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Abstract

The use of a control tab in a simple autopilot is discussed. The system is different from conventional installations in that the autopilot does not move the main control surface directly with a servo actuator. A servo tab is used to provide the necessary hinge moment. A much smaller control actuator may then be used. A further benefit of this approach is that the system may be operated full-time with only minor control force feedback to the pilot. For the case of the wing leveler system, the result is a full time stability augmentation system in the lateral axis. With improved stability, a large number of accidents due to loss of control could be prevented. Pilot workload is also reduced. The failure modes of such a system are benign, eliminating the need for redundancy and the associated costs. The system is shown to be stable and effective using either angular rate or attitude feedback. For the case of the light, four seat airplane studied, the basic wing leveler would weigh less than nine pounds and would cost no more than a comparable conventional autopilot. Potential applications to other autopilot modes and to decoupled flight control systems are also discussed.

Nomenclature

c	Wing chord length
c_a	Average aileron chord length
C_h	Hinge moment coefficient
HM	Hinge moment
I_c	Moment of inertia
p	Roll rate
q	Dynamic pressure
r	Yaw rate
r_g	Gyro axis angular rate
s	Laplace transform variable
S_a	Aileron surface area
α_{tilt}	Rate gyro tilt angle
δ_a	Aileron deflection
δ_t	Tab deflection
ϵ	Feedback error signal
$\mathcal{L}$	Laplace transform operator
ω_c	Control system natural frequency

Acronyms:

IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
SSSA	Separate Surface Stability Augmentation
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions

Introduction

The vast majority of airplanes in service today have near neutral stability or are mildly unstable in the spiral mode of dynamic lateral/directional motion. A divergent spiral is characterized by a gradually increasing bank angle resulting in a turn of increasing load factor. At the same time, the airplane begins a descent and the airspeed will increase. This combination is often termed a 'graveyard spiral' for, if left uncorrected, will result in loads beyond the airplane design limits and/or collision with the ground. This instability is easily controlled by the pilot. In operations conducted under Visual Flight Rules (VFR), the pilot maintains a wings-level attitude by reference to the horizon. Under Instrument Flight Rules (IFR), the pilot uses an artificial horizon, among other instruments, to maintain level flight.

A significant number of accidents every year are attributed to in flight loss of control by pilots. Accident data from the National Transportation Safety

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Year	All Accidents No.	%	Fatal Accidents No.	%
1978-81*	517	13.3	233**	34.7
1982	311	9.5	123	20.3
1983	401	12.9	147**	26.2
1984	383	12.6	132	23.7
1985	367	13.2	115	22.6
1986	350	13.4	120**	24.6
1987	326**	13.1	113**	25.7
1988	346**	14.5	135**	29.7
Average:		13.2		29.5

* Data for 1978-81 are yearly average values.

** Inflight loss of control was the most common cause.

Table 1: Accidents Where 'In Flight Loss of Control' is Listed as the First Occurrence, 1978-1988, All Aircraft, All Operations.

Year	All Accidents No.	%	Fatal Accidents No.	%
1980	140	3.9	102	16.4
1981	167	4.8	114	17.4
1982	127	3.9	98	16.6
1983	116	3.8	91	16.4
1984	96	3.2	74	13.6
1985	93	3.4	69	13.9
1986	68	**2.6**	52	11.2
1987	74	3.0	N/A	N/A
1988	71	3.0	N/A	N/A
Average:		3.6		15.3

Table 2: Accidents Where 'VFR Flight into IMC' is Listed as a Cause or Factor, 1980-1988, All Aircraft, All Operations.

Board for the calendar years 1978-88 [1] are shown for all aircraft and all types of operations in Table 1. For this period; single reciprocating fixed wing aircraft accidents accounted for 80% of the total of all accidents. These data are taken from tables of the 'first occurrence' which led to the accident. It is not clear exactly how many total accidents were due to the characteristics of spiral divergence. Certainly not all accidents in the categories shown are of this type. For example, mechanical control system malfunctions would be included here. An unstable spiral, however, could easily have contributed to accidents listed in other categories. The amount of concentration required to simply 'fly the airplane' will certainly detract from a pilot's ability to deal with any type of emergency. Notice that, in several years, in flight loss of control was the most prevalent first occurrence. In every year, this cause was at least the second most common cause of fatal accidents. On the average, in flight loss of control contributed to 13.2% of all accidents and 29.5% of fatal accidents. This type of accident is much more likely to be fatal than most other types, such as engine failure.

There is a surprising number of pilots without an instrument rating who either deliberately or inadvertently enter Instrument Meteorological Conditions (IMC). Accidents where 'Continued VFR into IMC' is listed as a cause or factor are listed in Table 2 for the years 1980-88. The average for this period was 3.6% for all accidents and 15.3% for fatal accidents (1980-86). Although all VFR pilots receive specific training in instrument flying, these data show that all too often such operations exceed the pilot's capabilities. As with the statistics for loss of control accidents, not all of the VFR into IMC cases would have been due to the pilot simply losing control of the aircraft. Some of these accidents may have been caused by weather conditions which posed a direct hazard to the aircraft, such as severe turbulence or icing. The VFR pilot is less likely than the IFR pilot to be knowledgable about weather conditions conducive to such hazards.

Loss of control by IFR pilots also occurs occasionally, due to a number of different causes. In light aircraft operations, there is usually only one pilot and the workload during IMC can be very high.

Automatic pilots are often used by both IFR and VFR pilots to reduce workload. In extreme cases they have been used by VFR pilots in IMC to maintain control of the airplane. The simplest type of autopilot is often called a wing leveler, which commands zero bank angle by sensing either the bank angle or the yaw rate. Many general aviation airplanes, however, are not equipped with even simple autopilots.

Conventional autopilots use servo-actuators to drive the entire control system in the axis desired. For example, a wing leveler uses the aileron controls to correct excursions in bank angle. The servo must be sized not only to overcome the forces due to aerodynamic hinge moments, but forces due to friction, stiction, and inertia.

Another characteristic of conventional autopilots is that pilot-in-the-loop operations are not possible. In other words, either the pilot is in control, or the autopilot is in control, but never both at the same time. This is a consequence of the design of the primary flight control system. General aviation aircraft almost always use reversible controls, which use cables or pushrods to drive the aerodynamic surfaces. Conventional autopilot servos are directly connected to the control cables/pushrods. If the autopilot is engaged, then the pilot must physically override the servo to make an input. Note that the autopilot must be designed so that the pilot has this capability, in case of a malfunction.

An alternative to the conventional installation is to use a control tab to drive the primary flight control. For example, a wing leveler system would use a tab to drive the aileron controls. The principle is exactly the same as a servo tab, which has often been used on large aircraft with cable driven controls (most modern large aircraft use powered controls now). For an autopilot installation, a small actuator is connected directly to the tab, and does not interfere with the primary aileron control system. Such a system is lightweight, inexpensive, and can be easily retrofitted to existing light airplanes. Since the servo is not directly coupled to the pilot controls, the system can be active at all times. Such a full time system would significantly enhance safety and reduce pilot workload during operations in both VMC and IMC.

Returning to the subject of accident prevention, it must be recognized that a wing leveler or other autopilot will not always save the aircraft in adverse weather. Adequate performance of the tab driven wing leveler in turbulence is important, but that assessment is beyond the scope of this study.

This paper shows the feasibility of the tab driven wing leveler concept. First, a discussion of related research is presented, including some actual installations of similar systems. A general description of the system and components is then presented. A dynamic model of the aileron control system is derived and a stability analysis is conducted. Weight and cost data for commercially available sensors and actuators are presented. Finally, applications to yaw and pitch axis control are discussed, including the potential for fully decoupled flight control systems.

Related Work

The concept of a full-time wing leveler system is not new. The Mooney Aircraft Company had one available as an option on some of their earlier model single-engine airplanes [2]. This system sensed yaw rate from the airplane turn coordinator and drove the aileron and rudder control systems with electro-pneumatic servo actuators. During maneuvering flight, the system could be disengaged by pressing a button on the grip of the pilot control wheel.

A different approach to the general problem of automatic flight control is Separate Surface Stability Augmentation (SSSA) due to Roskam. This approach has been demonstrated for both a simple wing leveler system [3] and as a full stability augmentation system [4]. In principle, the wing leveler system can be used for the purpose as intended here: a full time system that stabilizes the spiral mode, without any feedback to the pilot. The implementation as a separate surface requires one aileron to be cut into two pieces, and the extra section of aileron is used only for autopilot functions.

Although not an automatic stabilization device, an electrically driven trim tab has been developed for light airplanes [5]. It is manually controlled from the cockpit and is used for trim in the roll axis. The system has been certified by the Federal Aviation Administration for installation on a broad range of aircraft from light singles up through twin-engine airplanes.

A system very similar to the one herein has already been developed [6]. The system was intended to demonstrate fluidic rate sensor technology, and was installed on a light, amateur-built airplane. An electrically driven trim tab already existed for the aileron system, and the autopilot was installed so as to drive the trim tab rather than the aileron directly. It is interesting to note that the servo used in this installation was of the type used in radio controlled model aircraft. This gives an indication of how small the tab hinge moments can be.

There has been considerable recent work aimed at increasing the utility of general aviation aircraft [7]. One aspect of this effort is to improve the presentation of information to the pilot, including guidance and navigation data. Another is to use 'decoupled' flight controls, where the stick controls rate of climb and the throttle controls speed. This requires the use of a completely integrated flight control and navigation system, probably using fly-by-wire (FBW) or fly-by-light (FBL) controls. This approach is taken in [8]. The design of the flight control system is very similar to the present study. Redundant tab/control surfaces are provided for each control axis.

One disadvantage to the servo tab control approach is that the control response can become sluggish at low speeds. This is because the hinge moment generated by the tab is proportional to the dynamic pressure whereas the control system inertia is constant. This can become a major problem in the design of closed loop systems during maneuvers where precision is required (e.g. landing flare).

An aircraft which is controlled exclusively by FBW/FBL systems requires several levels of redun-

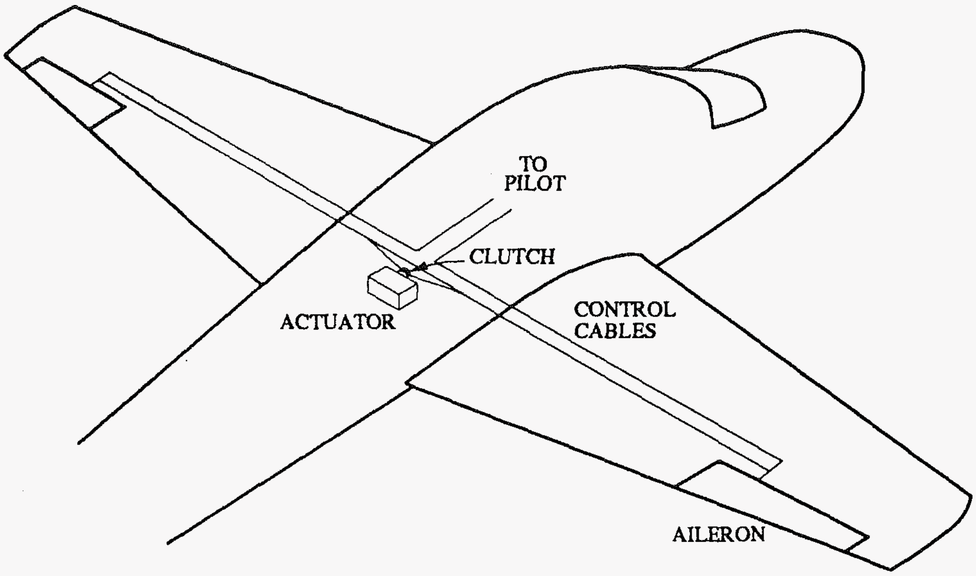


Figure 1: Installation oi tne Actuator for a Conventional Wing Leveler.

dancy because a complete system failure will result in the loss of the aircraft. These guidance and control systems must be designed into the airplane from the beginning, and add considerably to the cost. The system cost is a relatively weak function of the size and cost of the airplane itself. The added cost may be justifiable for a large expensive airplane, but it would be prohibitive on a light, general aviation airplane.

This is an unfortunate situation, for one of the goals of current flight controls research is to make flying 'as easy as driving a car' – thus increasing the utility of light aircraft and reduce training requirements. However, the resulting, very expensive, airplane is quite unlikely to be owner-flown. Rather, it will be operated by one or two professional pilots who have the training which make the advanced control system unnecessary.

The approach in the present work is an intermediate step in this direction. A high degree of stabilization is possible without eliminating the reliability inherent in conventional reversible control systems. This should significantly reduce the total system cost.

System Description

The tab driven wing leveler system would have the same basic components as a conventional wing leveler autopilot. These basic components are the attitude or angular rate sensor, autopilot computer, and servo-actuator.

An angular rate sensor is required to sense the airplane yaw rate. A standard cockpit instrument in most airplanes is the turn coordinator, which indicates rate of turn. Many turn coordinators are equipped with electrical pickoffs for use with autopilots. This would work well for this system. However, it may be desirable to use a separate rate sensor so that the entire system is self-contained. Most autopilot systems use an attitude gyroscope instead of or in addition to a rate sensor. This improves system performance considerably, but at additional cost. Attitude gyros have a lower mean time between failure as well. The present research considers the use of both types of sensors.

The autopilot computer is used to convert the signal input by the rate sensor into a command for the actuator. It would be a very simple device, and may be analog rather than digital.

The actuator takes the electrical input from the computer and provides the force to deflect the control surface a prescribed amount. It is the size and function of the actuator that is the principle difference between this system and a conventional wing leveler.

As mentioned earlier, a conventional autopilot actuator is connected directly to the primary control surface cables. This is shown in Figure 1. It must be powerful enough to drive the entire system and overcome its friction. The actuator is usually connected to the cables through a clutch which serves two func-

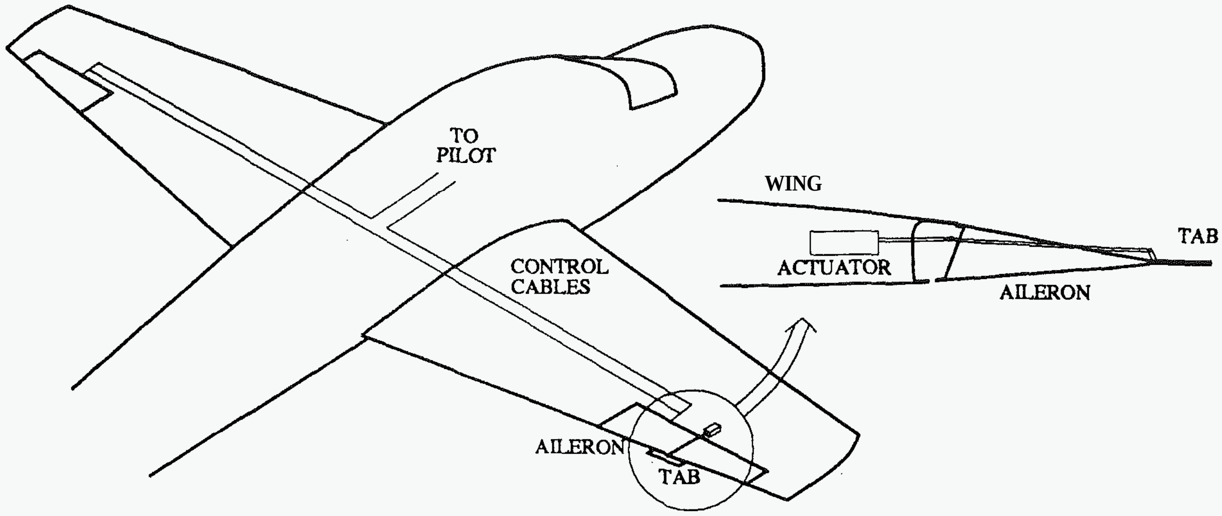


Figure 2: Installation of the Tab-driven Wing Leveler.

tions. First, it disconnects the actuator from the controls when the autopilot is turned off. This minimizes any forces the pilot may feel during normal flying. Second, the clutch is designed to slip when the force reaches a prescribed threshold value, so that the pilot may override the autopilot in case of a malfunction.

For a tab driven system, the actuator would deflect a tab on the primary control surface, as in Figure 2. Then the aerodynamic force generated by the tab would deflect the primary surface. The primary surface deflection would by proportional to the tab deflection. Several advantages would result.

The actuator size would be significantly smaller than for the conventional system. This is because the tab itself would be quite small, and the inertia and friction of the primary system would not be as significant of a factor. Recall that in the system described in [6], the servo used was similar to those used in radio controlled model airplanes. Thus the weight and power requirements are substantially 'smaller.

No clutch would be required to disconnect the actuator from the primary flight control system. In a worst-case malfunction, the pilot would have to override the aerodynamic force generated by the tab. This would be one of the sizing criteria. Also, the potential for jamming the primary controls is reduced.

The feedback to the pilot will no longer interfere with normal control inputs. The actuator is not connected to the primary control cables, so there is no clutch to override. Thus the system could be operating at all times, even during takeoff and landing. There will be an aerodynamic hinge moment generated by the tab during steady turns, but this does not at all prevent pilot-in-the-loop operations. The implications of this hinge moment are discussed further in a later section of this paper. It would still be required, however, to have the ability to disable the system in case of malfunction or during maneuvering.

Stability Analysis

The first step in this feasibility study is to conduct a stability analysis of the closed-loop system using root-locus methods, described in [9]. The root-locus method is based on the analysis of dynamic systems which may be described by one or more linear differential equations. Laplace transforms are then used to solve these equations. The dynamic characteristics of each component are described in the 's' domain by a transfer function, which, when multiplied by the Laplace transform of the input forcing function, gives the Laplace transform of the system output. *The* transfer functions in this analysis will always be the ratios of two polynomials in the Laplace transform variable s. The system stability is determined by the roots of the the denominator polynomial (the characteristic equation), which are called 'poles.'

Once the component transfer functions are known, then the transfer function may be derived for the entire closed-loop system. A block diagram for the attitude based tab driven wing leveler is shown in Figure 3. A discussion of each block in the system and the transfer functions used to describe them follows.

The system gain, K, determines the magnitude of

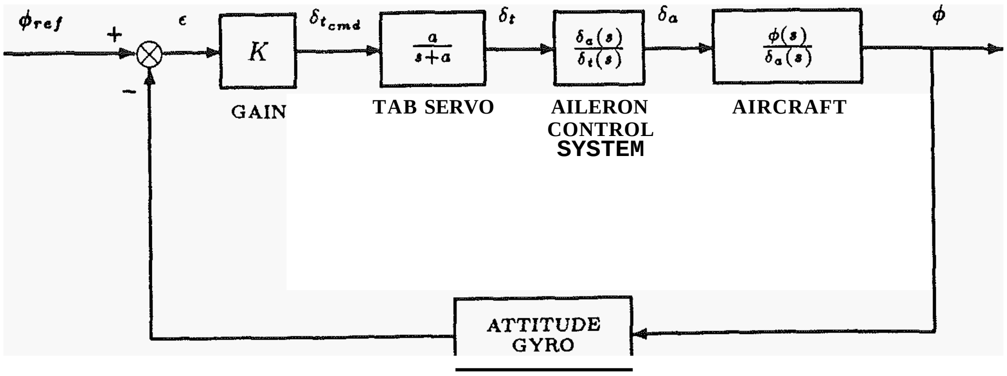


Figure 3: Block Diagram For the Tab-driven Wing Leveler Using Roll Attitude Feedback.

the commanded control tab deflection per unit of attitude error. The roots of the characteristic equation of the closed loop transfer function will change depending on the value of the gain. The specific value chosen will be a compromise between system effectiveness and system stability, as will be shown below.

For this level of analysis, the servo transfer function is well approximated by a first order lag:

$$\frac{\delta_t(s)}{\delta_{t_{cmd}}(s)} = \frac{a}{s+a} \tag{1}$$

where the constant a is the break frequency, in rad/sec. For periodic inputs with frequencies above the break frequency, the servo response will be too slow to keep up. For general aviation applications, a value of a $= 10$ rad/sec is usually quite adequate. Since slower servos are generally less expensive, system performance with lower break frequencies will also be investigated.

The dynamic model of the aileron control system is derived by summing moments about the aileron hinge, as shown in Figure 4. The aileron control system is defined here to include the aileron surface plus all of the cables, pushrods, pulleys, bellcranks, etc. which move with it. In this analysis, aileron control system inertia and steady aerodynamic forces will be included. Then, from Newton's second law:

$$I_c\ddot{\delta}_a = HM \tag{2}$$

where I, is the moment of inertia of the aileron control system referenced to the hingeline and HM is the total aerodynamic hinge moment due to aileron and control tab deflections:

$$HM = qS_ac_a\left(C_{h_{\delta_a}}\delta_a + C_{h_{\delta_t}}\delta_t\right) \ . \tag{3}$$

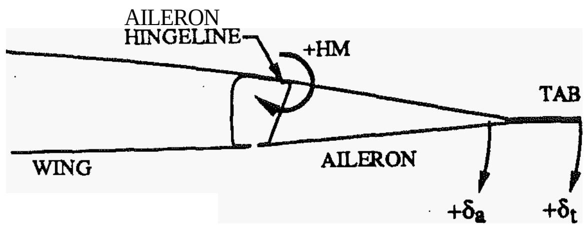


Figure 4: Sign Conventions for Determination of Aileron Control System Model.

This gives

$$I_c\ddot{\delta}_a - qS_ac_aC_{h_{\delta_a}}\delta_a = qS_ac_aC_{h_{\delta_t}}\delta_t \ . \tag{4}$$

Applying the Laplace transform, and using the property $\mathcal{L}\{\ddot{\delta}_a\} = s^2\mathcal{L}\{\delta_a\}$, we have

$$s^2\delta_a(s) + \omega_c^2\delta_a(s) = -\omega_c^2\frac{C_{h_{\delta_t}}}{C_{h_{\delta_a}}}\delta_t(s) \tag{5}$$

where

$$\omega_c = \sqrt{\frac{-qS_ac_aC_{h_{\delta_a}}}{I_c}} \tag{6}$$

is the natural frequency of the aileron control system. Solving for the transfer function gives

$$\frac{\delta_a(s)}{\delta_t(s)} = \frac{-\omega_c^2\left(C_{h_{\delta_t}}/C_{h_{\delta_a}}\right)}{s^2+\omega_c^2} \ . \tag{7}$$

The hinge moment coefficient $C_{h_{\delta_a}}$ is always negative ($C_{h_{\delta_t}}$ as well), so the frequency ω_c will be real.

The airplane chosen for study is a Cessna **172,** which is representative of light, four-seat, single engine aircraft. The hinge moment coefficient $C_{h_{\delta_a}}$ is predicted using empirical methods contained in [10]. For the Cessna **172:**

$$\begin{aligned} S_a &= 9.15\, ft^2 \text{ (each side)}, \\ c_a/c &= .20 \text{ (average)}, \\ C_{h_{\delta_a}} &= -.661\, rad^{-1} = -.01153\, deg^{-1} \ . \end{aligned} \quad (8)$$

It should be noted that prediction of hinge moments is not an exact science and the value above could be in error by **as** much **as 25%.** Unfortunately, methodology for estimating the hinge moments due to control tab deflections is even more inferior. Experimental data for a variety of aileron/tab combinations are contained in [11]. From these data, a reasonable approximation for a tab with a chord of **25%** of the aileron chord and a span **1/3** of the aileron span is:

$$C_{h_{\delta_t}} = 0.25 C_{h_{\delta_a}} \quad (9)$$

This should provide adequate control authority to the wing leveler. **As** before, this estimate for the tab hinge moment coefficient could be in considerable error. To determine this quantity more exactly will probably require experimental investigation.

There is no straightforward method for estimating the moment of inertia of the aileron control system, referenced to the hingeline, unless a dimensioned engineering drawing is available showing all cables, pushrods, pulleys, bellcranks, etc. The inertia of the surface itself, obtained from [12], is **0.0725** slug ft^2 for both sides. To estimate the inertia of the remaining components, an estimated weight and average radius of gyration of **15** lb and **0.25** ft are used. These add up to a total system inertia of $I_c = .1016$ slug ft^2.

The dynamics of the airplane are approximated with a linear, small-perturbation model. **A** complete list of the stability and control derivatives for the Cessna **172** in the cruise flight condition is contained in [9]. These data are then used to determine the airplane transfer function, which gives the airplane response to aileron control inputs. For this case, the bank angle to aileron transfer function is:

$$\frac{\phi(s)}{\delta_a(s)} = \frac{57.4s^2 + 60s + 349.4}{s^4 + 13.82s^3 + 28.61s^2 + 142.1s + 1.553} \, . \quad (10)$$

This is the complete three degree of freedom lateral/directional model.

For the conventional system, where the servo drives the ailerons directly, all transfer functions are identical with the exception of the aileron control system model. In this case, that transfer function is eliminated completely. **A** root locus for the conventional system is shown in Figure **5.** These results are identical to a similar system analyzed in [9]. Recall that for the system to be stable, the real part of all poles must be negative. Since all complex roots occur in complex conjugate pairs, the root locus plot is symmetric about the real axis and only the upper half is shown. The behavior with three different values for the servo break frequency, a in Equation 1, of **10, 5,** and **2** rad/sec. These values correspond to a 'good,' 'medium, and 'slow' servo, respectively. It is seen that the servo pole combines with the spiral pole and then moves toward the zero pair located at $s = -.5217 \pm 2.40923$. The roll and dutch roll poles move to infinity along asymptote angles of $180°$ and $\pm 60°$, respectively. The performance of the system in all three **cases** is good, with a marked stabilization of the spiral pole and ,no adverse effects on the dutch roll behavior for moderate gain settings.

The root locus for the tab driven wing leveler is shown in Figure **6.** For the cruise flight condition, the natural frequency of the aileron control system is ω_c=71.5 rad/sec, which far exceeds that for any rigid body mode. There is essentially no effect on the performance of the wing leveler due to the aileron control system. Close examination of the aileron control system poles show no unwanted characteristics there either.

As indicated in Equation **6,** the aileron control system natural frequency is dependent on dynamic pressure. For the cruise case this is relatively high. There is a greater chance of adverse effects at lower dynamic pressure, and lower ω_c. For example, a typical approach airspeed results in a value of ω_c=16.4 rad/sec. To be consistent, however, the stability and control derivatives should be computed for the angle of attack and flap deflection angle required for this condition. These data were not available for this study. However, the root locus analysis for the cruise airplane transfer function with the low frequency aileron control system model is shown in Figure **7.** For this case, the dutch roll poles move to the unstable (positive) side of the imaginary axis at a slightly lower gain setting than in the cruise case. However, it is still quite possible to choose a gain that results in adequate performance for both flight conditions. No gain scheduling, with the accompanying increase in system complexity, is **as** yet required.

It is also possible to design a wing leveler system using angular rate rather than attitude feedback. This is based on the principle that in level flight a steady bank angle results in a steady turn. In practice, it has been found to be useful to feed back a combina-

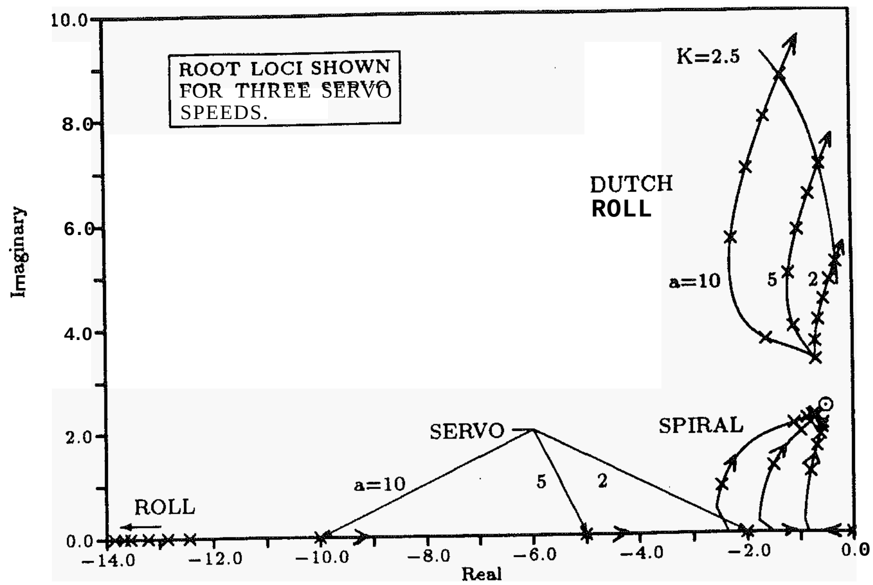
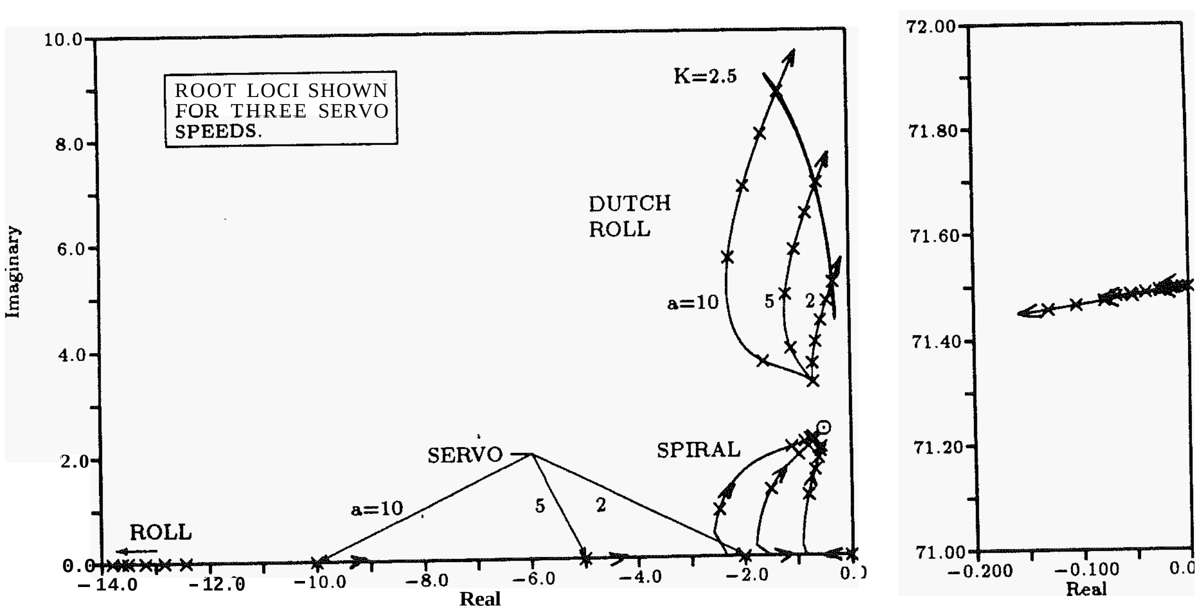


Figure 5: Root Locus for the Conventional Wing Leveler Using Roll Attitude Feedback.



a) Aircraft Rigid Body Poles

b) Aileron Control System Poles

Figure 6: Root Locus for the Tab-driven Wing Leveler Using Roll Attitude Feedback, ω_c=71.5 rad/sec.

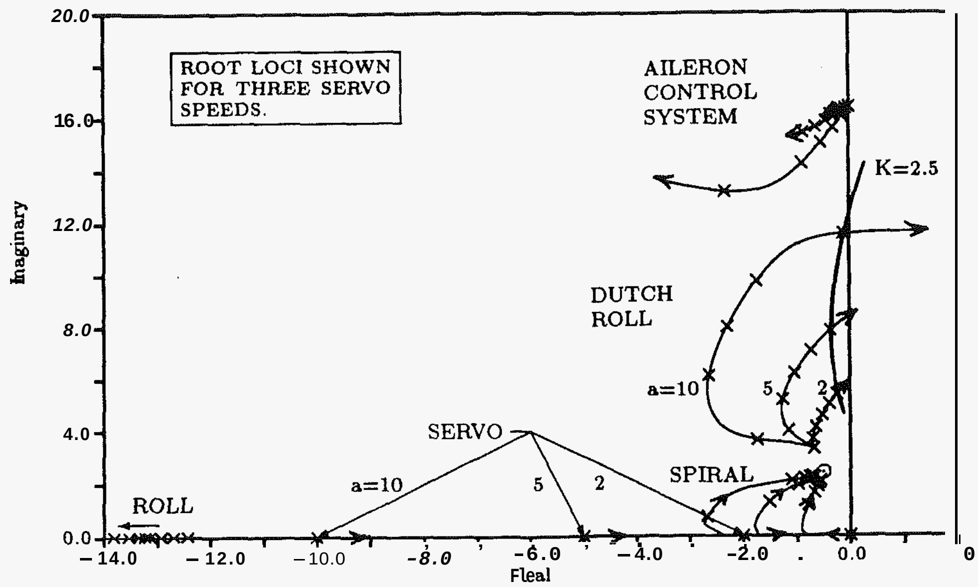


Figure 7: Root Locus **for** the Tab-driven Wing Leveler Using Roll Attitude Feedback, ω_c=16.4 rad/sec.

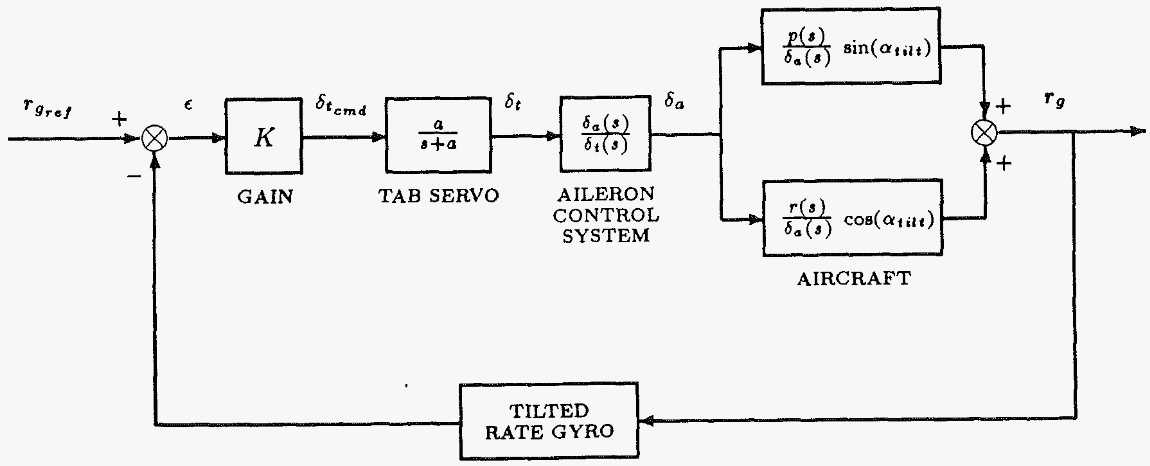


Figure 8: Block Diagram for the Tab-driven Wing Leveler Using Angular Rate Feedback.

tion of yaw and roll rate. This is shown in the block diagram of Figure **8.**

The basic blocks in the feedback loop are as described above with two exceptions. The airplane transfer functions required are now the roll and yaw rate to aileron transfer functions. **As** before, these are obtained from [9]:

$$\frac{p(s)}{\delta_a(s)} = \frac{s(57.4s^2 + 60s + 349.4)}{s^4 + 13.82s^3 + 28.61s^2 + 142.1s + 1.553} \quad (11)$$

$$\frac{r(s)}{\delta_a(s)} = \frac{-8.251s^3 - 125.6s^2 - 18.81s + 50.63}{s^4 + 13.82s^3 + 28.61s^2 + 142.1s + 1.553} \quad (12)$$

The combined roll and yaw rate feedback is accomplished by tilting the sensitive axis of the rate gyroscope by an angle α_{tilt} relative to the airplane *stability x* axis. Then the rate sensed by the gyro is

$$r_g = p\sin(\alpha_{tilt}) + r\cos(\alpha_{tilt}) \ . \quad (13)$$

Many wing levelers based on this concept use the airplane turn coordinator, which is a required cockpit instrument installed in all airplanes. Turn coordinators are constructed with a tilt angle of **45'** relative to the ***body*** x axis. **A** change in α_{tilt} of $\pm 10^\circ$ does not make a significant difference in the closed loop performance, so the distinction between body and stability axes is not important here.

As with the roll attitude feedback case, a conventional system is identical to the tab driven case with no aileron control system block. The root locus of this system is shown in Figure **9.** It is seen that the use of rate feedback does not stabilize the spiral mode as well as when using roll attitude feedback. This is due at least in part to the numerator zero located at $s = -0.1483$, since the spiral pole cannot move to the left of this point. The time to half amplitude of the the spiral mode is inversely proportional to the value of this pole. The complex zero pair located at $s = 0.7403 \pm 2.5267i$ attracts the dutch roll poles toward the unstable part of the complex plane. Notice that even a relatively poor servo would still be adequate for this application.

The root locus for the tab driven system with rate feedback is shown in Figure 10. While the behavior of the airplane rigid body modes is similar to the conventional case, the aileron control system modes are unstable for any positive value of gain. Recall that in the aileron control system model, no damping is included. While aerodynamic and friction forces will contribute some positive damping (below flutter speeds), there is no guarantee that that will be sufficient to stabilize the aileron control system modes. **A** simple solution is to add a double-lag filter to the forward path ***so*** all signals to the aileron control system will be well below the natural frequency of the aileron control system. This will change the breakaway angle of the aileron control system poles. The transfer function of the filter is

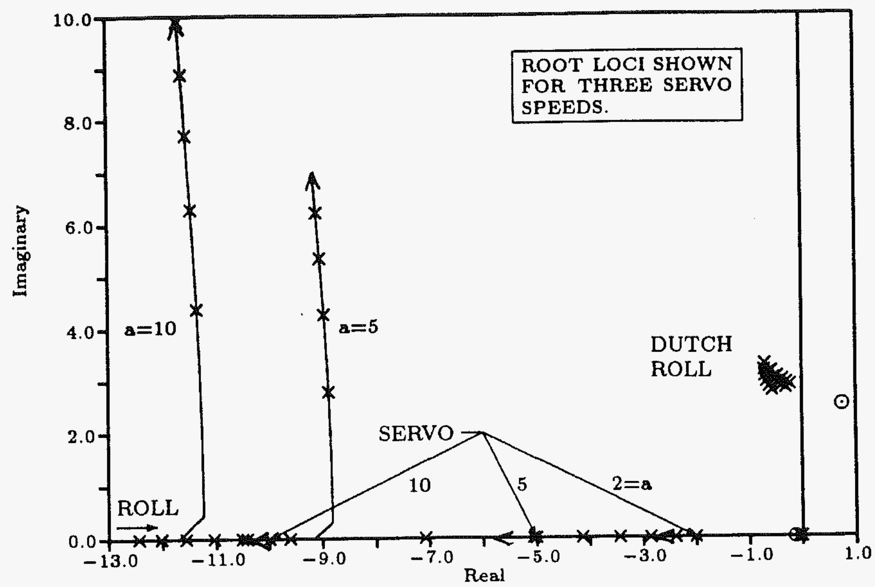
$$\frac{\epsilon_{filt}(s)}{\epsilon(s)} = \frac{1}{(\tau s + 1)^2} \quad (14)$$

and a time constant $\tau = 0.3$ sec is used. The root locus with this filter is shown in Figure 11. The filter freezes the aileron control system poles in their open-loop location. It is assumed that the damping due to aerodynamic and friction forces will be sufficient. The effect of the filter on the dutch roll mode is to improve damping, while there is no real change in the spiral behavior. The root locus for the approach case, where $\omega_c = 16.4$ rad/sec, is shown in Figure **12.** There is still very little interaction between the aileron control system and aircraft modes, probably due to the filter.

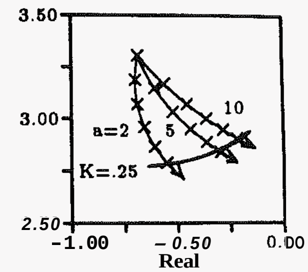
System Design Considerations

A preliminary investigation into the available sensors and actuators has been conducted. To minimize cost, off the shelf components should be used. Some typical characteristics of gyroscopes are listed in Table **3.** It is common in light aircraft to use the gyroscopes mounted on the instrument panel as autopilot sensors as well. Panel mounted gyroscopes are either powered electrically or by a vacuum. Vacuum powered gyros are lighter and less expensive, but tend to fail more often. Remote mounted gyros are almost exclusively electric. There are other types of sensors that may be used. Fiber optic rate gyros have the potential for excellent reliability, but will probably be too expensive. On the other hand, the fluidic rate sensor described in **[6]** is extremely inexpensive.

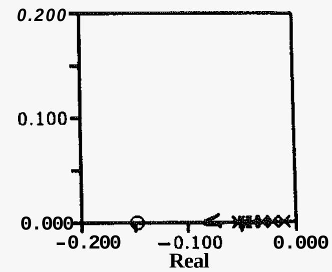
The weight and cost of the servo is mainly dependent on the speed and maximum load requirements. The load on the actuator at a maximum dive speed of **151** knots with a 10° tab deflection will be approximately **20** lb. The values listed in Table **4** show values for different speeds in the **40** lb load range. It is difficult to relate the servo output shaft speed to the break frequency used in the first order **lag** approximation of the root locus analysis. The first order lag transfer function is a linear model, whereas the speed is one of several, non-linear, limiting characteristics of the actual servo. The final choice of servo would be based on a number of characteristics including speed, acceleration, friction, deadband, etc. It is quite possible that a faster servo than analyzed here may be required due to these considerations.



a) Basic Performance

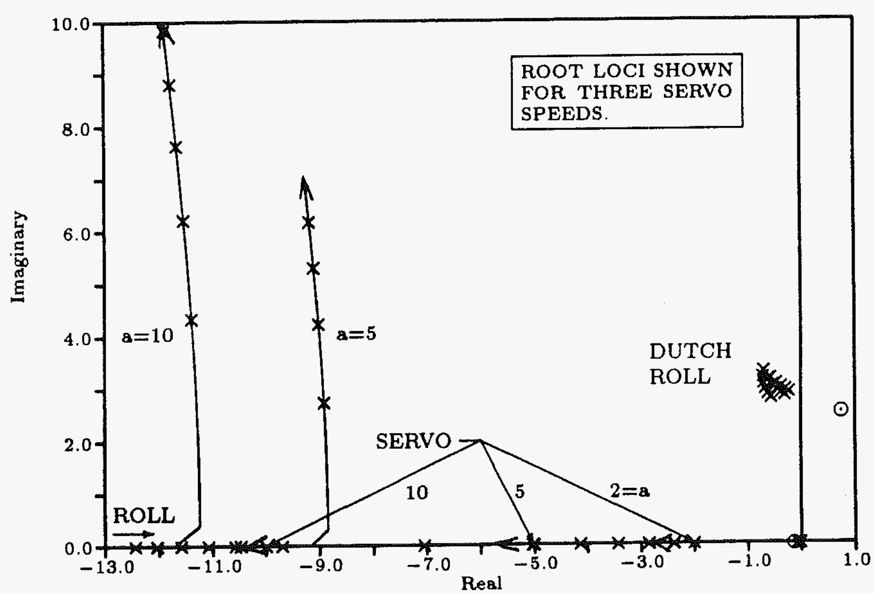


b) Dutch Roll Poles

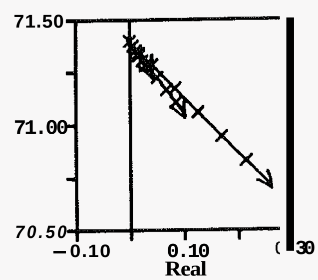


c) Spiral Poles

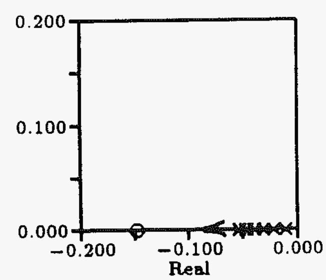
Figure 9: Root Locus for the Conventional Wing Leveler Using Angular Rate Feedback, $\alpha_{tilt} = 45°$.



a) Basic Performance

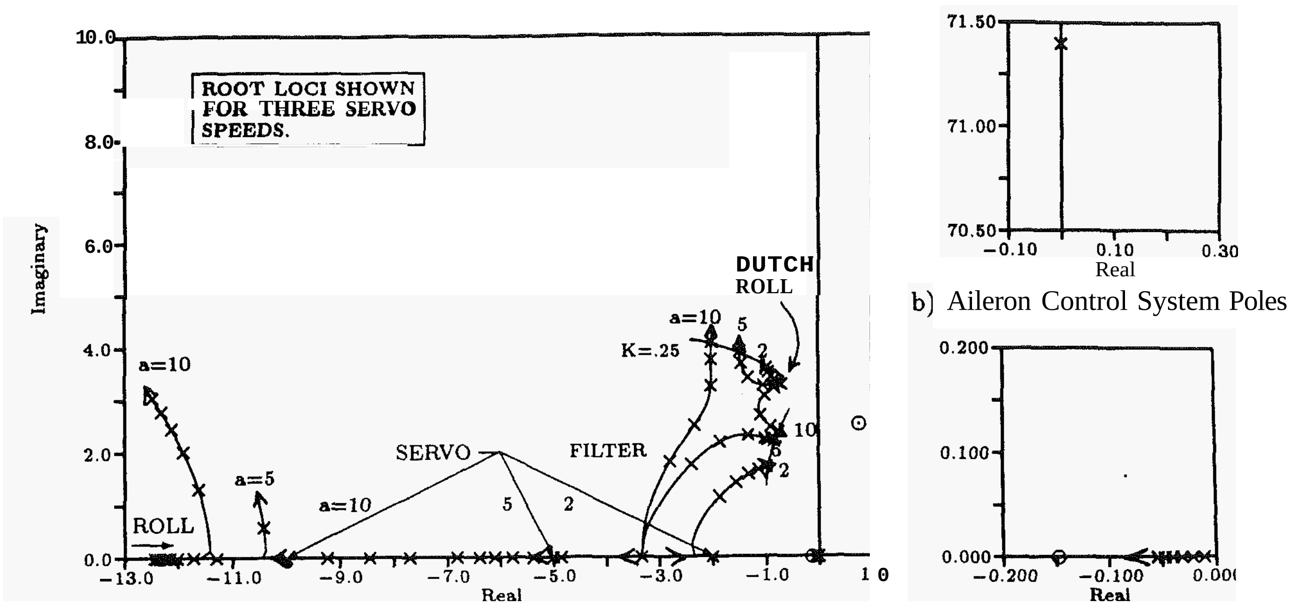


b) Aileron Control System Poles



c) Spiral Poles

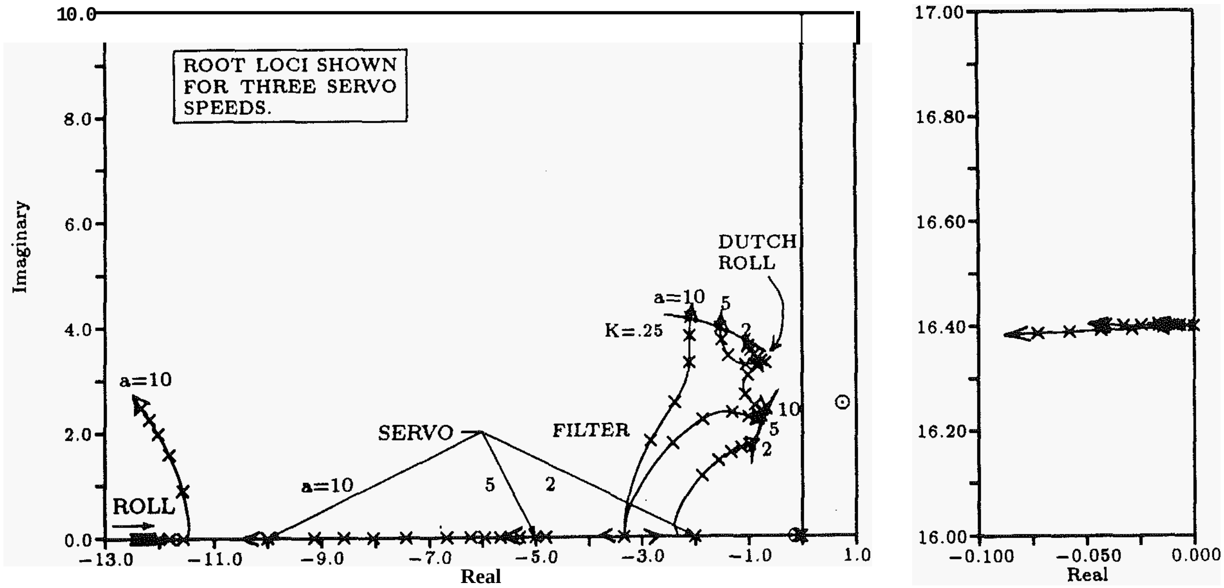
Figure 10: Root Locus for the Tab-driven Wing Leveler Using Angular Rate Feedback, $\alpha_{tilt} = 45°$, ω_c=71.5 rad/sec.



a) Basic Performance

c) Spiral Poles

Figure 11: Root Locus for the Tab-driven Wing Leveler Using Angular Rate Feedback, With Double-lag Filter, $\tau = 0.3$ sec, $\alpha_{tilt} = 45°$, ω_c=71.5 rad/sec.



a) Aircraft Rigid Body Poles

b) Aileron Control System Poles

Figure 12: Root Locus for the Tab-driven Wing Leveler Using Angular Rate Feedback, With Double-lag Filter, $\tau = 0.3$ sec, $\alpha_{tilt} = 45°$, ω_c=16.4 rad/sec.

The control tab size used in this study has a chord length of 5% of the main wing chord and a span of one third the aileron span, or .226 by **3.04** feet. Note that the tab would be installed on one side only. The tab would probably be constructed of fiberglass, and would weigh approximately **0.5** Ib. To maintain aileron mass balance, a counterweight must be added to the aileron ahead of the hingeline.

The total system weight and cost would be around five to eight lb and $600 to **$3000** respectively, depending on the choice of components. It is very difficult to estimate accurately the certification costs at this stage in the design. A separate certification effort would probably be necessary for each type of aircraft. Then the total cost would be amortized over the number of units sold for each aircraft type. The additional cost for certification could easily far exceed the cost of the components alone.

One of the most adverse failure modes for this system is a hardover servo failure. For a 10° tab deflection at the maximum dive speed for this airplane, the control force required to override the tab is 18 lb. This force diminishes to nine and four pounds at normal cruise and approach speeds, respectively. According to FAR **23.143,** the maximum control wheel forces allowed for temporary and sustained application are 60 and 5 lb, respectively. While the temporary requirement is easily fulfilled, speed must be reduced to meet the requirement for sustained operations.

A complete flutter analysis is beyond the scope of this study. The possibility of adverse effects on the flutter characteristics of the aileron and wing definitely exists. As a first step, the same degree of mass balance will be required as on the unmodified airplane. The modified airplane will also need to be flutter free in the case of a complete tab pushrod failure. A novel solution to this problem, used in the trim tab system described in [5], is the addition of a 'mouse trap' spring to the tab to eliminate free motion in this case. This will add to the weight and servo size, however. Prevention of flutter is certainly feasible, as evidenced by numerous airplanes certified with aileron trim tabs.

It is desired that the system have good performance in moderate levels of turbulence. Indeed, one of the motivating factors behind this study is to reduce workload and prevent accidents in instrument conditions, which often involve turbulence. This should be a topic of future study.

Type	Mount	Power	Weight	Cost
Attitude	Panel	Vacuum	2.0 lb	$ 800
Attitude	Panel	Elec.	2.8	2000
Attitude	Remote	Elec.	1.3	7000
Rate	Panel	Elec.	1.4	500
Rate	Remote	Elec.	0.8	2900

Table **3:** Typical Characteristics of Attitude and Rate Gyroscopes.

Speed	Weight	Cost
0.75 in/sec	**1.0** lb	$ 800
0.09	**0.3**	**50**

1) Maximum Load ≈ **40** lbs.
2) Speed is under no load.

Table **4:** Typical Characteristics of Servo Actuators.

Future Research

There are questions in several areas which must be addressed before development can proceed. A flutter analysis is perhaps first on this list. Also important is an investigation into certification requirements. A more thorough search for low cost sensors and actuators should also be conducted.

More detailed analysis of system performance, including the effects of atmospheric turbulence, may require a full simulation of the system and the airplane. An engineering simulator, without pilot controls or instruments, may be adequate initially. Ultimately, a full simulator evaluation, including pilot in the loop operation, will be necessary.

Once the concept is fully validated, it may be readily extended to other autopilot functions. A yaw damper would incorporate a tab on the rudder whereas pitch attitude or altitude hold functions would use a tab on the elevator.

Application to Decoupled Flight Controls

It is possible to duplicate many of the capabilities of decoupled flight control systems using the tab driven system. To understand this, it must first be recognized that pilots gauge the magnitude of a control input by sensing control force, not displacement. This feature has been carried to the extreme in the case of the F-16 sidestick controller. Pilot control inputs are measured by strain gages, and the stick ***does* not *move* at all.**

Consider the case of a conventional aileron control. **A** control force input will deflect the aileron surface until it is balanced by the hinge moment. The aileron deflection will then result in a steady roll rate. In other words, the roll controls in airplanes are 'rate based.' To perform a steady turn, the pilot deflects the aileron until the desired bank angle is reached, and then neutralizes the control. The airplane will turn **as** long **as** the bank is maintained. When the desired heading is achieved, the pilot then rolls to a wings-level attitude.

Now consider the case of the tab driven wing leveler using attitude feedback. The initial result of an aileron input will cause a steady roll rate. However, as the bank angle increases the wing leveler will command a tab deflection. The tab will deflect **so as** to add to the hinge moment generated by the main control surface. If the pilot maintains a constant force input at the wheel., then the main surface deflection must decrease so that the total hinge moment is constant. Eventually a bank angle is reached where the hinge moment generated by the tab exactly balances the pilot control force and the main aileron surface deflection will be zero. The pilot may not even be aware that the deflection is zero because force is the primary source of information. When the wheel force is released, the tab will force the aileron to deflect so as to level the wings.

The result is now a bank angle command, or 'attitude based', control system as opposed to the rate based system. For the case where angular rate rather than attitude feedback is used, then the system becomes a 'heading rate' command system.

This concept can be extended to the pitch axis **as** well. With conventional systems, speed and altitude are coupled – an elevator input will cause excursions in both speed and altitude. Precise changes in one or the other require a coordinated control of both the control stick and the throttle. The primary aim of decoupled flight control systems is to make the stick control only altitude (or rate of climb) and the throttle control speed. This requires both an autopilot and autothrottle. The concept of a tab driven system to control pitch attitude, altitude, or rate of climb would have the same principle of operation **as** the wing leveler described herein. The autothrottle would be of conventional design – there is no aerodynamic control tab for the powerplant.

The primary advantage to this approach over conventional systems is that multiple levels of redundancy would not be required. A conventional decoupled system would probably be a FBW type system, with the inherent requirements for redundancy. The failure modes of the tab driven system are benign and a complete failure would only mean reversion to conventional controls. Such a system would be much less expensive and considerably easier to certify. **Low** cost is a definite requirement for any system which is to be used in general aviation aircraft.

Assuming a full time stability augmentation system is installed in many aircraft, one must ask the question: Will pilots lose the ability to control the aircraft if the system fails? Certainly the pilot must maintain competency in flying the aircraft with conventional controls only. Otherwise redundant systems will become necessary.

Concluding Remarks

The concept of an automatic wing leveler for light airplanes which uses a tab to drive the primary aileron control is described. This system can be engaged full time without undesirable feedback to the pilot and has the potential to enhance safety and reduce pilot workload in instrument flight conditions. A linear root locus analysis of system performance and stability has been conducted. The system is stable and effective for cruise and approach airspeeds. The system is light weight and low in cost – no more than similar conventional autopilots.

Tab driven control of the yaw and pitch axes are also possible. **A** complete decoupled flight control system can be based on tab driven controls. This approach has the potential to be considerably less expensive than a conventional FBW/FBL approach because the tab driven system does not inherently require multiple levels of redundancy. With its lower cost, the tab driven system is very well suited for the general aviation market.

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