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# Flight Test Results for an Advanced Technology Light Airplane

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**A single-engine light airplane was modified by the installation of a wing with reduced area, Fowler flaps, Kruger flaps, and spoilers. Flight test results show that zero-lift drag was reduced 13.8% and a trimmed maximum lift coefficient of 2.73 was achieved. Gust response was significantly reduced and excellent roll control was achieved with spoilers. Several design features employed in the new wings have excellent potential for incorporation in future light airplanes.**

## Nomenclature

$A$ = aspect ratio
$b$ = wing span
$\bar{c}$ = mean aerodynamic chord
$C_D$ = airplane drag coefficient
$C_{D_0}$ = zero lift drag coefficient
$C_l$ = rolling moment coefficient
$C_{l_{\delta_s}}$ = roll power $\partial C_l / \partial \delta_s$
$C_{l_p}$ = roll damping coefficient
$C_L$ = airplane lift coefficient
$e$ = induced drag efficiency factor
$p$ = roll rate
$S_w$ = wing area
$THP$ = thrust horsepower
$THP_e$ = equivalent thrust horsepower
$V_e$ = equivalent velocity
$V_T$ = true airspeed
$W$ = gross weight
$\beta$ = sideslip angle
$\delta_f$ = Fowler flap deflection
$\delta_k$ = Kruger flap deflection
$\delta_s$ = spoiler deflection
$\phi$ = roll angle
$\rho_0$ = standard sea-level density
$\sigma$ = density ratio, $\rho/\rho_0$

## Introduction

THIS paper reports the final results of flight tests of a modified Cessna 177 Cardinal aircraft. The purpose of this program was to evaluate the effects of a research wing incorporating increased wing loading and several aerodynamic features not ordinarily found on light aircraft.

The changes incorporated in the new wing are 1) wing area reduced by 37%, 2) thickness ratio reduced, 3) Fowler trailing-edge flaps installed, 4) Kruger leading-edge flaps installed, and 5) spoilers installed for roll control.

The basic design philosophy involved the improvement of cruise performance by increasing wing loading. An auxiliary benefit is a considerable improvement in ride quality in turbulence. To maintain acceptable stall speeds improved trailing-edge flaps were employed along with Kruger leading-edge flaps. Spoilers for roll control were also investigated because they can permit the use of full-span flaps. Details of the design philosophy, parametric studies, wind-tunnel tests, flight simulator studies, and preliminary performance estimates were presented in Refs. 1-4.

It should be emphasized that the modified Cardinal, herein referred to as the Redhawk, is strictly a research vehicle designed to investigate several different aerodynamic improvements which might be applied to the design of general aviation aircraft. The constraint of mounting the new wings on an existing fuselage and wing carry-through structure compromised the design in several respects; thus, the Redhawk should not be considered as a prototype airplane or proposed modification to the Cessna Cardinal.

Prior to modifying the test airplane, an extensive set of base performance data was obtained through flight testing.[5] These data are used in this paper for comparison. The same instrumentation system used for the base data flight tests was used for these tests. Details of the system are reported in Ref. 5.

## Airplane Configuration

A three-view of the Redhawk and relevant geometric data, compared with the original Cardinal, are presented in Fig. 1 and Table 1. The ailerons are available only as a backup roll control system and are connected to the control wheel on the right side. The spoilers are connected to the left control wheel. This independent arrangement made in-flight comparisons between aileron and spoiler roll control characteristics very convenient.

Both leading-edge and trailing-edge flaps were driven independently by standard Cessna Cardinal flap motors. Other than the wings, no other changes were made to the aerodynamic configuration or engine of the standard Cessna Cardinal.

## Lift and Drag Characteristics

The lift and drag characteristics of the Redhawk were determined from a series of steady, level flight data points conducted at two pressure altitudes, 2500 ft and 7500 ft.

Engine brake horsepower was determined from engine manifold pressure, rpm, pressure altitude, ambient temperature, and the power chart supplied by the engine manufacturer. The power predicted from the engine chart was then reduced by 5% to account for losses from inlet temperature rise and miscellaneous losses.

Thrust horsepower was determined from brake horsepower, propeller rpm, air density, true airspeed, and propeller performance charts. The actual calculations were performed with the aid of a computer program supplied by Cessna Aircraft Company.

Weight was determined for each point by plotting the approximate fuel consumed vs time using the known fuel

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consumption characteristics and approximate power settings, and the initial and final weight of the airplane. Drag characteristics were determined as follows. Assuming that drag can be represented by a standard parabolic drag polar,

$$C_D = C_{D_0} + C_L^2/\pi Ae$$

then thrust horsepower may be expressed in the following manner:

$$THP_e = THP\sqrt{\sigma} = \frac{C_{D_0}\rho_0 S_w V_e^3}{1100} + \frac{W^2}{275\pi eA\rho_0 S_w V_e}$$

$$THP_e(V_e) = \frac{C_{D_0}\rho_0 S_w}{1100} V_e^4 + \frac{W^2}{275\pi eA\rho_0 S_w} = K_1 V_e^4 + K_2$$

Thus, if $THP_e(V_e)$ is plotted as a function of $V_e^4$, a normal drag polar will appear as a straight line and $C_{D_0}$ and $e$ can be determined from the slope, $(K_1)$ and intercept $(K_2)$ of the line. If $V_e$ is in miles per hour, $S_w$ is in ft$^2$, and $\rho_0$ is in slug/ft$^3$, then

$$C_{D_0} = \frac{K_1 348.4}{\rho_0 S_w} \qquad e = \frac{W^2}{403.4\pi A\rho_0 S_w K_2}$$

Figure 2 presents typical flight test data corrected to a standard gross weight of 2500 lb. Complete data for all configurations are available in Ref. 6. A summary of the Redhawk drag characteristics and a comparison with the Cardinal are presented in Table 2. Note that since the drag coefficients are based on two different areas, the quantity $C_D S_w$, the equivalent flat plate frontal area, should be compared to determine relative amounts of actual drag.

Several significant results appear in Table 2. First, the reduced wing area of the Redhawk results in a 13.8% reduction in zero lift drag. As shown in the power-velocity curves of Fig. 3, that produces an increased maximum airspeed of approximately 3 to 6 mph, depending on altitude.

The induced drag efficiency factor for the Redhawk is very close to that of the Cardinal except for the 10-deg Fowler flap setting. The improved efficiency for this condition is believed to be the result of reduced separation at the wing-body attachment area. Note that $e$ accounts for all drag contributions which are a function of angle of attack, including trim drag; the values of $e$ in Table 2 are representative of this class of airplanes.

The total zero lift drag for the Redhawk is only slightly larger than that of the Cardinal for the full flaps landing configuration. The very small increase in $C_{D_0}$ due to Kruger flaps with $\delta_f = 40$ deg is probably a result of designing the Kruger flaps to be most effective with the 40-deg Fowler flap position. The large leading-edge upwash in this condition results in very little separation from the undersurface of the Kruger flap compared with the $\delta_f = 10$-deg configuration.

The ratio of induced drag of the Redhawk and Cardinal at a given airspeed in the cruise configuration is

$$\frac{(D_i)_{\text{Redhawk}}}{(D_i)_{\text{Cardinal}}} = \frac{(S_w ARe)_{\text{Cardinal}}}{(S_w ARe)_{\text{Redhawk}}} = 1.34$$

If the span of the Cardinal had been retained for the Redhawk, with no change in Redhawk wing area, $C_{D_0}$ and $e$, the increase in maximum speed at 7500 ft would be approximately 8.6 mph, as shown in Fig. 3, because the increase in induced drag of the Redhawk would be eliminated.

Figure 4 presents the trimmed lift curves of the Redhawk. The Fowler flaps provide a substantial $\Delta C_L$ as well as increase in $C_{L_\alpha}$. The Kruger flaps provide virtually no increase in $C_L$ at constant $\alpha$ but extend the lift curve to a higher stall angle and a higher $C_{L_{\max}}$.

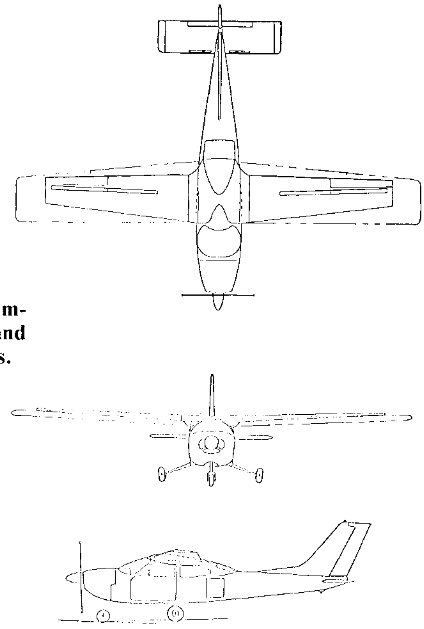

**Fig. 1 Three-view comparison of Redhawk and Cardinal configurations.**

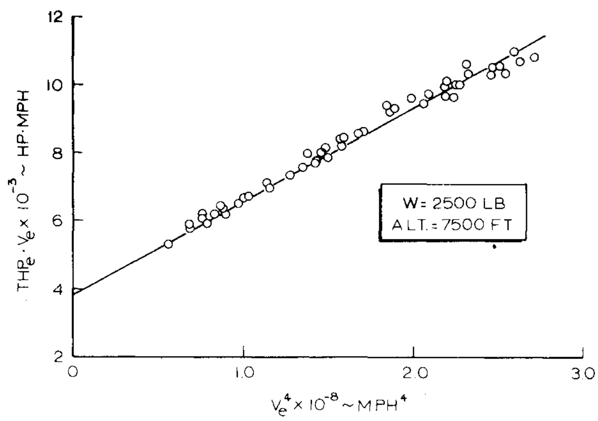


**Fig. 2 Level flight power requirements, cruise configuration.**

**Table 1 Geometric properties of the Cardinal and Redhawk wings**

| | Cardinal | Redhawk |
|---|---|---|
| Gross weight, N, (lb) | 11,120, (2500) | 11,120, (2500) |
| Wing area, m$^2$ (ft$^2$) | 16.23, (175) | 10.21, (110) |
| Wing loading, N/m$^2$, (psf) | 648, (14.3) | 1089, (22.7) |
| Span, m, (ft) | 10.82, (35.5) | 9.58, (31.4) |
| Aspect ratio | 7.2 | 9.0 |
| Taper ratio | 0.7 | 0.5 |
| Twist, deg | 3.0 | 3.0 |
| Dihedral, deg | 1.5 | 3.0 |
| Airfoil section | | |
| Inboard | NACA 64A215 | NACA 2412 |
| Outboard | NACA 64A212 | NACA 2409 |
| Trailing-edge flap | | |
| Type | Single Slot | Fowler |
| Span, percent | 53 | 47 |
| Area (both), m$^2$, (ft$^2$) | 2.74, (29.5) | 2.93, (31.5) |
| Leading-edge flap | ... | Kruger |
| Span, percent | ... | 83 |
| Deflection, deg | ... | 135 |
| Aileron | | |
| Type | Frise | Round nose |
| Chord, percent | 41 | 24 |
| Span, percent | 33 | 36 |
| Spoiler | | |
| Chord, cm (in.) | | 10.16 (4) |
| Span | | |
| Inboard, percent | ... | 28.5 |
| Outboard, percent | ... | 32 |

**Table 2 Comparison of drag characteristics determined from flight test**

| | | $C_{D_0}$ | $C_{D_0} S_w$ | $e$ |
|---|---|---|---|---|
| Redhawk | Cruise | 0.0366 | 4.026 | 0.55 |
| | $\delta_f = 10$ deg, $\delta_k = 0$ deg | 0.0546 | 6.006 | 0.67 |
| | $\delta_f = 10$ deg, $\delta_k = 135$ deg | 0.0770 | 8.47 | 0.685 |
| | $\delta_f = 40$ deg, $\delta_k = 0$ deg | 0.0746 | 8.21 | 0.58 |
| | $\delta_f = 40$ deg, $\delta_k = 135$ deg | 0.0752 | 8.27 | 0.59 |
| Cardinal | Cruise | 0.0267 | 4.67 | 0.564 |
| | Full flaps | 0.0462 | 8.08 | 0.545 |

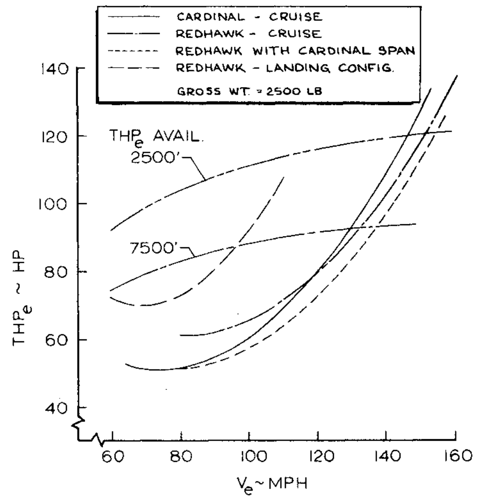


Fig. 3 Power required and available for the Redhawk and Cardinal.

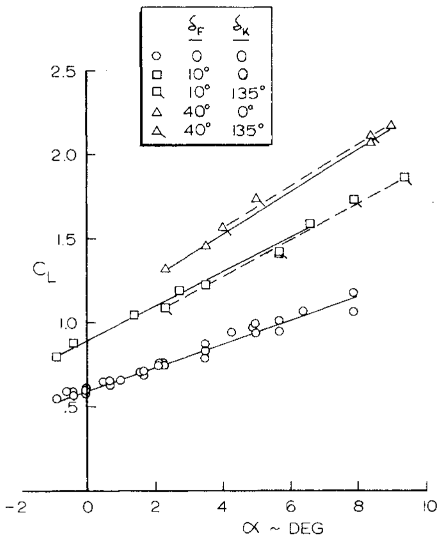


Fig. 4 Trimmed lift curves for the Redhawk.

**Table 3 Comparison of stall speeds and maximum lift coefficients**[a]

| Configuration | Redhawk $V_s$, mph | Redhawk $C_{L_{max.}}$ | Cardinal $V_s$, mph | Cardinal $C_{L_{max.}}$ |
|---|---|---|---|---|
| Cruise | 79.6 | 1.40 | 64.7 | 1.35 |
| Kruger flaps only | 69.8 | 1.82 | ... | |
| Fowler flaps 10 deg | 71.2 | 1.75 | ... | |
| Fowler flaps 10 deg and Kruger flaps | 62.8 | 2.25 | ... | |
| Fowler flaps 40 deg (30 deg for Cardinal) | 64.4 | 2.14 | 55.0 | 1.84 |
| Fowler flaps 40 deg and Kruger flaps | 57.0 | 2.73 | | |

[a]Gross weight = 2500 lb; Redhawk c.g. location 7.2% m.a.c. (109 in.), Cardinal c.g. location 19% m.a.c. (109.3 in.).

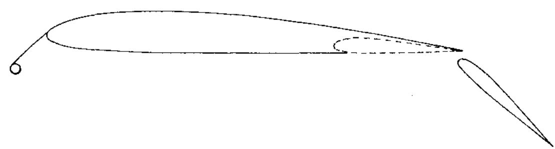

Fig. 5 Cross section of wing in landing configuration.

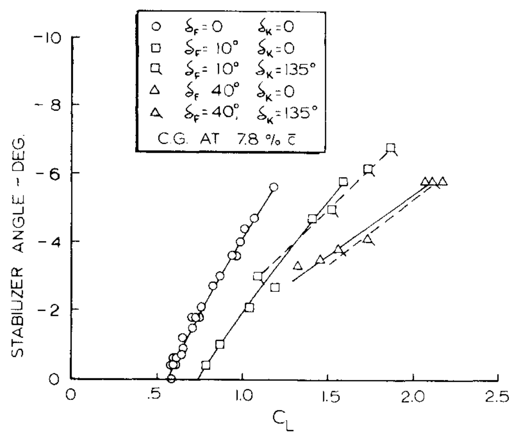


Fig. 6 Longitudinal trim data for the Redhawk.

## Stall Performance

The greatly reduced wing area of the Redhawk necessitated the use of very effective high lift devices to obtain takeoff and landing performance comparable to the original Cardinal. Extensive use of available NASA data and two-dimensional wind-tunnel tests at the University of Kansas[7] contributed to the design of the Fowler flaps and Kruger flaps. A cross section of the airfoil and flaps is shown in Fig. 5.

Stalls were conducted by establishing equilibrium level flight approximately 10 to 15 mph above the anticipated stall speed. Power was then reduced such that the airplane decelerated approximately 1 knot/s at constant altitude until a stall occurred. Power was generally very close to idle by the time the airplane stalled. Stall speed was defined as the minimum airspeed recorded during the stall maneuver.

Data for the stall performance are presented in Table 3. While the Redhawk cruise configuration has a relatively high stall speed, the maximum lift coefficient exceeds that of the Cardinal, probably due to the higher aspect ratio. Use of Fowler and Kruger flaps almost doubles the maximum lift coefficient of the clean configuration, producing a trimmed lift coefficient at stall of 2.73 and a stall speed within two mph of the Cardinal. Use of full span trailing-edge flaps would reduce Redhawk stall speed at landing below that of the Cardinal.

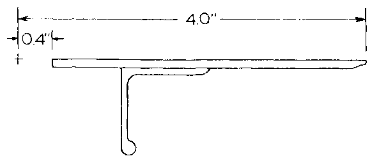


**Fig. 7 Redhawk spoiler cross section.**

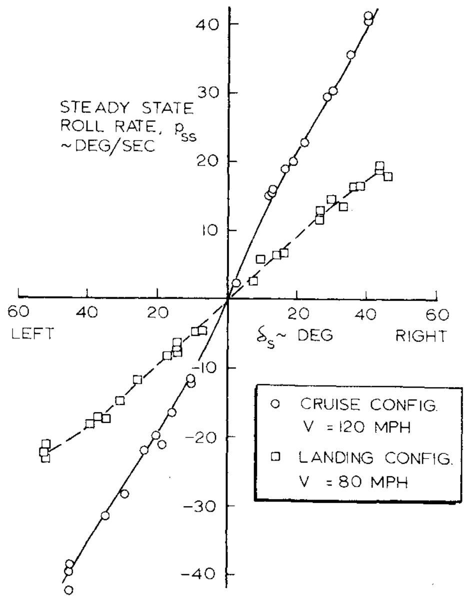


**Fig. 8 Redhawk spoiler roll rate data.**

The full span Kruger leading-edge flaps are particularly effective, producing approximately a 10-mph reduction in stall speed when deployed with any Fowler flap deflection. The $\Delta C_{l_{max}}$ due to Kruger flaps is 0.59 with full 40-deg Fowler flap deflection.

Stall characteristics were acceptable in all configurations, but the use of Kruger flaps greatly improved the controllability and gentleness of the stall. Spoiler roll control is effective throughout the stall maneuver.

## Longitudinal Trim

Longitudinal trim data are presented in Fig. 6. Several characteristics are apparent. Fowler flap deployment causes an aft shift in the neutral point, increasing the static stability. It also results in a mild nose-up pitching moment. Thus, transition from pattern speed to final approach is very comfortable with only moderate trim wheel inputs required. Kruger flap deployment causes virtually no trim change. The only noticeable effect during Kruger flap actuation is a slight buffet at a Kruger angle of about 90 deg.

## Spoiler Roll Characteristics

Although ailerons were installed on the Redhawk as an alternate means of roll control, spoilers are the primary roll control surfaces. The spoilers are actuated by a cam and pushrod linkage which deflects one spoiler while holding the other in a fixed position. The cam is connected by cable to the pilot's control wheel. Two spoiler segments are provided on each wing, the inboard segment extending from 35% to 63.5% semispan, and the outboard from 64.5% to 96.5% semispan. Initially, both inboard and outboard spoilers were used for roll control. However, after extensive flight testing and a mechanical modification to permit greater spoiler deflection, it became apparent that adequate control could be achieved using the outboard segments only, and control forces due to friction and spoiler weight could be reduced. The data reported herein are for outboard spoiler segments only.

Figure 7 shows the spoiler cross section. There is a 0.4-in. gap between the hingeline and leading edge of the spoiler, but no direct venting from the undersurface of the wing to the spoiler cavity. The entire span of the roll spoilers is in front of a fixed aileron with the Fowler flap completely inboard of the spoiler. Roll performance was determined by initiating steady-state roll rates with many different values of step spoiler inputs with a clean configuration and with full Fowler flap and Kruger flap deflections.

Figure 8 presents the flight test results for the Redhawk in terms of roll rate as a function of spoiler deflection. Figure 9 converts the roll rate data to roll helix angle, $pb/2V_T$. Figure 10 shows time histories of both low- and high-speed roll response.

Several characteristics are apparent. Roll rate is very nearly a linear function of spoiler deflection. Roll rates are adequate for good handling qualities, even though only a relatively small spoiler span is used. There is no perceptible yawing moment produced by spoiler deflection. Pilots reported that there was no lag in rolling moment following a step spoiler input. There is a decrease in roll helix angle, $pb/2V_T$, when flaps are deployed, primarily because of the inboard shift of the lift distribution, giving the spoilers a smaller fraction of the total lift to spoil.

A series of design charts to predict spoiler effectiveness is presented in Refs. 8 and 9. Although aspect ratio and taper ratio were not exactly matched, the similar lift distributions for straight tapered wings should give reasonably close results. The steady-state roll equation

$$\frac{p}{\delta_s} = -\frac{C_{l_{\delta_s}}}{C_{l_p}} \frac{2V_T}{b}$$

was used to determine $C_{l_{\delta_s}}$ from flight test data with $C_{l_p}$ determined analytically from Ref. 10.

The results are presented in Table 4. There is good agreement for the clean wing, while the wind-tunnel data with a straight taper overpredicts the flaps-down roll power for the airplane because of the inboard shift in loading caused by the Fowler flaps. The rolling moment characteristics of the Redhawk spoilers are similar in nature to the data reported by Wentz[11] from wind-tunnel tests of an unvented spoiler on a clean wing with a GA(W)-1 airfoil. No wheel force data were recorded for the Redhawk; however, all pilots reported a positive centering force for the spoilers under all flight conditions.

## Dynamic Stability

Dynamic stability data were recorded to determine whether the decreased wing area had a significant effect on the dynamic flight characteristics.

### Longitudinal

Longitudinal dynamic data were taken in the following manner. The airplane was stabilized and trimmed in level flight. The elevator was deflected to provide a longitudinal disturbance, then returned to the original trimmed position. The resulting phugoid mode was allowed to oscillate through several cycles. Lateral inputs were made as required to keep the wings level.

**Table 4 Summary of the lateral control power for the Redhawk**

| | $C_{l_{\delta_s}}$ Clean wing | $C_{l_{\delta_s}}$ Full flaps deployed |
|---|---|---|
| Flight test results using steady-state roll approximation | 0.042 rad $^{-1}$ | 0.025 rad $^{-1}$ |
| Predicted from wind-tunnel data[8] | 0.042 | 0.037 |

Table 5 Phugoid mode characteristics, $W = 2500$ lb

| | Configuration | $V_e$ mph | Frequency, $\omega_p$, rad/s | Damping ratio, $\zeta_p$ |
|---|---|---|---|---|
| | Clean | 120 | 0.226 | 0.1097 |
| | Clean | 120 | 0.225 | 0.0746 |
| Redhawk | Clean | 120 | 0.225 | 0.0746 |
| | $\delta_f = 40$ deg | 80 | 0.259 | 0.1336 |
| | $\delta_k = 135$ deg | 80 | 0.270 | 0.1336 |
| | | 80 | 0.253 | 0.1245 |
| Cardinal | $\delta_f = 30$ deg | 80 | 0.339 | 0.045 |
| | | 80 | 0.324 | 0.044 |

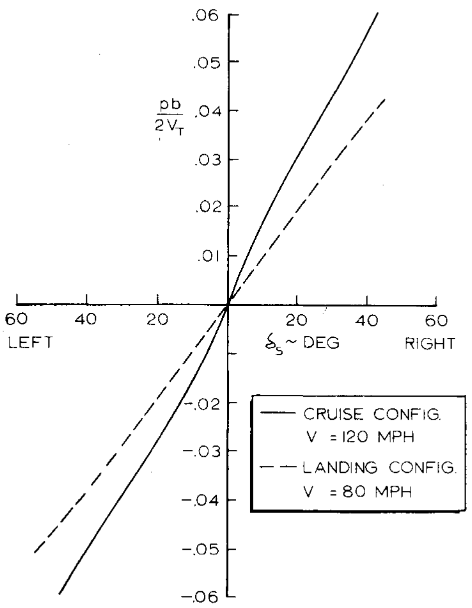


Fig. 9 Steady-state roll helix angle with spoilers.

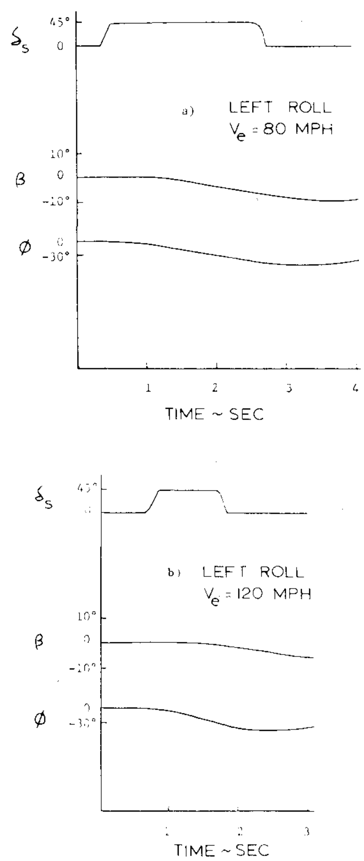


Fig. 10 Roll time histories for the Redhawk.

The results are summarized in Table 5. Frequency and damping ratios were determined from analysis of the oscillographic time history of pitch angle assuming a standard second-order dynamic system model. The short period mode had such a high frequency and damping ratio that no meaningful quantitative data could be obtained.

No Cardinal data were taken at 120 mph. In the landing mode, at 80 mph, the Redhawk had a decreased phugoid frequency but a significantly increased damping ratio. This can be attributed to the lower lift/drag ratio of the Redhawk compared to the Cardinal in the landing configuration.

#### Lateral-Directional

As is usually the case with light, single-engine aircraft, the Dutch roll mode was highly damped. The maneuver was initiated by inducing a large side-slip angle with the rudder, then centering the rudder and spoiler quickly while allowing the oscillation to damp. The high damping ratio makes it extremely difficult to extract accurate quantitative results from the data, but the frequency appears to be approximately 2.57 rad/s and the damping ratio $\zeta_d$ is 0.22 at 120 mph EAS.

Although it was not possible to obtain quantitative data, the spiral mode appeared to be stable for all airspeeds and configurations. This was a design objective achieved by increasing dihedral from 1.5 deg on the Cardinal to 3 deg on the Redhawk. This caused an obvious increase in roll sensitivity to rudder input and decreased the Dutch roll damping ratio at 120 mph from about 0.4 for the Cardinal to 0.22 for the Redhawk.

## Conclusions

Quantitative flight data and test pilot evaluations of the Redhawk have demonstrated the following:

1. Ride quality in turbulence is significantly improved due to the higher wing loading.
2. Zero-lift drag was reduced 13.8%.
3. The combined Fowler and Kruger flap system provides a trimmed maximum lift coefficient of 2.73.
4. Spoilers provide adequate roll acceleration and very favorable roll control characteristics, particularly the elimination of adverse yaw.
5. Although the Kruger flaps are probably too heavy and complex for very light aircraft, they are very effective high-lift devices and provide very favorable stall characteristics.
6. The Fowler flaps and spoilers are simple, lightweight systems which could be easily incorporated in light aircraft designs.

In summary, there are significant advantages to increasing the wing loading of typical light aircraft. The high-lift devices, and possibly spoilers, required to employ higher wing loading, represent a well-developed technology which can be readily applied to the next generation of light aircrtaft.

## Acknowledgment

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