JOURNAL OF AIRCRAFT
Vol. 44, No. 6, November–December 2007

Design Forum

DESIGN FORUM papers range from design case studies to presentations of new methodologies to speculations about emerging design trends. They vary from 2500 to 12,000 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Experimental Study of a Micro Air Vehicle with a Rotatable Tail

José Rivera Parga,* Mark F. Reeder,† and Troy Leveron‡
U.S. Air Force Institute of Technology, Wright–Patterson Air Force Base, Ohio 45433
and
Ken Blackburn§
U.S. Air Force Research Laboratory, Eglin Air Force Base, Florida 32542

DOI: 10.2514/1.24192

An experimental study of a rotatable tail mechanism applied to a small unmanned aerial vehicle was performed using a six-component wind-tunnel balance in the U.S. Air Force Institute of Technology low-speed wind tunnel. Attributes of the control and stability characteristics of the original vehicle, which were documented in an earlier study, are compared with those of a unique control methodology, a tail consisting of a single surface, with controllable elevation and rotation. An advantage of this change is a reduction in the storage length of the vehicle. Because there are similarities in the rotatable tail mechanism and the tail of many birds, the rotatable tail reflects a biomimetric feature. Measured force and moment coefficient measurements for the actual vehicle at a typical flight speed indicated that a rotatable tail provides a sufficient yaw moment for turning. For example, yaw moment coefficients C_n, ranging from -0.02 to $+0.02$, which is typical for a rudder, were achievable as long as the absolute value of the tail elevation angle was large. The dependence of the yaw moment coefficient on the elevator angle and angle of attack, in addition to the tail rotation angle, indicates that there would be significant challenges in applying a robust flight control scheme with the current actuator configuration. An additional feature of the tail design is that by deflecting the tail upward, it could also function effectively as an air brake. A more than twofold increase in drag coefficient for constant angle of attack was measured when the tail elevation angle was increased to nearly 70 deg.

Introduction

FOR a variety of reasons, there is a rising need for the development of smaller and lighter unmanned aerial vehicles (UAVs) to perform surveillance missions. The U.S. Air Force Research Laboratory, Munitions Directorate, Flight Vehicles Integration Branch (AFRL/MNAV) developed a man-portable, carbon-fiber-matrix UAV with a flexible wing of 24-in. span, 6-in. root chord, and 18.2-in. length. One important design goal is to minimize the storage volume of the vehicle to improve its portability, and the present investigation was performed to explore a unique approach that could accomplish this. In the configuration studied and described here, a rotatable tail mechanism was applied. One of its potential advantages is that the tail may be folded over the fuselage, reducing the storage length of the vehicle by approximately 50%. Naturally, although any reduction in the vehicle's storage length is desirable, the primary function of the tail is to provide a means to control and stabilize the aircraft.

The objective of this experimental study was to determine the general behavior and the aerodynamic characteristics of a rotatable tail used for stability and control using wind-tunnel testing. The mechanism enabled control of two degrees of freedom for a single control surface, which was the tail in its entirety. The controls were configured to provide elevation and rotation. In some respects, this type of control mechanism is analogous to a simplified form of a bird's tail. Although some general literature (including one patent and several biological research studies) is germane to this subject, there is a surprising dearth of aerodynamic studies on how a rotatable tail mechanism might be applied. This experimental study was undertaken using the U.S. Air Force Institute of Technology (AFIT) low-speed wind tunnel to address this need.

It is important to point out that aircraft enthusiasts and engineers have built aircraft with rotatable tails. To the authors' knowledge, the earliest work documenting this effort is contained in the U.S. patent granted to William Nash in 1990, but the patent itself contains limited information on the aircraft's handling characteristics [1]. The patent describes a mechanism whereby a control surface can be controlled in two axes, supported by two sets of bearings. In that sense, it is similar to the mechanism studied. The application differs, however, in that the inventor described the primary application of the tail as a means to account for Mach number effects and generally envisioned an application of dual-tail planes on full-scale manned aircraft. By contrast, an article authored by Hoey [2] at nearly the same time (1992) described the handling characteristics of a rotatable tail model aircraft in considerable detail.

Presented as Paper 4756 at the 35th AIAA Fluid Dynamics Conference and Exhibit, Toronto, 6–9 June 2005; received 24 March 2006; revision received 8 November 2006; accepted for publication 9 May 2007.

*Lieutenant, Navy, Republic of Mexico.
†Assistant Professor, Department of Aeronautics and Astronautics. Member AIAA.
‡Ensign, U.S. Navy; Graduate Student.
§Research Engineer, Munitions Directorate, Flight Vehicles Integration Branch.

Another more recent example of a bio-inspired tail design is described by Intercept Technologies on their company web site. This company has developed an aircraft termed the Robofalcon™ [3] that likewise uses a rotatable tail and may be used in proximity to airports. The aircraft is designed to mimic the flight of a predator bird of prey, and its primary application is to prevent smaller birds from entering the flight path of aircraft as they take off and land. A point of emphasis is that the requirement that the aircraft closely mimic bird flight to achieve the application goal suggests that a rotatable tail should be used regardless of whether it provides as much control authority as a traditional aircraft tail. Thus, this illustrates one practical situation for which quantitative data on the characteristics of a rotatable tail would be desirable. With the growing interest in small unmanned vehicles, it is plausible, and perhaps likely, that there are other bio-inspired tail designs that have been developed and tested. This investigation is dedicated to improving knowledge of rotatable tail characteristics and performance through measurements of force and moment coefficients conducted in a wind tunnel for a specific aircraft and tail design.

The aircraft, originally designed with a V-tail, described herein was based on a flexible wing design, as described in earlier work [4–6]. The original aircraft is shown in Fig. 1a, and views of the modified aircraft configuration are given in Figs. 1b–1d. Note that the original vehicle included a V-tail, spaced approximately half the wingspan aft of the wing. Two ruddervators were used to control the aircraft, which enabled control of pitch and, primarily, yaw. In Fig. 1b, a top view of the vehicle with the modified tail is shown. Figures 1c and 1d illustrate the aircraft with the tail positioned as noted. It is worth noting that the definition of the tail elevation is consistent with that of a traditional aircraft tail. The rotation convention noted in Fig. 1d was drawn from the right-hand rule with the body axis of the aircraft.

Details of the control configuration for the rotatable tail are shown in Fig. 2. As configured, the actuator for elevation control was connected to a thin rod that in turn was affixed to a rack. Elevation was controlled by moving the rack along the longitudinal axis, in turn, rotating a gear affixed to a shaft upon which the tail was mounted. The actuator for rotation turned a gear, or in an alternative design extended a control rod, which caused the rotation of a trunnion supported by two bearings. The trunnion was made using rapid prototyping and included a square, hollow, center section so that the rack could be inserted with freedom of motion in the longitudinal direction. The net result of this configuration was two-degree-of-freedom control of the tail. One benefit of this configuration is that various tail geometries may be changed out easily. Herein, only one tail design, consisting of a frame of thickness 0.07 in., maximum chord of 4.66 in., and with an area of 9.4 in.^{2} was used. No attempt was made to generate a tail with an airfoil shape, though a very mild dihedral was included in this tail design, as is visible in Fig. 1.

This relatively simple mechanical design provides a level of tail control in two axes. Considering that a typical bird can change its tail geometry by spreading it or retracting it, in addition to simply rotating and elevating it, this design clearly represents a simplification of a bird's tail. Therefore, a review of some pertinent biological data is worthwhile. As a first step in this process, the horizontal tail volume coefficient for a variety of bird species was estimated using plan views of various bird species provided by Rayner [7], and this is shown in Fig. 3. Here, the center of gravity of the bird is estimated as being at the quarter-chord at the root of the extended wing. Values are typically lower than those of traditional aircraft, though some crossover is evident.

From this, one might draw one of two possible conclusions. One plausible conclusion is that perhaps a bird uses the additional degrees of freedom related to wing flexure to control its flight. In support of this view, some in the biological community view the primary importance of a bird's tail as ornamental rather than for aerodynamics [8]. On the other hand, one might hypothesize that a typical bird's tail might more effectively provide a side force to control turning and flight. In this case, the generally lower value of the tail volume coefficient might simply result from improved flight control function compared with that of a typical aircraft.

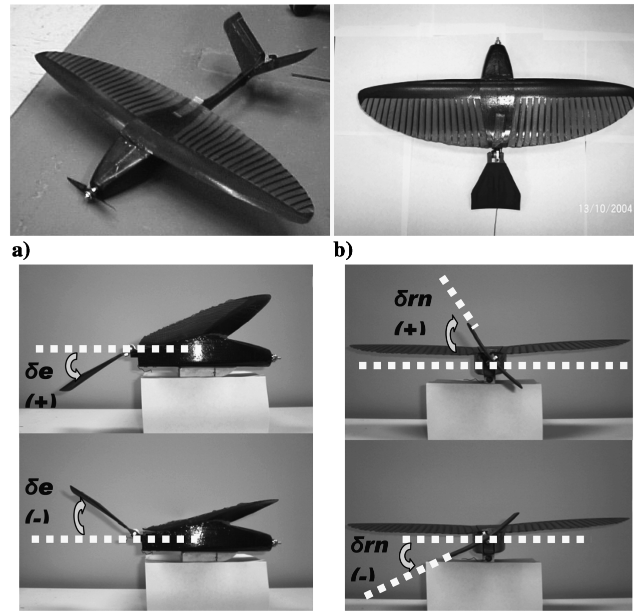

Fig. 1 Shown are a) the original aircraft, b) the aircraft modified to include the rotatable tail (propeller off), c) side views of the rotatable tail aircraft with the elevation convention noted, and d) a rear view of the rotatable tail aircraft with the tail rotation convention noted.

In historical literature, there are a wide variety of opinions on the function of the tail in birds. For instance, one author (Horton-Smith [9] in a 1938 text, *The Flight of Birds*, page 38) states, "A bird, like an airplane, uses rotation of wing and tail. There is no vertical fin in the bird's tail so it has to relay on banking. It is possible that a long tail, when bent to one side, may function as a rudder."

Likewise, John H. Storer [10], author of the book *The Flight of Birds Analyzed Through Slow-Motion Photography* (1948), concurs:

> The tail of a bird, indeed, has many uses. It can steer in any direction, act as a brake, form a slot behind the wings, or become a part of the bird's lifting surface, supplementing the wings. The swallow-tailed kite twists its tail to steer. It may turn its tail so that either the upper or the lower surfaces will strike the air stream in steering. The tail sides of the tail maybe controlled separately.

By contrast, Karl Nickel and Michael Wohlfahrt [11], in their much more recent book, *Tailless Aircraft in Theory and Practice* (1994, p. 25), make the case that a bird's tail is not as critical for flight control, as follows: "The tail of birds virtually has no stabilizing effect. It is hence not a stabilizing instrument. Only to a limited extent is it used as a steering device. Mostly it is used at low speed as a landing flap."

The current biological debate on the function of a bird's tail in aerodynamics is far from settled and reflects these two views of tail function. For example, the following quote drawn from an article in Science News dated 2001 [8] typifies the discussion. "The study of bird tails 'is very polarized,' Rayner says. One camp of theorists emphasizes the importance of ordinary physics, and the other camp points to the extraordinary tails of male peacocks and barn swallows as examples of sexy fashions overpowering sensible aerodynamics."

A valuable discussion of observed tail positions and muscle activity during flight is given by Warrick et al. [12]. One comment from the Introduction of this paper reinforces the uncertainty in some areas of the role played by the bird's tail: "Beyond its theoretical capabilities, the precise use of the tail in flying birds has not been thoroughly documented."

However, Warrick et al. [12] do go on to present a histogram of occurrences of tail elevation, twist, depression, combined twist and depression, and no tail manipulation for a swallow during a series of videotaped prey-capture maneuvers. Though the data are limited to a

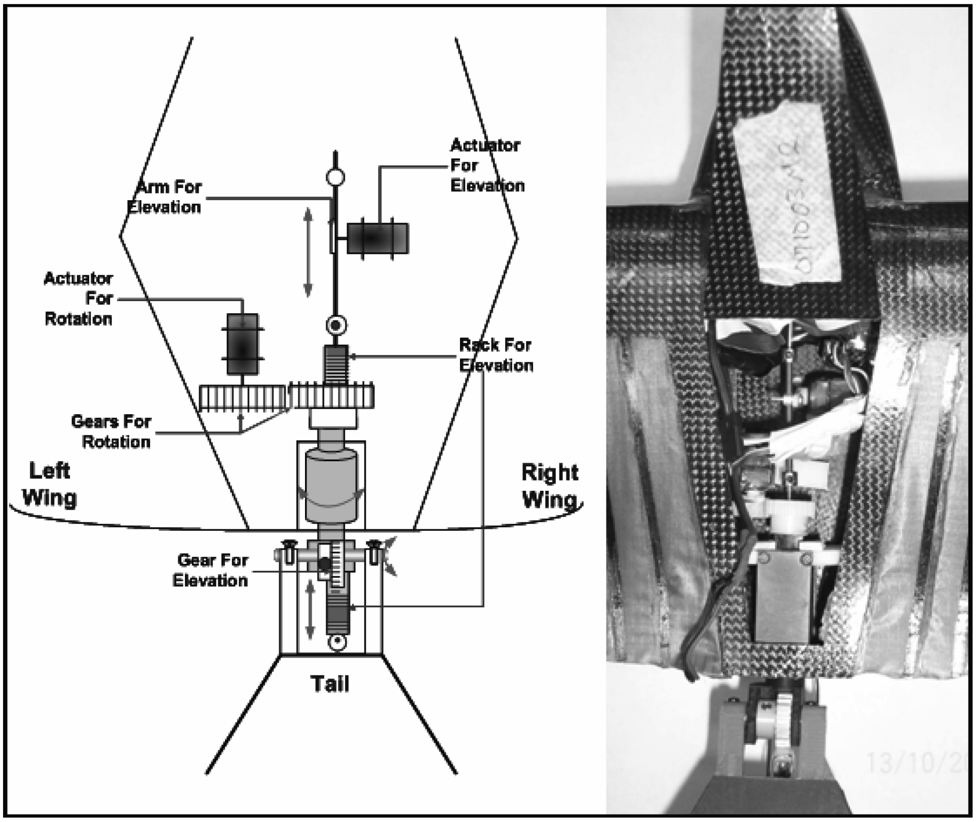

Fig. 2 Top view of the flight controls used for the rotatable tail.

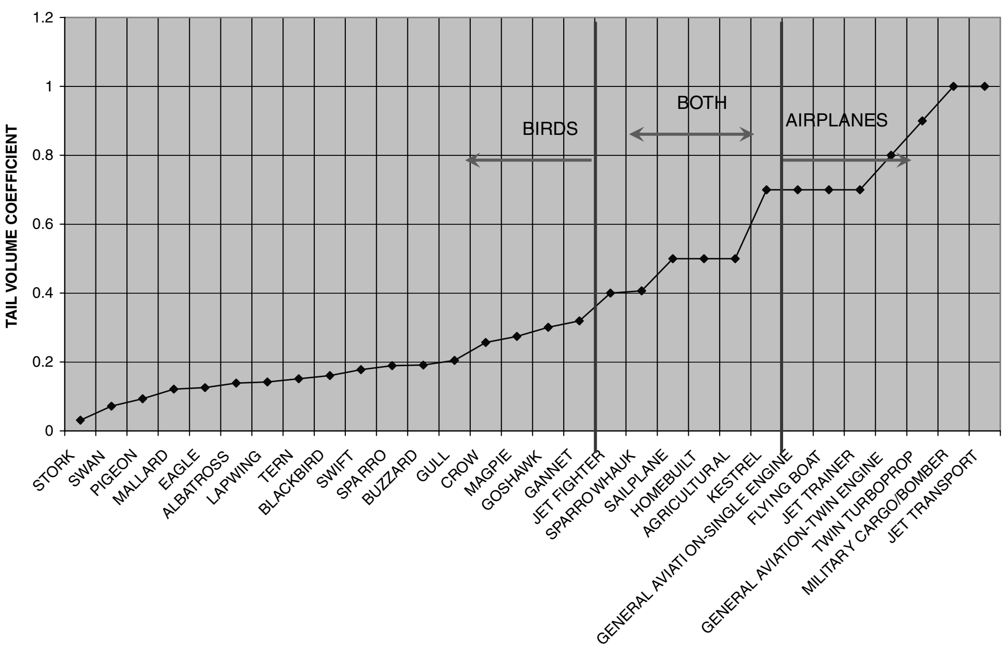

Fig. 3 Summary of horizontal tail volume coefficient data for birds and typical aircraft.

few hundred maneuvering observations, the data suggest that tail elevation (pitch up) is used only to increase drag to stall the flight and initiate a dive. Furthermore, the most common tail orientation during a level turn was a combined tail depression and twist, whereas the most common tail orientation during a climb was depression (pitch down) only. These observed behaviors of birds using their tails are by and large consistent with the wind-tunnel results of the present investigation devoted to studies of a small unmanned aerial vehicle with a rotatable tail, which, by comparison, is highly simplified.

Experimental Setup

The wind tunnel used for this study was the AFIT low-speed wind tunnel. It is capable of operating at speeds up to approximately

Table 1 Wind-tunnel balance specifications

AFIT-1 Modern Machine Tool balance specifications	
Normal force, total	10 lb
Side force, total	5 lb
Axial force	5 lb
Pitching moment	10 in.-lb
Rolling moment	4 in.-lb
Yawing moment	5 in.-lb

145 mph and has optical access on three sides. The dimensions of the section are 31-in. height, 44-in. width, and 72-in. length. Inside this section, the model is supported by a remotely controlled sting. This sting can be moved from −20 to +20 deg of angle of attack and from −20 to +20 deg sideslip angles using two servomotor controls. More details of the tunnel and configuration is given by earlier work [6,13]. The forces and moments acting on the model are sensed by a balance, and data are sent and stored in the control computer located in the wind-tunnel control room.

An internal six-component balance manufactured by Modern Machine & Tool Company, Inc. was used, and its specifications are given in Table 1. The balance was inserted inside a block mounted on the lower portion of the air vehicle. This block was built to closely match the dimensions of a camera pod on a version of the original vehicle, and a front view of the aircraft in the tunnel is given in Fig. 4. Moments were transferred to a reference center of gravity (c.g.) of the aircraft. The term "reference" alludes to the fact that the tail deflection itself caused slight changes in the c.g., and this small change was not factored into the moment coefficient calculations. The longitudinal location of the reference c.g. was the actual center of gravity for the aircraft with both the tail elevation and rotation set to zero. This longitudinal location as tested was slightly forward of the quarter-chord of the wing. The small balance was appropriate for the raw measured loads during the test. The operation of the wind tunnel at 30 mph led to raw values for roll moment ranging from −0.12 to 0.12 in. · lbf, which is reasonable when compared with the manufacturer's rated balance resolution of 0.01 in. · lbf. The smallest value of the axial force measured during the test was approximately 0.13 lbf, which was 2.6% of the full range of the axial gage.

The data were acquired and averaged over a period of about 30 s and processed in accordance with the procedure described in the literature [14]. Solid blockage was taken into account, though notably, the small thickness of the wing led to only a minor correction in the load data due to this effect. The 6 by 27 interaction matrix was provided by the balance manufacturer. It should be pointed out that the tare was performed with the tail having zero elevation and rotation, as opposed to measuring the actual moment applied for each tail setting. This was deemed to be an acceptable approach due to the light weight of the tail and its relatively small displacement through actuation. This was confirmed through measurements of the change in the wind-off roll moment, which was the most sensitive to tail position. The weight of the modified vehicle was approximately 400 g, and all tests were performed with the propeller off. The mass of the tail was 15 g. Additional details of the data processing are given in [6,13,15].

Fig. 4 Picture of the vehicle mounted in the tunnel. As viewed, the tail is oriented with negative elevation and negative rotation.

Results and Analysis

Throughout the test, a wide variety of measurements were conducted on the aircraft. From the standpoint of the tail design, however, the most straightforward set of results as it concerns the fundamental effect of the rotatable tail on the forces and moments of the aircraft is via a parametric study of tail positions. This was done by maintaining both the pitch and sideslip angles as constant and adjusting the control surface actuators to position the tail through a matrix of elevation and rotation angles. These data were collected for a single air speed, 30 mph, which corresponded to a Reynolds number, based on mean aerodynamic chord, of 1.3×10^5. The value for α was 4.7 deg, whereas the sideslip angle was set to 0 deg. It is notable that the reference angle used for α was taken with respect to the nearly flat bottom surface of the vehicle, which in turn resulted in a positive lift at, nominally, $\alpha = 0$ deg.

Figure 5 shows how the lift coefficient varies with elevation and rotation angles. Note that a positive elevation is consistent with a downward deflection of the tail. For this reason, positive elevation is shown as downward on this plot, and this convention is also used for the remaining contour plots. The most important features of this contour plot are that the tail does influence the lift coefficient through elevation, as one would expect. Rotating the tail to values of δ_m other than zero does slightly reduce the lift coefficient. This result is anticipated if one considers that the tail rotation mildly reduces the horizontal lifting area of the tail.

Figure 6 shows how the drag coefficient varies with elevation and rotation angles. With reference to Fig. 5, this contour plot indicates that the effect of tail rotation and elevation on drag through this range of angles is primarily due to induced drag. As with the lift coefficient, rotation of the tail has a relatively small effect. One subtle but important trend is that for negative elevation angles of less than approximately −10 deg, the drag coefficient shows a mild increase, rather than a decrease, as the tail is defected upward (toward a more negative δ_e). Because this was not accompanied with an increase in lift for similar elevation angles, it is an indication that under this condition, the tail is, in part, acting as a spoiler. A similar circumstance cannot be ruled out when the tail elevation is positive (deflected downward).

Figure 7 shows how the pitching moment coefficient varies with elevation and rotation angles. In the particular test sequence ($\alpha = 4$ deg), the trim condition ($C_m = 0$) would occur only with the tail setting at or near −12 deg. It should be noted that, in practice, it would be desirable to reduce the drag at this trim condition by repositioning the wing to a more forward position along the fuselage.

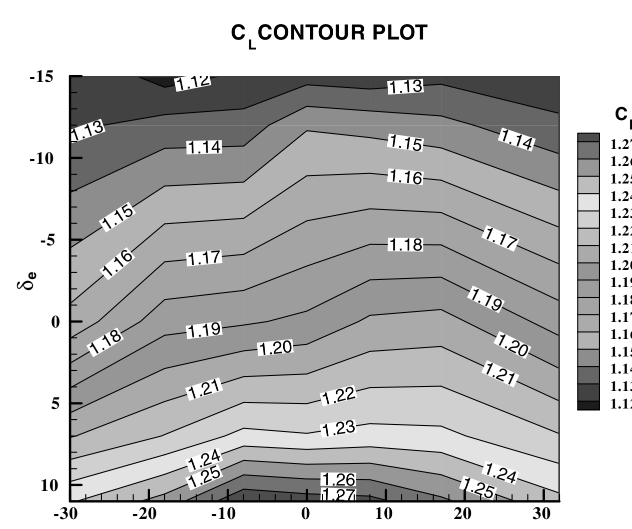

Fig. 5 Lift coefficient data as functions of tail elevation and rotation.

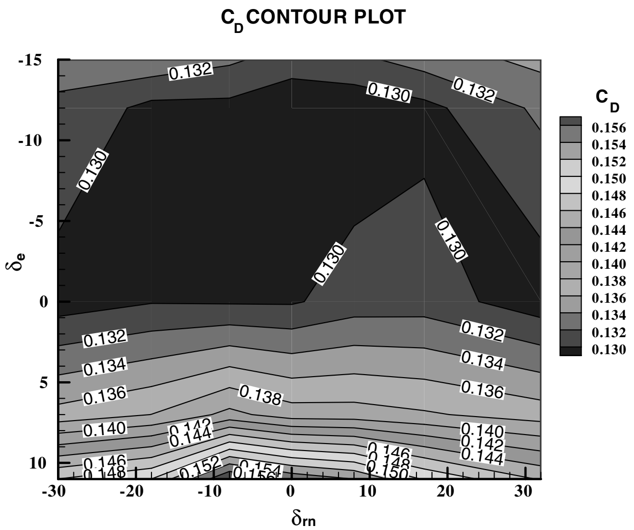

Fig. 6 Drag coefficient data as functions of tail elevation and rotation.

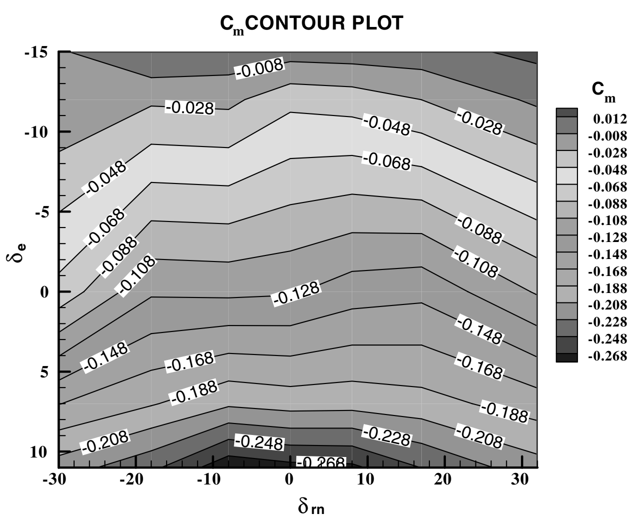

Fig. 7 Pitching moment coefficient data as functions of tail elevation and rotation.

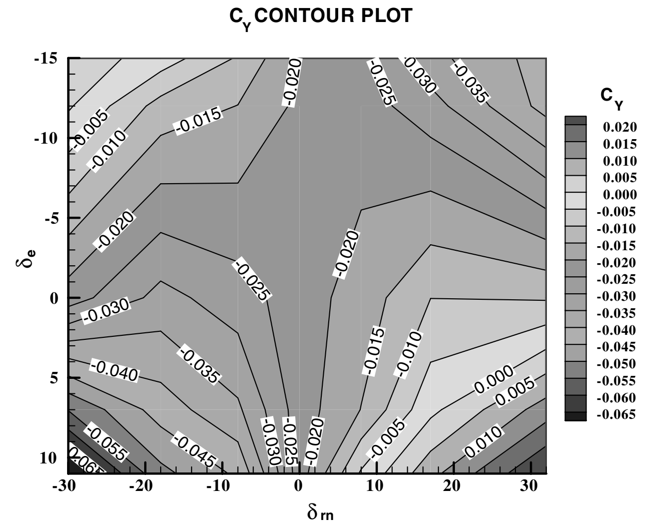

Fig. 8 Side force coefficient data as functions of tail elevation and rotation.

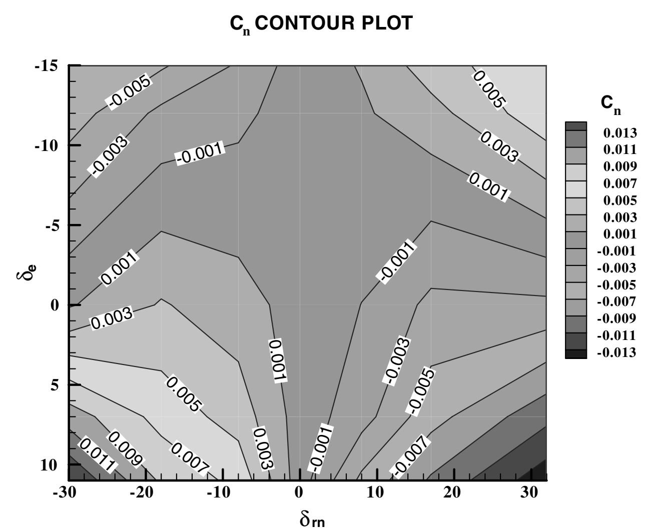

Fig. 9 Yawing moment coefficient data as functions of tail elevation and rotation.

As follows from the lift and drag coefficient data, the pitching moment is only slightly affected by the rotation angle within a range of ± 20 deg. Nevertheless, even a relatively small undesired change in the pitch moment coefficient during a turn should be avoided, and this would introduce a level of complexity to a flight control scheme.

Arguably, the most illuminating set of data about the function of the rotatable tail are shown in Fig. 8. Therein, the side force coefficient is shown as a function of elevation and rotation angles. As anticipated, the tail rotation angle can affect the side force. Note, however, that when δ_e is approximately equal to $-\alpha$ (-4 deg), the effect is extremely small. By contrast, the magnitude of the effect of the rotation angle on the side force increases as the tail elevation angle deviates from this -4- deg value. Recalling that the micro air vehicle angle is set to $+4$ deg, this $\delta_e = -4$ deg setting corresponds to the tail elevation angle at which the tail is essentially parallel to the incoming air.

A potential difficulty in implementing flight control is also evident in Fig. 8, in that the sign of the side force coefficient caused by a rotation of the tail also depends on the tail elevation. In other words, the direction of a turn is not exclusively a function of rotation but also depends on whether the tail is elevated (negative δ_e) or depressed (positive δ_e). For example, rotating the tail in a positive direction would result in a right turn when the elevation angle is negative, but the same rotation would result in a left turn if the elevation angle were positive. The most logical approach to circumventing this potential problem is to limit elevation to values only above or below a critical level determined by the angle of attack of the aircraft. Interestingly, this is consistent with the observed behavior of birds documented by Warrick et al. [12]. Specifically, the most commonly observed tail orientation of swallows in a turning prey-capture maneuver was depressed and rotated. Further, the tail was observed to be elevated primarily when preparing for a dive.

The yawing moment coefficient is plotted as a function of tail elevation and rotation in Fig. 9. The direction and magnitude of C_n are consistent with the side force given in Fig. 8. From this data, the range of attainable values may be compared with that of a typical aircraft. The largest range of yawing moment coefficient, corresponding to the largest elevation angle used in this series of tests, $+12$ deg, leads to $C_n = -0.013$ to $+0.013$. According to the classic text by Perkins and Hage [16], a typical range achievable through rudder control is about twice as high ($C_n = -0.025$ to 0.025) for a typical aircraft. As tested, the ranged yaw moment coefficient was relatively low compared with a conventional vehicle. However, with a few straightforward changes in the specific aircraft configuration implemented, either by lengthening the moment arm (for example, by using a more forward wing and battery location) or simply by increasing the range of motion of the tail, a doubling of the yaw moment coefficient of values is likely attainable.

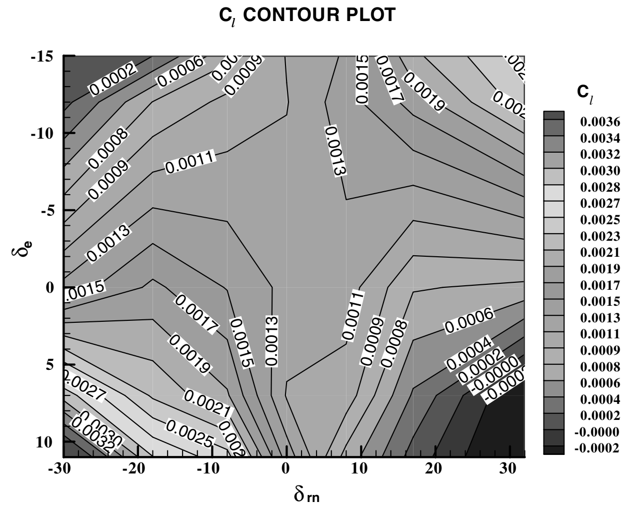

Fig. 10 Rolling moment coefficient data as functions of tail elevation and rotation.

The effect of the tail elevation and rotation on the rolling moment coefficient C_1 is given in Fig. 10. The range of values of C_1 are approximately an order of magnitude less than that attained through normal use of ailerons [16]. This suggests that although the rotatable tail has a moderate influence on the roll moment, it would be challenging to implement full roll control using only the rotatable tail. Conceivably, ailerons could be added to the aircraft, but they were not included in this study because they also were not included as part of the original aircraft. Notably, the magnitude of the effect on roll moment was comparable with that of the ruddervators on the V-tail of the original aircraft.

It is important to note that in flight, of course, minor adjustments to the aircraft trim would be required to shift both the roll and yaw moment coefficients to values more closely centered about zero. If, in fact, the aircraft were trimmed such that these initial values were centered about zero, it is noteworthy that the sign of the changes in the roll and yaw moments are the same, suggesting that the rotatable tail offers favorable yaw.

These results suggest that the effect of the tail on the yawing moment coefficient C_n might be further increased with larger tail deflection angles. To investigate this in more detail, another set of data was obtained for the tail and is given in Fig. 11. Here, the rotation angle was not increased, but larger tail elevation angles were achieved through the use of a slightly modified balance block to permit larger positive deflections. The data indicated a leveling out of the effect due to tail elevation once the angle fell below −30 deg. The wind-tunnel model support geometry limited the downward (positive) tail deflection beyond 20 deg.

A comparison of the yaw moment coefficient controlled by the rotatable tail at a large value for the elevation angle and of a typical rudder, as described by [16], is given in Fig. 11b. As suggested by the contour plots, the sign is reversed depending on whether positive or negative elevation is generated.

The tail was investigated for possible use as a braking device, or spoiler, by setting the rotation angle at 0 deg and increasing the tail elevation to approximately 65 deg, which was the mechanical limit for the tail as tested. The resulting drag coefficient data are shown in Fig. 12. The data indicate that the drag coefficient of the vehicle could, in fact, be increased by more than double by severely deflecting the tail in the negative (upward) direction. Additional details of this experiment are contained in [15]. The relatively flat region between 0 and 20 deg for the positive 4-deg setting reflects the induced drag due to lift. As the tail elevation is increased, lift decreases but drag increases, suggesting that form drag on the tail is occurring.

Although the primary focus of this study was to determine the general characteristics of the control effectiveness of a rotatable tail, it was deemed necessary to attain a level of stability to achieve controlled flight for the specific aircraft tested. The lack of vertical

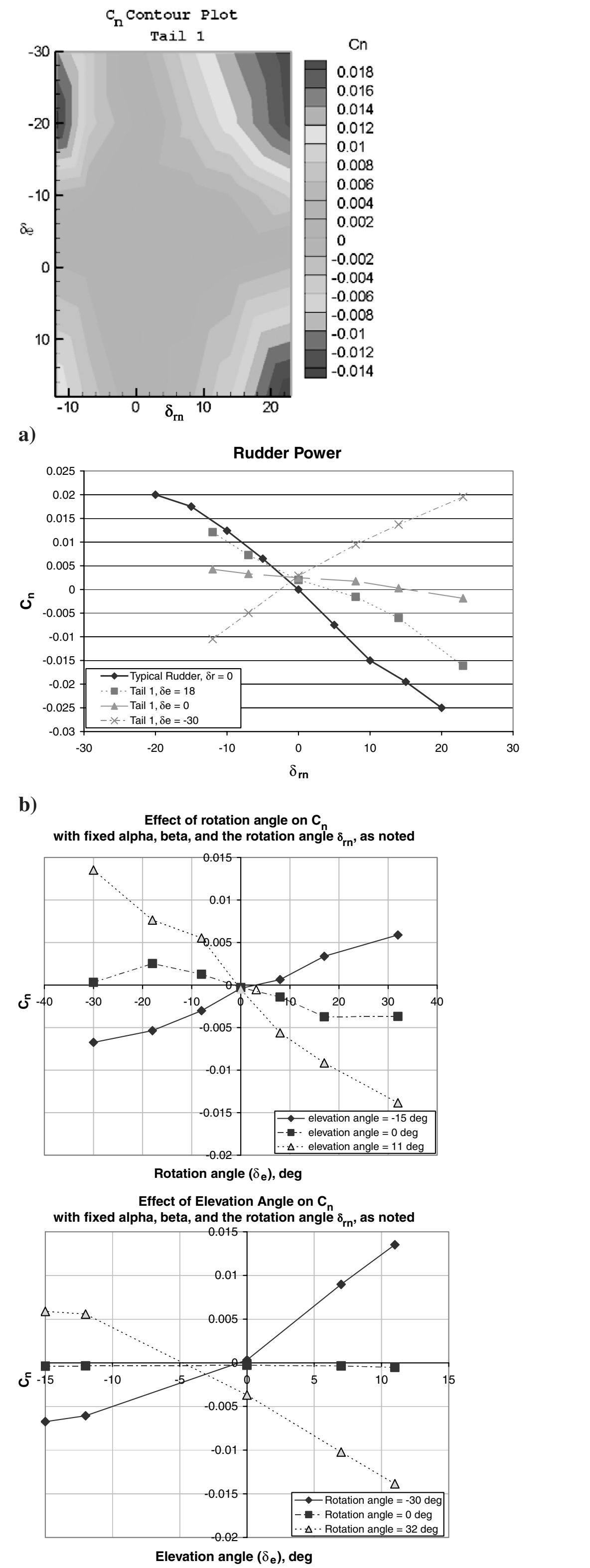

Fig. 11 Yaw moment coefficient given a) as a function of both tail elevation and rotation; b) in the *x–y* format for a fixed elevator-angle setting, as noted; and c) for a fixed rotation-angle setting, as noted. A typical rudder power plot is also shown in Fig. 11b, with angles corresponding to the rudder angle δ_r, and the remainder of the data are for rotation angle δ_{rn}.

surface aft of the center of gravity of the aircraft was deemed likely to lead to problems with directional stability. Therefore, a set of vertical stabilizers were added to the bottom aft portion of the fuselage for a few experimental conditions. Beta runs were conducted on both

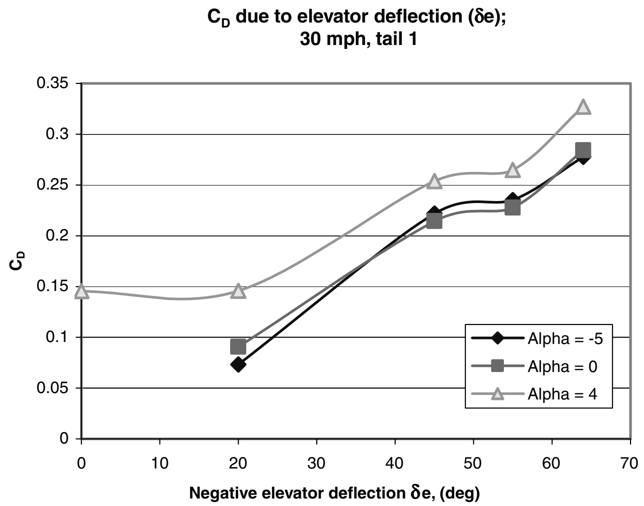

Fig. 12 Drag coefficient as a function of large tail elevation deflection angles, as it might be applied as an air brake, for three α settings.

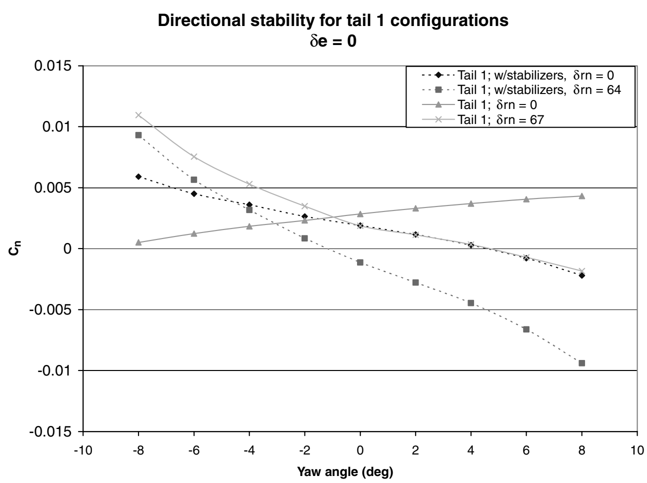

Fig. 13 Plot of C_n-ψ for the rotatable tail with and without vertical stabilizers added; two values of tail rotation angle are shown for each case.

stabilized and unstabilized designs for two tail rotation-angle settings, and the results on C_n are shown in Fig. 13. In fact, the initial rotatable tail design was directionally unstable, and the design with stabilizers improved it to only a marginal level. An experimental matrix of elevation and rotation angles for the aircraft with stabilizers in place was also performed. This yielded resulting force and moment coefficients that were characteristically similar to the results reported earlier for the unstabilized aircraft, though a mild influence of the stabilizers could be discerned in the positive elevation data due to flow interference. More details of the study relating to the stabilizers are contained in [15]. It should be emphasized that a better solution to the problem would be to shift both the wing and the center of gravity more forward within the fuselage, which would have the effect of increasing the vertical area aft of the center of gravity. With reference to Fig. 1b, there is room to perform such a change, but this would require additional considerations for this aircraft, such as changes in the wing-mounting geometry and the prop wash, to be accounted for in the vehicle design. Thus, it was deemed beyond the focus of the current study to make changes to the wing location.

An interesting facet of the rotatable tail design, which can be seen with reference to Fig. 13, is that the rotation-angle setting has a significant effect on the lateral stability of the aircraft. This is not unexpected, because the amount of vertical surface increases with the absolute value of the rotation angle. Increasing the absolute value of the rotation angle to turn the aircraft also increases the directional stability. As a result, directional stability would be expected to increase when a turn is executed, and flight-handling quality would likely be influenced.

To fly such an aircraft, stability and trim is required in each axis. As summarized in Table 2 (demonstrated in Fig. 14, which is drawn from [14]), the wing dihedral is such that the roll stability is achieved. However, even the best-case condition, in which the vertical stabilizers were employed, has an unsatisfactory directional stability. This situation could be remedied by shifting both the wing and the center of gravity of the aircraft forward, as discussed earlier. Notably, this would also slightly increase the control surface effects by lengthening the moment arm. In light of the manner in which the modifications to the aircraft were applied, it is not terribly surprising that more changes would be necessary to fly the aircraft. These design modifications would need to be employed before determining the full effectiveness of the rotatable tail concept in a flight condition.

Conclusions

The primary focus of this study was to measure and to document the forces and moments imparted to a small unmanned aircraft by a bio-inspired rotatable tail through wind-tunnel tests. The measurements of the range of yaw moment coefficients obtained for different tail elevation and rotation settings suggest that a level of control comparable to that of a typical rudder control can be attained. Although the values achieved for roll control were about an order of magnitude lower than that of a typical set of ailerons, the yaw and roll moment coefficients were of the same sign, resulting in favorable yaw. As such, the rotatable tail concept offers promise as an effective control mechanism, though several issues would need to be addressed to fully develop a full flight control scheme.

One of the most challenging aspects of putting a rotatable tail into practice is related to the highly coupled nature of the two actuators. To wit, when the tail is deflected in elevation, a change in the rotation of the tail would alter both the roll and the yaw. Similarly, if the tail were rotated and the actuator controlling its elevation were changed, both roll and yaw would be strongly affected. Furthermore, the fact that turns may be better executed when the tail is elevated may result in small, but undesirable, changes in the pitch moment.

In many ways, the tail tested represents a highly simplified version of a bird's tail. It is notable that a study described in [2] includes a description of several flight tests of a vehicle that employed a tail that could be both elevated and rotated, though the exact mechanism for control was not documented. The author notes, "Although flying the model required constant attention in pitch, the observed tail activity was very similar to that observed on ravens in flight. The handling qualities were not very comfortable for a human pilot, but they are probably completely normal to a raven." One could argue that a bird would also be able to mitigate pitch-stability issues introduced through tail motion by rotating its wings forward. Future work may provide a better answer to whether a control scheme could be implemented on a small aircraft.

Table 2 Summary of the dihedral and yaw stiffness derivatives for four tail configurations

Configuration	$C_{l\text{-}\Psi}$	$C_{n\text{-}\Psi}$	Nominal flyability[a]
Tail 1 without stabilizer, $\delta_{\mathrm{rn}} = 0\,\mathrm{deg}$	0.0019	0.0002	Unflyable
Tail 1 without stabilizer,$\delta_{\mathrm{rn}} = 64\,\mathrm{deg}$	0.0017	−0.0008	Marginal flyability
Tail 1 with stabilizer, $\delta_{\mathrm{rn}} = 0\,\mathrm{deg}$	0.0022	−0.0005	Marginal flyability
Tail 1 with stabilizer, $\delta_{\mathrm{rn}} = 67\,\mathrm{deg}$	0.0018	−0.0012	Flyable

[a]The representation of flyability is based on Fig. 13.35 of [14].

The dependence of the turning direction resulting from the execution of rotation on elevation can be partially addressed by positioning the center of gravity such that the tail elevation is generally slightly positive in straight and level flight. This suggested approach is buttressed by observations of birds in a natural setting. Gradual turns might then be executed simply by activating the rotation actuator. A more robust option would be to couple the controls of the actuators with a sensor array to account for the nonlinear effects. It is notable that tail rotation significantly increases the vertical surface while reducing the horizontal surface, and therefore stability is affected as the control surface is deflected.

For the aircraft configuration studied, advantages of the rotatable tail concept include an approximately 50% reduction in storage volume required and a potential increase in versatility, through its use as an air brake, compared with a traditional tail. With the tail elevation fully deflected to a 67-deg setting, the drag increased by a factor of 3, suggesting that the tail conceivably could be employed as an air brake. Notably, observers of birds in flight have noted that birds' tails are commonly used in this manner [12].

Acknowledgments

This work was completed thanks to the support of the U.S. Air Force Research Laboratory, Munitions Directorate under the supervision of Ian Bautista. The authors would like to thank Dwight Gehring, whose technical expertise was instrumental in the execution of the wind-tunnel experiment. The views expressed in this article are those of the author and do not reflect the official policy or position of the U.S. Air Force, Department of Defense, or the U.S. Government.

References

[1] Nash, W., British Aerospace, Preston, Lancashire, England, U.K., U.S. Patent 5096143 for a "Tail Unit with Rotatable Tailplane," filed 31 July 1990.

[2] Hoey, R. G., "Research on the Stability and Control of Soaring Birds," AIAA Paper 1992-4122, 1992.

[3] Uscher, J., "It's a Bird! It's a Plane! It's...Robofalcon!" *Popular Science* [online journal], 25 Mar. 2002, http://www.popsci.com/popsci/aviationspace/40b7d4d03cb84010vgnvcm1000004eecbccdrcrd.html.

[4] Lian, Y., Shyy, W., Ifju, P. G., and Verron, E., "Membrane Wing Model for Micro Air Vehicles," *AIAA Journal*, Vol. 41, No. 12, 2003, pp. 2492–2494.

[5] DeLuca, A., Reeder, M. F., Freeman, J., and Ol, M., "Flexible- and Rigid-Wing Micro Air Vehicle: Lift and Drag Comparison," *Journal of Aircraft*, Vol. 43, No. 2, Mar.–Apr. 2006, pp. 572–575.

[6] DeLuca, A. M., "Experimental Investigation into the Aerodynamic Performance of Both Rigid and Flexible Wing Structured Micro-Air-Vehicles," M.S. Thesis, Dept. of Aeronautics and Astronautics, Air Force Inst. of Technology, Wright–Patterson AFB, OH, Mar. 2004.

[7] Rayner, J. M. V., "Form and Function in Avian Flight," *Current Ornithology*, Vol. 5, 1988, pp. 1–66.

[8] Milius, S., "Tests Hint Bird Tails are Misunderstood (Aerodynamic Analysis of Bird Tails)," *Science News*, Vol. 160, No. 2, July 2001, p. 23.

[9] Horton-Smith, C., *The Flight of Birds*, HF&G Witherby, London, 1938, p. 38.

[10] Storer, J. H., *The Flight of Birds Analyzed Through Slow-Motion Photography*, Cranbrook Inst. of Science, Bloomfield Hills, MI, 1948.

[11] Nickel, K., and Wohlfahrt, M., *Tailless Aircraft in Theory and Practice*, AIAA Education Series, AIAA, Washington, DC, 1994, p. 25.

[12] Warrick, D. R., Bundle, M. W., and Dial, K. P., "Bird Maneuvering Flight: Blurred Bodies, Clear Heads," *Integrative and Comparative Biology*, Vol. 42, 2002, pp. 141–148.
doi:10.1093/icb/42.1.141

[13] Rivera Parga, J., "Wind Tunnel Investigation of the Static Stability and Control Effectiveness of a Rotary Tail in a Portable UAV," M.S. Thesis, Dept. of Aeronautics and Astronautics, Air Force Inst. of Technology, Wright–Patterson AFB, OH, Dec. 2004.

[14] Barlow, J., Rae, W. H. and Pope, A., *Low-Speed Wind Tunnel Testing*, 3rd ed., Wiley, New York, 1999.

[15] Leveron, T., "Characterization of a Rotatable Flat Tail as a Spoiler and Parametric Analysis of Improving Directional Stability in a Portable UAV," M.S. Thesis, Dept. of Aeronautics and Astronautics, Air Force Inst. of Technology, Wright–Patterson AFB, OH, June 2005.

[16] Perkins, C. D. and Hage, R. E., *Airplane Performance Stability and Control*, 7th ed., Wiley, London, 1958.