection of 30°, and the associated negative pitching moment on the model was recorded. Finally, the horizontal stabilizer was moved to one of five predetermined X locations behind the CR, set about 30 mm apart, and the new resulting negative pitching moment for each location was measured. As stated above, placement of dense electrical motors and sensor equipment inside the autogyro body made the model relatively heavier than functional autogyro, and the model's centre of mass did not align with its CR. This misalignment induced an artificial pitching moment around the CR. However, by following the same pitching moment zeroing routine for all five predetermined horizontal stabilizer locations behind the CR, this artificial pitching moment was trimmed out in all the tests and therefore did not impact the result.

The experimental uncertainty in X was estimated at ±2.5 mm, the accuracy with which the leading edge of the horizontal stabilizer could be located with respect the CR using a calliper. The uncertainty in the pitching moment was estimated at ±20 N-mm, a value driven by normal airframe vibration during testing. Vibrations necessitated time-averaging of the pitching data generated from each configuration, and to ensure accuracy, the reported uncertainty arose from the largest deviation between an average and peak values for the entire data set. Despite larger-than-desired pitching moment uncertainty, the resulting data retain adequate fidelity for analysis.

Results

Figure 1(a) shows the autogyro model as it appeared at minimum attainable straight-and-level flight speed with the propeller thrust vector running through the CR. The body was inclined to 19° and there was no elevator deflection. Consequently, this position yielded the highest achievable main rotor tip-path-plane angle of incidence, 38°. At this highest angle of body and main rotor incidence, the pitch moments created by the fully deflected elevators at five locations behind the CR (five X-values) were measured, and these data are represented by the black markers in Figure 2.

Figure 2 Pitching moments about the model's CR for varying elevator position, X, at two thrust-line positions

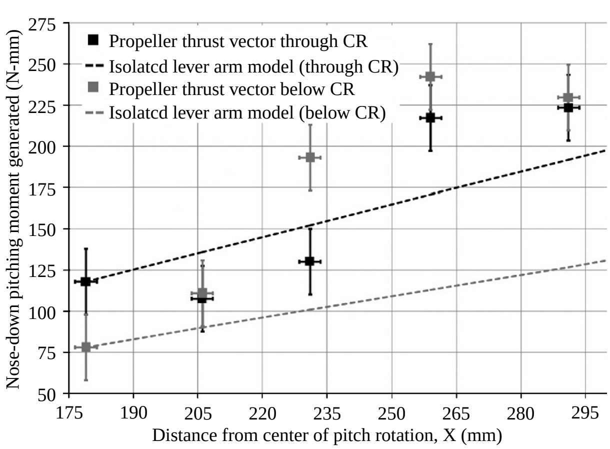

Figure 1(b) shows the horizontal tail at X = 291 mm, the longest lever arm used in this set of experiments.

For this condition with the propeller thrust vector running through the CR, the pitching moment is essentially identical (within experimental uncertainty) for the three horizontal stabilizer X positions closest to the CR. It then abruptly increases at the two farthest positions. It was hypothesized that this sudden change resulted from the elevator clearing the autogyro's cowling wake for larger X-values, and the observed increased pitching moment resulted from a deflection of both the propeller wake and the free stream flow. While tufts might have been used to qualitatively test this hypothesis, a more quantitative experimental technique was opted for instead. The propeller and horizontal tail assembly were repositioned vertically downward, as far as possible from the main rotor. This position was selected because at high autogyro body incidence the elevators cleared the cowling wake at a smaller of X than the first position. Thus, for the second position, a jump in pitching moment was expected to appear at lower X because the elevators intersected the free stream flow when closer to the CR; this result is exactly what was observed. The gray data markers in Figure 2 represent measured pitch moments created by the fully deflected elevators at five locations behind the CR (five X-values) with the propeller thrust vector running below the CR.

It was recognized that the propeller thrust vector running below the CR induced a nose-up pitching moment that was not present when the propeller thrust vector ran through the CR. This extra pitch moment was trimmed out using the iterative technique described in methods to achieve a zero-pitch starting condition for experiments with thrust-line below the CR.

Discussion

Figure 2 confirms the motivating hypothesis of this paper: tail-mounted elevators intentionally located in the propeller wake provide meaningful low-speed pitch control through thrust deflection. Regardless of how far away from the CR the elevators are placed, these control surfaces always induce a nose-down pitching moment on the aircraft. Two additional important Figure 2 observations with respect to elevator placement also warrant discussion.

First, there is an abrupt increase in the pitching moment at X = 259 mm for the centred propeller thrust-line position, and at X = 231 mm in the data taken with the thrust line below the CR. As described in the results section, this sudden change in pitching moment is attributed to the horizontal tail and elevator leaving shadowing effect of the autogyro cowling for larger X at high body incidence. In this position these surfaces deflect both the propeller wake and the free stream flow, increasing pitching moment beyond what was possible by deflecting the propeller wake alone. Although smoke-based flow visualization was not available on this closed-circuit wind tunnel, Figure 1(b) clearly shows at high body incidence that the elevator surfaces are below the bottom part of the cowling (Figure 1(b) shows X = 291 mm and centred thrust-line) and likely beyond its shadowing effect. Moving the thrust line toward the bottom of the model allows these horizontal surfaces to interact with the free stream flow at lower X, as is verified in Figure 2 by the difference in pitching moments at X = 231 mm between the two thrust line locations.

Second, with the exception of the abrupt increases in pitching moment when the elevators and horizontal tail enter the free stream flow, there is no clear X dependence on pitching moment (within the experimental uncertainty) for either thrust-line location data set. Pitching moment induced by the elevator follows the relation in equation (4), which upon first inspection suggests that the moment should increase with increasing X:

$$\sum M_{cg,z,ele} = F_{y,ele} X \tag{4}$$

To clarify this point, $M_{cg,z,ele}$, the pitching moment induced about the aircraft's centre of gravity by the elevator, in equation (4) is shown in Figure 2, but with $F_{y,ele}$, the force induced in the vertical direction by the elevator, held constant at the measured values for X = 179 mm. In this "isolated lever arm model" increase in $M_{cg,z,ele}$ is attributed only to increasing X. However, for data with thrust vector through the CR, $M_{cg,z,ele}$ is not increasing with X and does not follow the isolated lever arm model. Moreover, a better representation for the thrust-line-centred data where the stabilizer is in the cowling wake (for X = 179, 206 and 231 mm) is a horizontal line with no X dependence. For the data with thrust vector below the CR, the isolated lever arm model does provide a reasonable prediction for $M_{cg,z,ele}$ where the stabilizer is in the cowling wake (for X = 179 mm and 206 mm). However, it is equally valid to represent these data with a horizontal line, leaving interpretation ambiguous.

Lack of observed clear X dependence in the data requires $F_{y,ele}$ be proportional to 1/X. Preventing $F_{y,ele}$ from tending to infinity for small X is the geometry of the autogyro; X less than 179 mm implies the leading edge of the horizontal tail intersects the propeller, which is unphysical. The competing effects of lever arm length and force induced by propeller wake momentum deflection cancel. To model $F_{y,ele}$ for a control surface deflecting propeller wake, Roskam and Lan suggest an approximation based on actuator disk theory where the velocity (and hence momentum density) of the propeller wake is uniform at all downstream stations and radial locations within the wake (Roskam and Lan, 2000). An important result from this model is that the force produced by the elevator is proportional to the velocity (and therefore the momentum) of the deflected flow. However, if the Roskam and Lan approximation were viable for this case, $F_{y,ele}$ would have no X dependence, and $M_{cg,z,ele}$ would grow linearly with X, which it does not.

Another possible model for the propeller wake is the velocity distribution of a turbulent axisymmetric jet formed from uniform plug flow issuing into quiescent fluid from a round orifice. By applying momentum conservation to simplified versions of the Navier-Stokes equation, Blevins suggests the velocity distribution, $u(X,R)$, approximation,

$$u(X,R) = \frac{M}{X} e^{-94 \cdot (R/X)^2} \tag{5}$$

where M is a constant proportional to the square root of jet's momentum (Blevins, 1984), and R is the radial distance from the jet's centreline. For large X and small R (jet locations far downstream and close to the centreline), this expression approximates 1/X, giving a mutual cancellation with the pitching moment lever arm. However, a propeller wake is not jet flow, particularly at locations near to the propeller where the elevators were operating. In fact, there is almost no flow velocity in the wake near the propeller hub, the flow velocity grows at larger propeller radius, and the propeller's tips shed complex vortex formations (Watanabe *et al.*, 1997).

As a simple bounding case that best captures the observed experimental result, it is proposed that the velocity field (and hence momentum density) of the propeller wake be approximated by the centreline velocity of a turbulent jet, equation (5) where R = 0, which is proportional to 1/X. The elevator is assumed to deflect propeller wake flow at this centreline velocity, meaning $F_{y,ele}$ is proportional to 1/X. The pitching moment remains constant for all X values, provided the elevators are shadowed from the free stream velocity by the autogyro's body cowling. This behaviour matches the pitching behaviour experimentally observed.

Conclusions

Results from experiments on a wind tunnel autogyro model show that pitching control can be achieved for autogyros in low-speed forward flight by the addition of elevators intentionally located in the propeller wake. These control surfaces could be used by autogyro pilots for recovery out of the minimum straight-and-level speed flight regime without altitude loss.

Absence of kinematic similarity between the model and any real aircraft prevents the pitching moment magnitude from being quantified for real autogyros using the data collected here. Nonetheless, two important conclusions were reached. First, the highest nose-down pitching moment is obtained by placing the horizontal tail and elevators far enough behind the autogyro's centre of pitch rotation that these surfaces interface the free stream flow when the aircraft is in its high-attack-angle low-speed flight regime. Autogyro designers should balance this benefit against the difficulty an overly large or lengthy horizontal stabilizer with elevators could present during landing. Second, when the elevator and horizontal stabilizer are in the autogyro cowling wake, there is no relationship between the magnitude of the nose-down pitching moment and the distance between the control surface and the autogyro's CR in the low-speed regime. By approximating the velocity field in the propeller wake with the centreline velocity of a turbulent jet, this phenomenon is explained by mutual cancellation. The pitching moment lever arm is proportional to X, and the momentum density of the propeller wake defected by the elevator is proportional to 1/X.

Further work

While increased pitching moment arising from the horizontal tail clearing the body cowling was inferred from the experimental results, future work will include flow visualization for direct verification. Moreover, flow visualization can also elucidate complex interactions between the main rotor and pusher propeller, which are not considered in this preliminary study. In the future, a comparison between the pitching moments with the horizontal tail in place and removed would differentiate between the pitch-stabilizing effects of the horizontal tail versus the pitch-controlling effect of the elevators. Also, this test program did not demonstrate the impact of the elevators at any deflections other than neutral and maximum nose down. Future testing should include elevator deflection as an independent variable.

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