RESEARCH on the STABILITY AND CONTROL of SOARING BIRDS USING RADIO CONTROLLED GLIDERS

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ABSTRACT

In 1990 I began a study of the stability and control of soaring birds using full-scale, radio controlled glider models of a Raven. The Raven models were air-launched from another radio-controlled airplane providing a consistent and repeatable method for conducting the tests. Various control schemes were tried. Successful flights were eventually accomplished without any vertical stabilizing surfaces, and using tail-tilt for roll control in a manner similar to that observed on real Ravens. Results of these tests were presented at the AIAA 6th Annual Flight Test Symposium in 1992. These earlier test results are summarized to help establish the source of lateral-directional stability for a soaring bird, and to set the stage for the more recent research work.

During the past two years successful tests have been conducted on full-scale, radio-controlled glider models of a Raven, Turkey Vulture, Seagull and Pelican, using a different lateral control scheme. This concept assumes that the forward tip feathers of a soaring bird are actually functioning in the upflow region outboard of the primary lift vortex. Theoretically these feathers can produce both lift and thrust while operating in this flow field, thereby providing proverse yaw when deflected differentially for roll control. The simple control mechanism will be described along with videos of the bird models in flight. Water tunnel tests conducted at NASA Dryden on a semi-span model of the Raven wing provided a visual perspective of the flow over the wing tip feathers. The potential application of this concept to airplanes will also be discussed.

NOMENCLATURE

\[ Cl_{\beta} \] Dihedral effect (roll due to sideslip) per radian
\[ Cn_{\beta} \] Static directional stability (yaw due to sideslip) per radian
\[ Cn_{\beta}^* \] Dynamic = \[ Cl_{\beta} \cos \alpha - Cl_{\beta} \sin \alpha \left( \frac{I_x}{I_z} \right) \] per radian
\[ \beta \] Angle of sideslip radians
Dryden NASA Dryden Flight Research Center, Edwards AFB

INTRODUCTION

My interest in the study of soaring birds started in 1990 and results of early experiments were published in 1992 (Ref. 1). By that time several gliders had been successfully flown in the configuration of soaring birds (Fig. 1). These experiments determined that the source of a soaring bird's lateral-directional stability was the span-wise distribution of dihedral and wing
sweep (Fig. 2). A simplified analysis of the dihedral and sweep distribution for a Raven wing was used to predict a value for $Cn_{\beta}^*$ (dynamic $Cn_{\beta}$) for the wing alone. The resulting prediction of the Dutch Roll frequency was within 15% of the values observed on the model. It is important to note that the magnitude of the value of $Cn_{\beta}^*$ for a bird configuration is only about 10% of the value for a normal airplane with a vertical tail.

![Baseline Raven Model](image1)

Lateral control for these early experiments was with either drag flaps on the bottom of the wing, or spoilers on the top of the wing. The additional drag on one wing caused the model to yaw into the direction of the turn, much like a rudder, and the dihedral-effect caused a roll in the proper direction (like the B-2). Although effective for experimentation, this roll control method was inefficient and not very "bird-like".

Tail-tilt for initiating turns was also tried and reported in Ref. 1. Several flights were completed using only tail-tilt for roll control, including several at an aft cg where the model turned in the opposite direction to the tail-tilt (the observed method used by soaring birds). Tail-tilt was a very weak roll control method, although it was useful for small corrections while the model was circling. Observations of birds actually soaring in thermals indicate that they are probably using their tails for small pitch and roll adjustments while their wing shape remains fixed.

**Definition of Problem**

Observations of birds in high speed flight showed that they were not using their tails for turning. (In fact their tails were tucked in tightly, probably to minimize drag). Instead there appeared to be some form of wing twist being used for roll control while flying at the higher speeds. Stability analyses based on dihedral and sweep showed that a high-speed configuration (more sweep, less area) could be statically stable although the margins would be even lower. Several combinations of wing twist methods were tested in an attempt to copy the bird's actions. Normal ailerons, long and narrow strip ailerons, differential ailerons, even leading edge flaps were tried. The reaction was always the same. Any deflection to raise one wing resulted in additional drag on that wing, and a roll in the wrong direction due to dihedral effect. Eliminating, or minimizing, the dihedral effect didn't really help. The models then just yawed rather severely with no appreciable roll in either direction. Adverse yaw is a minor problem for a normal airplane,
but is a huge problem for an airplane without a vertical tail. These models are very sensitive to any yaw producing devices. That is why the drag flaps or spoilers work so well. They provide drag for the down-going wing, and thus produce a small amount of proverse yaw (nose swings into the direction of the turn).

2-Dimensional Analysis

A simple analysis correctly suggests why ailerons produce adverse yaw. When the aileron is deflected downward it produces an increase in lift and drag which causes the wing to yaw away from the desired turn direction (Fig. 3). One way to counteract this effect would be to build the wing with some twist, or washout near the tips (Fig. 4). With the tips operating at essentially zero lift, the up and down going ailerons should balance out by producing equal amounts of drag on each wing. I did not even try this method because anyone can plainly see that the tip feathers on most soaring bird are not operating at zero lift. They are bent upward rather sharply indicating that they are experiencing an upward air load.

After reading a small pamphlet by Carl Horst, written in the early ’60’s (Ref. 2), I developed a new perspective. Horst believed that the tip feathers of a bird were "thrusters" not "lifters". He proposed that the tip feathers were part of the propulsion flapping mechanism, and therefore were primarily trying to produce thrust, or at least minimize drag.

3-Dimensional Analysis

The air flow around a wing tip is highly three dimensional. Just outboard of the end of the wing the air is flowing sharply upward as the lift vortex begins to roll up behind the wing. I began to wonder if birds were using that up-flow to their advantage (Fig. 5).
Imagine a blade (or feather) extended into the up-flow region beyond the normal wing tip. If we could first align it with the local flow, then introduce a very small incidence relative to the local airflow, we should be able to generate a small amount of upward lift, and some corresponding forward thrust (Fig. 6). There are several benefits from such an arrangement. The lift on the feather would bend it upward as we observe on the real birds. The forward thrust would hold the wing in an extended position, thus minimizing muscle power needed to hold the wings in place. When the feathers were deflected differentially for roll control, the increased lift and thrust on the up-going wing would produce proverse yaw and would thus help in creating the turn.

This concept might appear to violate the conservation of energy principals — that we are getting "something for nothing". In fact, we are merely using the energy already imparted to the air by the wing as the air curls around the tip in wave-like fashion. Our tip feather is acting in much the same manner as a surfer. By establishing a location on the front, sloping side of the wave a surfer will get a free ride as long as he stays in the proper location (Fig. 7).
Wing-Tip Aileron

The wing-tip aileron that evolved for the Raven model consisted of the three forward feathers, mounted together on a single block, and rotating about a span-wise axis (Fig. 8). The primary aileron control rotated the left and right tip-feather blocks differentially for roll control. The rotation travel was about plus or minus 10 degrees. A separate radio channel was used to rotate both tip ailerons together, either leading edge up or leading edge down. This bias feature allowed the neutral incidence angle for both tip feathers to be optimized in flight.

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THREE-FEATHER WINGTIPAILERON

Fig. 8

FLIGHT TEST RESULTS

Raven Model

The tip-aileron were immediately successful as a roll control method. The best neutral setting for the tip feathers was found by simple trial and error. There was an obvious "sweet spot" that allowed smooth turns to be performed. This setting was with the forward feather at a surprising
-27 degrees incidence relative to the wing chord. As the incidence angle of the forward feathers became more positive (greater than -20 degrees) the differential effectiveness essentially disappeared with no roll or yaw apparent from step inputs to the aileron. With the bias of the forward feathers near zero, adverse yaw was apparent with a resulting mild roll reversal. As the incidence angle became more negative (less than -30 degrees) the proverse yaw became quite abrupt and the model rolled into the turn based mostly on the dihedral effect of the model. I had expected a change in the optimum bias setting for lower angles of attack due to the reduction in strength of the tip vortex. So far there is little evidence that this is the case. The -27 degree setting is adequate throughout the normal speed range of the model. I also observed a small, but noticeable, improvement in performance (i.e. shallower glide slope) on the Raven with the new ailerons (Fig. 9).

RAVEN MODEL WITH WINGTIP AILERONS

Fig. 9

Water Tunnel

In the summer of 1999, following the successful development and flight testing of the tip-aileron on the Raven model, I had the opportunity to install a small, half-span model of the Raven wing in the water tunnel at NASA Dryden. Working with Jennifer Hansen, one of the summer hires at NASA Dryden, we tested the wing model at 10 degrees angle of attack. The Reynolds number was about 4000 for the water tunnel compared to about 60,000 for a real bird, so the match was not too good. Food die was introduced into the flow upstream of the model. We could never get the food die to travel in a smooth line (it formed into small blobs), so the photo’s and video’s were difficult to interpret.

With the wing tip feathers removed the sharp up-flow just outboard of the end rib was quite apparent. A very strong tip vortex formed behind the wing and extended clear to the bottom of the tunnel. This vortex was diffused whenever any of the wing tip configurations were installed. The flat wing tip configuration that I flew for the first few years of testing showed flow separation
at the leading edge of the front feather and the entire top surface of the tip feathers was turbulent and separated.

**Tip Aileron Flow Analysis**

Still photographs in the water tunnel were of little value, however flow patterns around the feathers could be discerned from a careful review of the video tape. The observed flow activity for the three aileron deflections that were tested is depicted in Fig. 10. With the forward feather at -27 degrees (the best neutral setting determined from flight), the flow was smooth over the top and bottom of the three forward feathers, but there was an area of moderate turbulence over the rear feathers (which were flat at 0 degrees incidence). At -22 degrees on the forward feather the flow remained smooth over the forward feathers, and the turbulence was reduced over the rear feathers. Note that this would be the up-going wing for an aileron input. At -32 degrees on the front feather, the flow remained smooth over the forward feathers, but there was heavy turbulence over the rear feathers. This would be the down-going wing for an aileron input.

**WATER TUNNEL VISUALIZATION**

For all three settings the flow over the forward three aileron feathers was smooth, but the flow was stalled at the leading edge of the 4th feather. The separation was considerably worse when the tip aileron was deflected leading-edge-down. Based on these test results the rear feathers were remounted on the flight model at negative incidence angles so they continued the cascade of the forward feathers (Fig. 11). Flight test indicated that the aileron effectiveness was reduced by this change, but was still adequate. Apparently by varying the size of the slot between the 3rd and 4th feathers the tip aileron was also serving as a spoiler thus amplifying the aileron effectiveness. I suspect that the flow is now smooth over all, or most, of the feathers and am hoping to verify this with another water tunnel entry.

**FOLLOW-ON TESTS**

Three additional bird models have been constructed: a Turkey Vulture, Seagull and Pelican. The primary purpose of the Turkey Vulture and Seagull models was to validate the lateral-directional stability analysis for wings of different planforms and dihedral patterns. Their flight characteristics
were consistent with the $Cn_{\beta}^*$ analysis for their individual wing shapes. The Turkey Vulture had too much $Cn_{\beta}^*$ and was oscillatory in flight. The Seagull, with the typical wing droop of a gull, had marginally low values of $Cn_{\beta}^*$ and was difficult to turn with either the drag flap or a rolling tail.

After finding success with the tip aileron on the Raven model, I installed a similar aileron system on the Turkey Vulture. The bias feature was retained, and the "sweet spot" again turned out to be -27 degrees on the forward feather. A new, lighter wing was constructed. With the new wing the lateral oscillations were still present in turbulence (as they are on a real Turkey Vulture) but they damped quickly and were easily controlled.

A Seagull does not have separated feathers at the tip like the Raven or Vulture, so I merely cut off the wing tip in a chord-wise direction, then hinged the entire tip on a span-wise axis at about the quarter chord of the wing (Fig. 15). Again the "sweet spot" for good lateral control was easily found by trial and error. The best bias position was with the tip at an incidence angle of -10 degrees with respect to the center section of the wing. There was already about 4 degrees of washout in the outer half of each wing, so the angular difference at the aileron hinge was only 6 degrees. Although I had always had difficulty using drag flaps and dihedral to turn the Seagull, the directional stability was good. The new tip aileron allowed a high level of maneuverability in spite of the low value of $Cn_{\beta}^*$.
I had often mused that the real test of my understanding of gliding birds would be with a model of a Pelican. The droopy wing, long destabilizing beak and a cranked, high aspect ratio wing planform were considered a real challenge. The model was completed last year and on early flights the model proved to be unstable in all axes. Luckily the model survived and eventually was tamed by making relatively small adjustments to the configuration. Wing dihedral was increased slightly, the cg was moved forward, and two small ventral fins in the form of “feet” were added to counter the destabilizing influence of the beak. Pelicans have separated tip feathers, so the tip ailerons are similar to those of the Turkey Vulture and the best bias position was also -27 degrees. The model has a very impressive flat glide, but is tricky to maneuver due to the low level of natural stability.

![PELICAN, SEAGULL AND TURKEY VULTURE MODELS](image)

**Weight/Span/Area Effects**

All of the work discussed thus far has dealt with stability and control. The performance (lift and drag) of a radio-controlled glider is extremely difficult to measure, but some observations and simple calculations are possible. While flying the model in thermals with other Ravens I have noticed that there is very little performance difference between my model and the real Ravens, even though the model is only 2/3 of the weight of a real Raven. They circle at about the same speed and bank angle, and seem to climb at about the same rate. When the real Ravens decide to leave the thermal and fly straight, however, there is a dramatic difference. My model is no match for the high speed and shallow glide angle that the birds can achieve in straight flight.

Based on photos and observations, it is estimated that both the wing span and wing area of a Raven in straight cruising flight are reduced by about 25% compared with the thermalling configuration (Fig. 1).

The standard lift and drag equations (including the change in lift curve slope due to the change in aspect ratio, Ref. 3) were used to analyze the effect of a 25% change in span and area. The effect of the lower weight of the model was also analyzed. The cumulative effect was quite dramatic, and explained the observed performance differences between my model and the real birds. Configured for high speed flight, real ravens can fly 67% faster than my model at the same glide angle, or they can glide at about half the glide angle at the same speed. Of course
they can change back to the thermal configuration (or anything in-between) with literally, a "flick of the wrist".

LESSONS LEARNED

It is apparent that the natural stability requirement for a gliding vehicle is quite low. The wing tip ailerons allow the optimization (or elimination) of adverse yaw, and are thus consistent with gliding and might allow smaller vertical tails to be used on full-scale gliders. Although tip ailerons would probably work on a powered airplane, their value is less obvious since a powered airplane requires considerably more natural stability to handle the torque, gyroscopic effects, etc. of current propulsion systems. Adverse yaw then becomes a minor effect. There is still much to learn from the study of bird flight and the use of radio-controlled models is an effective and low-cost, test method.

CONCLUSIONS

Four radio-controlled glider models of birds have been tested, (Raven, Seagull, Turkey Vulture and Pelican). The models do not have vertical fins or rudders. These tests lead to the following conclusions regarding how birds fly without vertical tails:

- Soaring birds appear to be statically stable in the lateral-directional axis.
- The stability source is the spanwise distribution of wing dihedral and wing sweep.
- The stability level is about 10% of that of a normal airplane.
- Soaring birds are probably neutral, or slightly unstable, in the longitudinal axis

Three methods were successfully developed for controlling turns on the models:

- Spoilers or drag flaps — utilized dihedral effect to initiate turns
- Tail tilt — low effectiveness, but useful while thermalling
- Forward tip-feather ailerons — smooth coordinated turns, independent from dihedral effect.

REFERENCES


2. Horst, Carl O., Flapping and Soaring, A pamphlet published in 1960,

BIOGRAPHY

Robert G. Hoey graduated from the University of Washington with a BS degree in Aeronautical Engineering in 1955. He worked for 32 years as a Flight Test Engineer and Supervisory Engineer at the Air Force Flight Test Center at Edwards AFB, CA. He participated in the AF testing of the century-series fighters as well as many research airplanes including the X-15, Lifting Bodies, X-29, Space Shuttle Orbiter and others. He retired from Civil Service in 1987 and has been working as a part-time consultant involved in Flight Readiness Reviews of new aircraft and computer math-modelling for training simulators. His spare time is spent designing and flying radio-controlled model airplanes. He also flies a four-place BD-4, homebuilt airplane which he completed in 1979. He earned a Diamond Soaring Badge in 1970 for flights performed in his homebuilt BG-12B sailplane.