AEROSERVOELASTIC TAILORING for LATERAL CONTROL ENHANCEMENT

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THE PURPOSE - AIRCRAFT ROLL EFFECTIVENESS AT REDUCED COST

The need for effective aileron power for aircraft lateral control and turning maneuvers dates back to the Wright Brothers and their wing warping concept for active stabilization of their aircraft. Early researchers in Great Britain, Japan, Germany and the U.S. explored ways to increase the effectiveness of control aileron to generate a roll moment. Figure 1 illustrates the basic problem of aileron effectiveness and the interrelationship between structural distortion and the loads applied by the control surface. A rigid wing/aileron surface will develop the capability to generate increased roll rates as airspeed increases. A flexible surface will become less effective as airspeed increases because of the twisting distortion created by the aft-mounted control surface. This tendency is further worsened by bending distortion of an aft swept wing. This study focuses its attention on the ability of a combined effort between structural redesign of a wing and sizing and placement of a control surface to create specified roll performance with a minimum hinge moment.

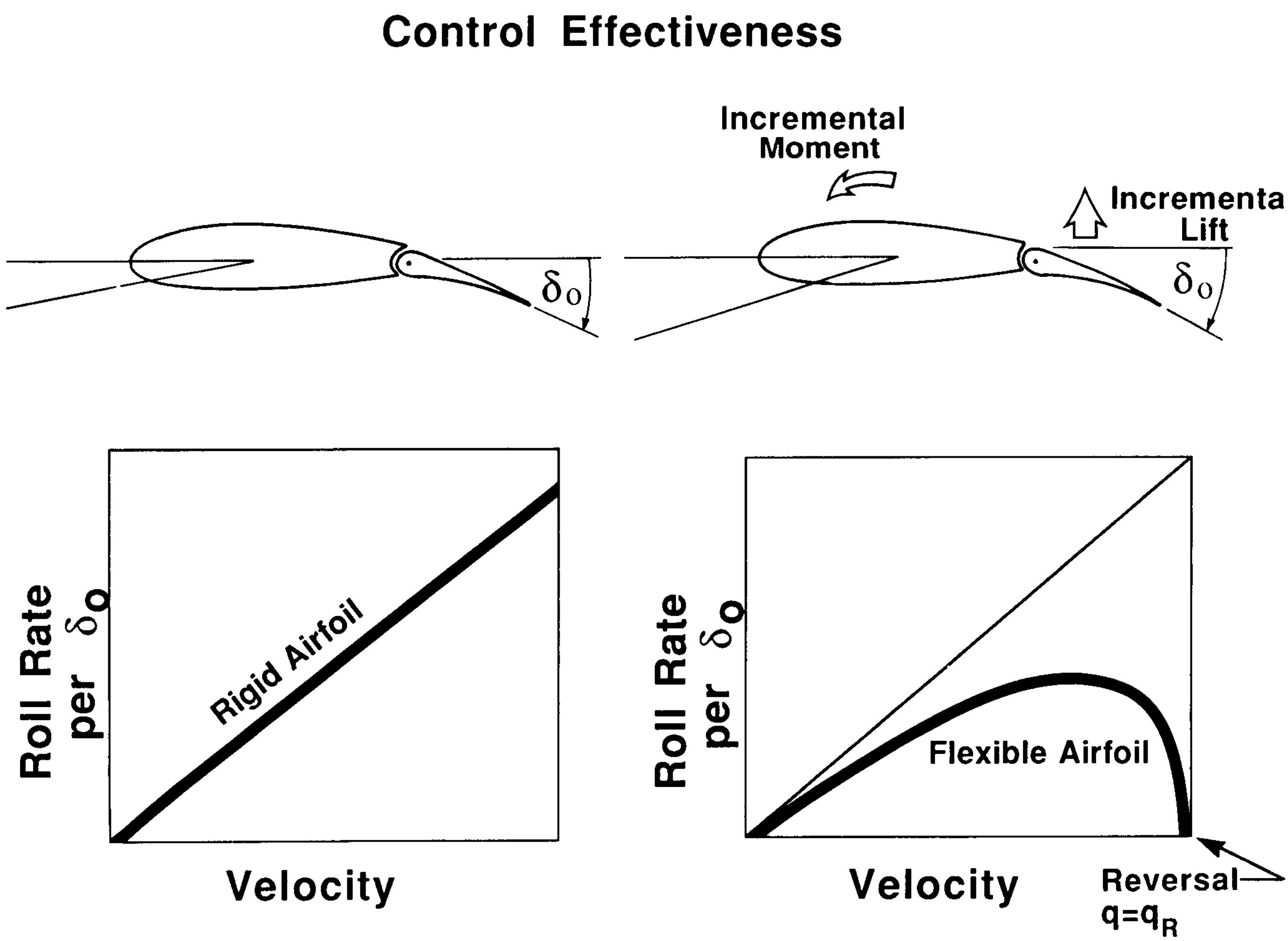


Figure 1

THE OPTIMIZATION PROBLEM AND DESIGN VARIABLES

The wing planform used for this study is shown in Figure 2. The wing is composed of 10 layers of Graphite/epoxy composite material. Three of the upper surface plies are treated as design variables so that cross-sectional stiffness and stiffness cross-coupling can be changed to decrease the aileron hinge moment while still maintaining the same roll-rate at a specified design airspeed. Because the laminate must be symmetric through the thickness so as to disallow warping during the manufacturing process, the three lower plies must also follow the reorientation of their upper surface counterparts. The sign convention for the ply orientation is shown on the planform diagram. The aileron surface is shown located at a distance N_a outboard of the wing root. This distance is also a design variable. The spanwise size of the aileron is fixed at 30% of the span; however, the chordwise size is allowed to change. The combination of 3 ply orientations and the spanwise position and chordwise size of the aileron defines the set of design variables.

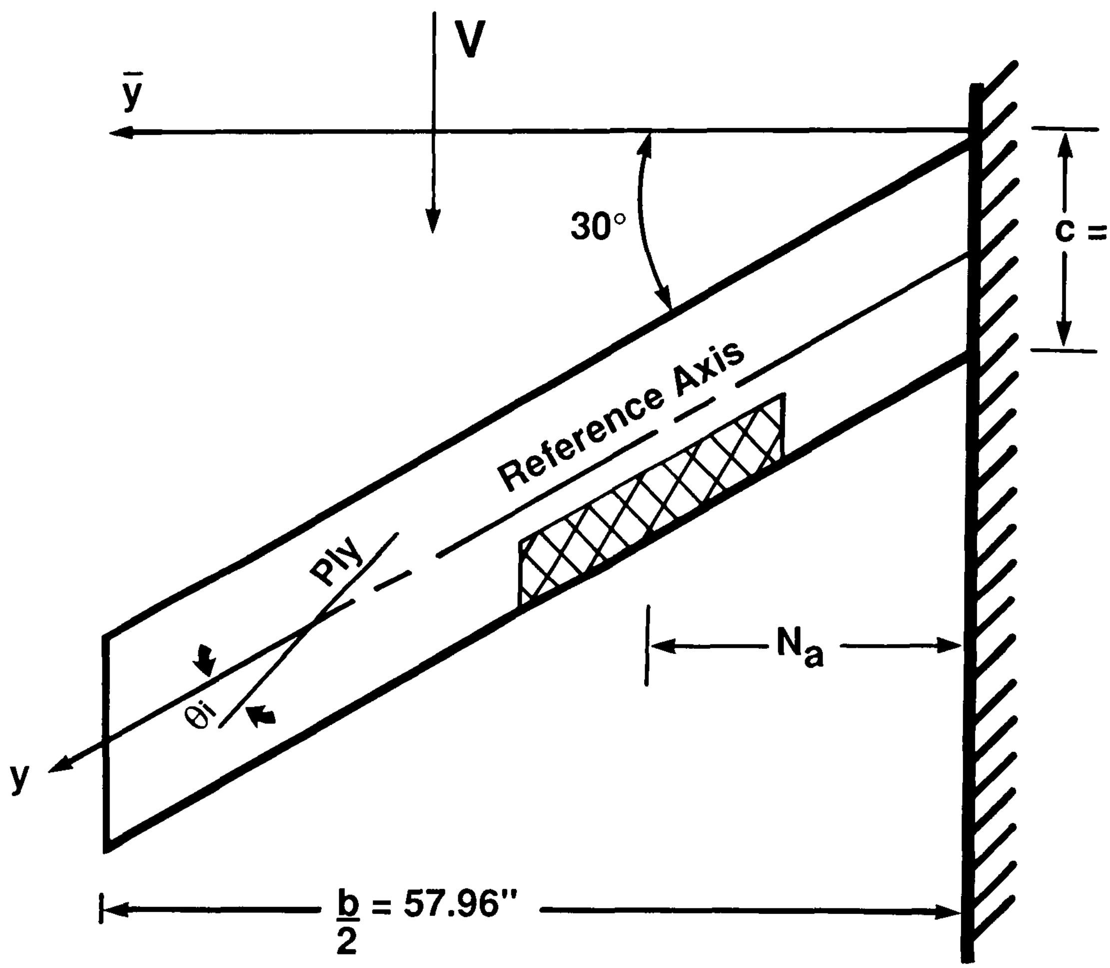


Figure 2

THE EFFECT OF PLY ORIENTATION AND AILERON POSITION ON HINGE MOMENT

Aileron hinge moment was chosen as the cost function for optimization because the actuator size necessary to move the aileron is a function of the power required. As a result, aircraft weight is buried within this cost function. A matrix method representation of the wing structural stiffness and the aerodynamic loads was used to provide the analytical representation of the wing in Figure 2. A computer code that had been used in previous FSW work was used as the basis of the optimization code developed at Purdue. This code has the acronym CWINGSM. Expressions for hinge moment and aerodynamic derivatives necessary to run the code were taken from DATCOM and classical references. The effect of aileron spanwise position and wing laminate orientation on the magnitude of the aileron hinge moment is indicated in Figure 3. Two local minima are observed on this diagram. One local minimum is associated with the inboard aileron position, while the other is associated with the outboard position. While the inboard position is predictable given the experience of the last 40 years, the outboard position is unusual. This diagram also indicates that the final outcome of any optimization procedure that minimizes aileron hinge moment will depend upon the initial conditions given to the program.

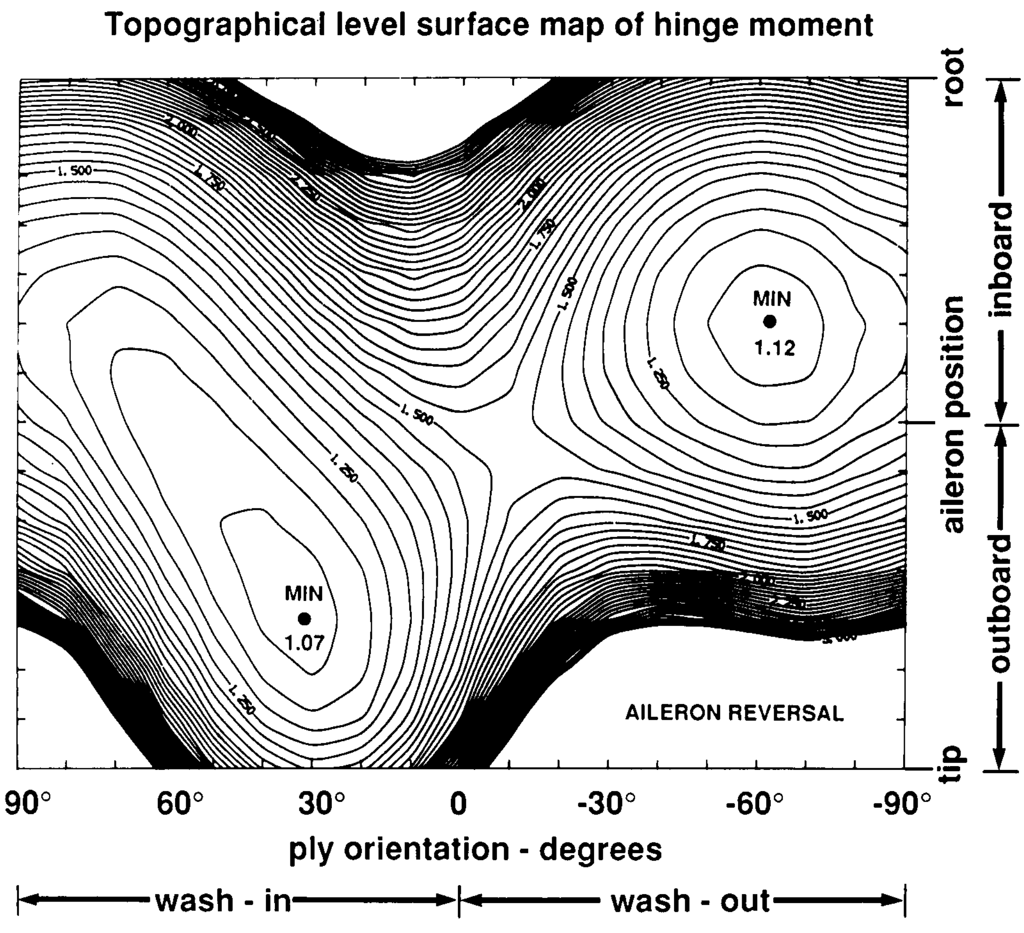
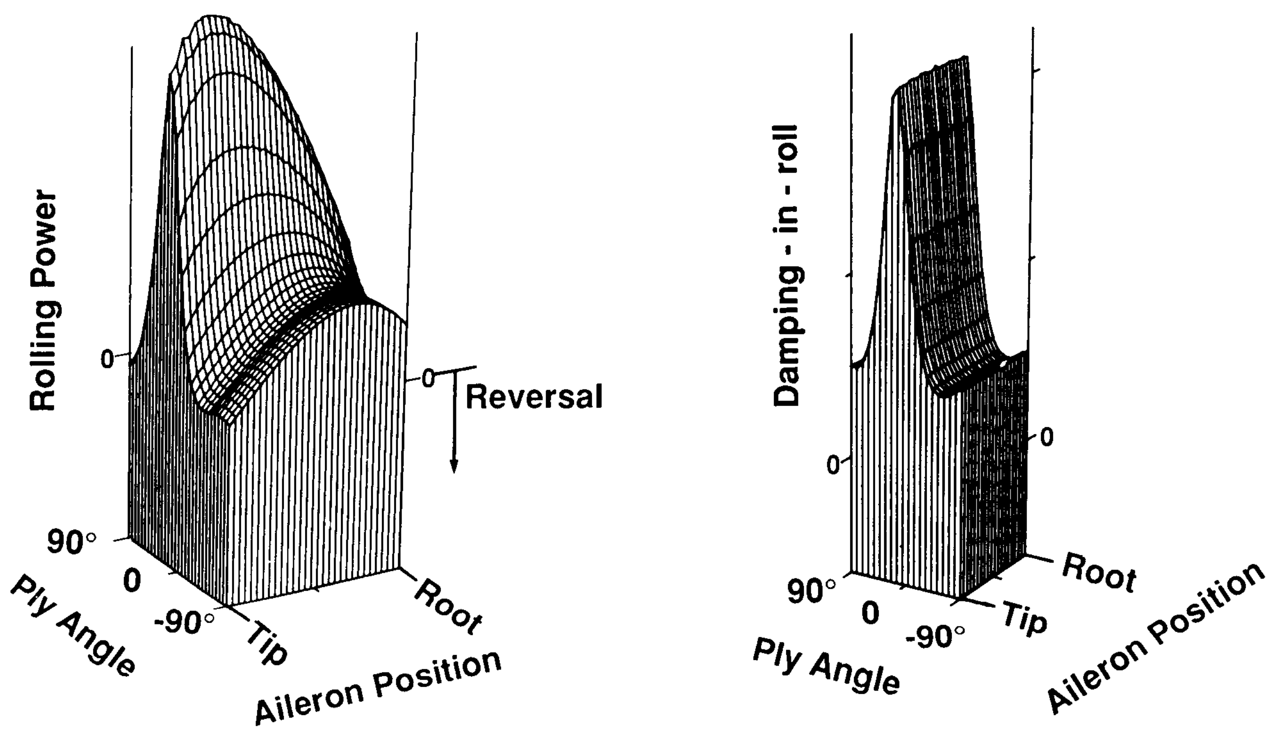


Figure 3

DESIGN CONFLICT AND COMPROMISE - ROLLING MOMENT versus DAMPING-IN-ROLL

The aileron hinge moment depends upon the orientation of the aileron with respect to the flow. This orientation depends upon the amount of mechanical rotation of the aileron and the wing surface distortion due to aeroelastic effects. For a certain size aircraft operating at a specified design airspeed, the roll rate is found by computing the ratio between the aileron rolling power and the wing damping-in-roll. The behavior of these two parameters as a function of aileron position and laminate orientation is shown in Figure 4. To generate this figure, all three laminate ply angles were constrained to be equal. Large values of aileron rolling power are generated when the aileron is outboard and ply angles are oriented in an aft swept position with respect to the swept wing center span line. Unfortunately, Figure 4(b) indicates that this wash-in laminate orientation leads to a situation for which damping-in-roll is also magnified.



(a) Aileron Power

(b) Damping - in - roll

Figure 4

AN OPTIMIZATION EXAMPLE PROBLEM-AILERON CHORD SIZE FIXED

To study the optimal design process itself, an example problem was developed. A series of optimization problems were solved in which the aileron chord dimension and the position of the aileron on the wing were held fixed. An unconstrained minimization problem was posed in which the three laminate ply angles were design variables and the roll rate was a constraint used to remove one of these variables. For the example cases chosen, convergence to the optimum design was rapid, as indicated in Figure 5. The inset to this figure shows a typical design cycle history for a case in which the aileron is in the outboard position. As anticipated, there are two local minima to be found by the procedure, depending upon the initial design condition chosen. Figure 5 also shows a comparison between the optimum design performance and the hinge moment for a similar, unoptimized, orthotropic laminate. Note that in this case all 3 final laminate ply angles are nearly equal.

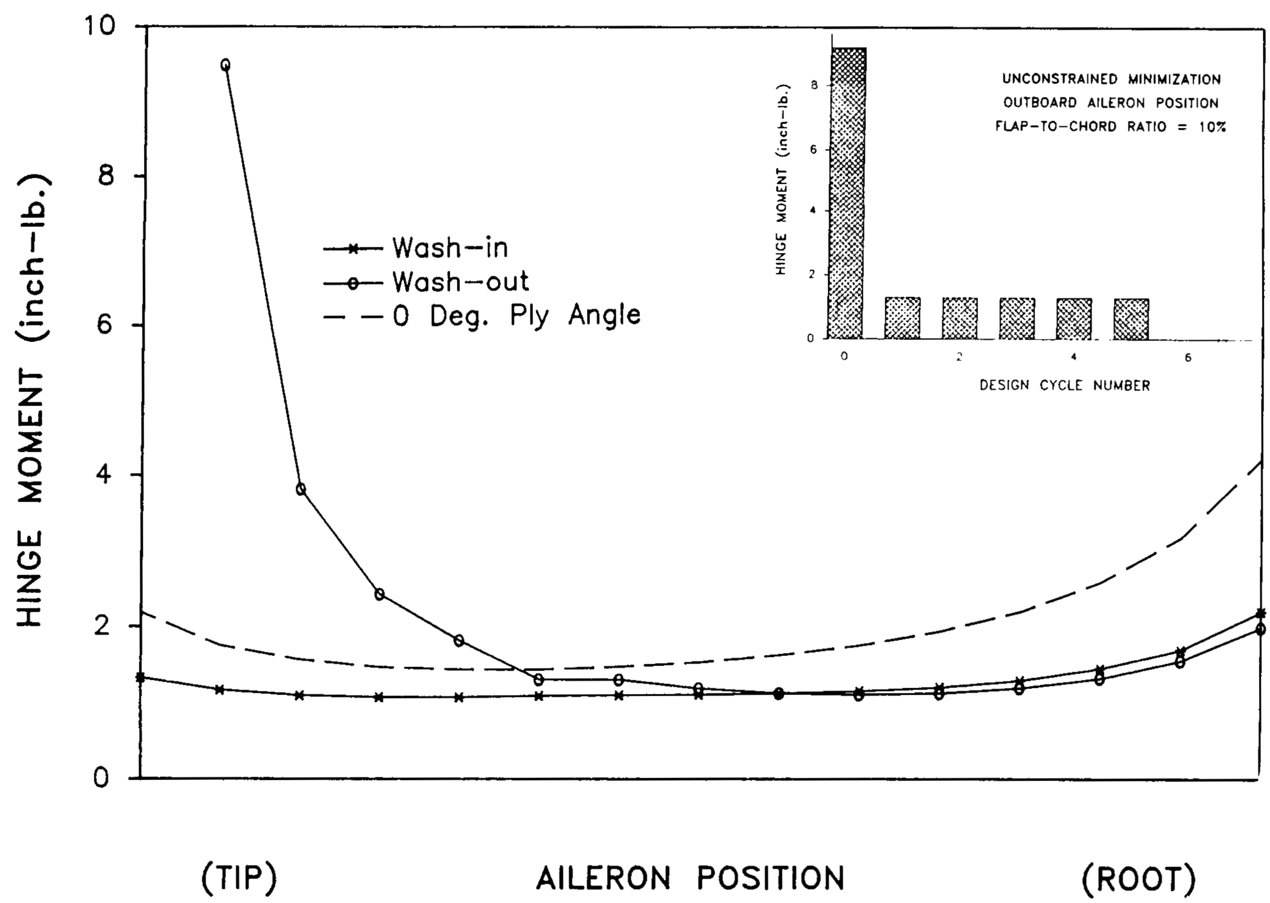


Figure 5

OPTIMAL PLY ORIENTATION FOR MINIMUM HINGE MOMENT

The ply orientations found to create minimum hinge moment while still allowing the specified roll rate are shown in Figure 6. While not constrained to be equal, in this case their values are indistinguishable from each other. The wash-in design orientation is created by sweeping the 3 plies aft to create a bending-shear coupling effect that causes the wing sections to rotate upward as they bend upward. This promotes aileron effectiveness and damping-in-roll (DIR), but the increase in rolling power outweighs the increase in DIR. The wash-out design is created by sweeping the plies forward. This couples nose-up twist with downward bending to create a less effective aileron surface. However, the damping-in-roll is also minimized so that the trade-off is favorable.

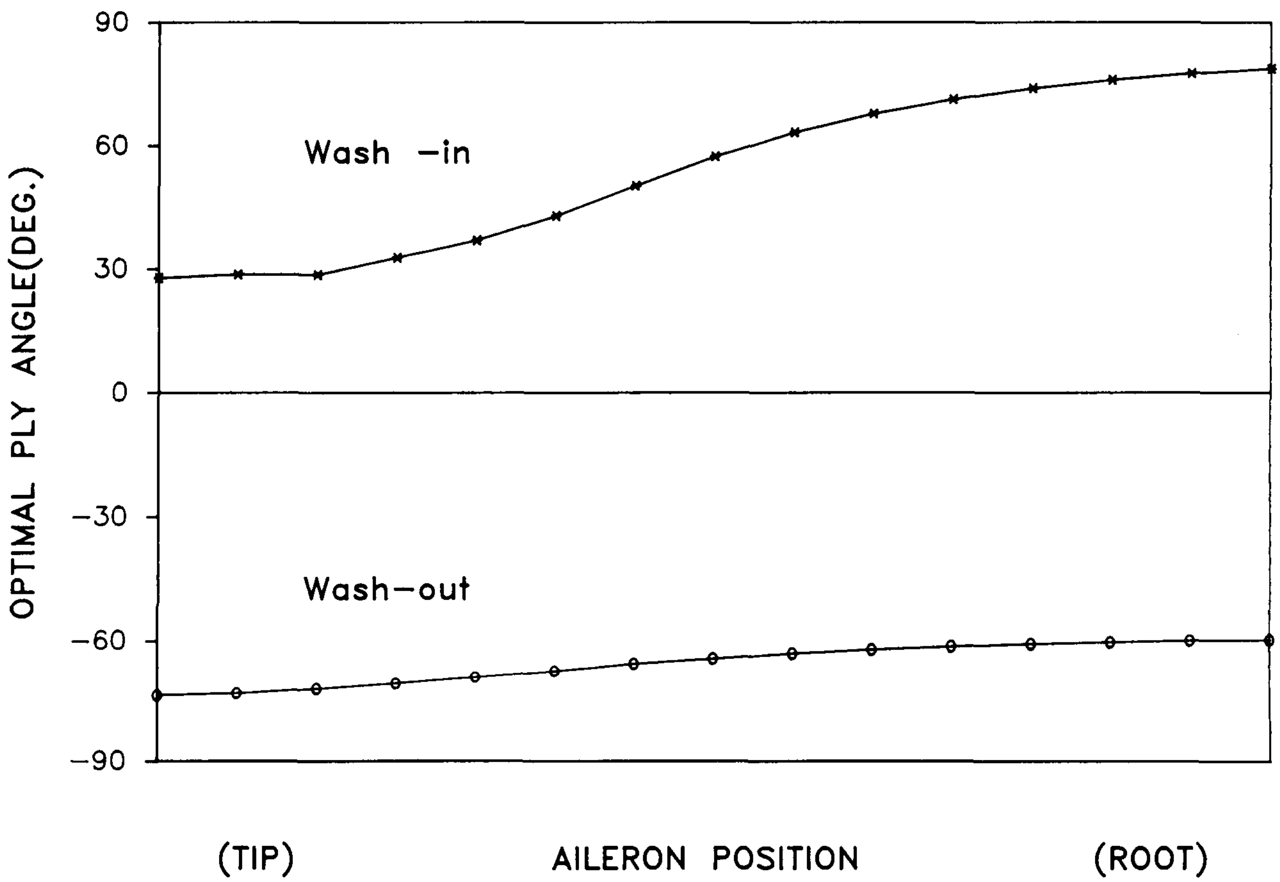


Figure 6

THE AEROSERVOELASTIC OPTIMAL DESIGN PROBLEM

When the aileron spanwise position and its chordwise dimension were included in the optimal design problem, the optimization technique chosen was an interior penalty function method. A pseudo-objective function was defined as the sum of the actual hinge moment and penalty functions representing; the aileron flap-to-chord ratio (which is free to take on any values above 0.075); the aileron spanwise position (which must lie between the wing root and tip); and the roll rate (which must be a specified rate). Figure 7 shows the values of this performance index as a function of design cycle history, plotted together with the value of the actual hinge moment. The Davidon-Fletcher-Powell method, in conjunction with a cubic interpolation method was programmed to generate these results.

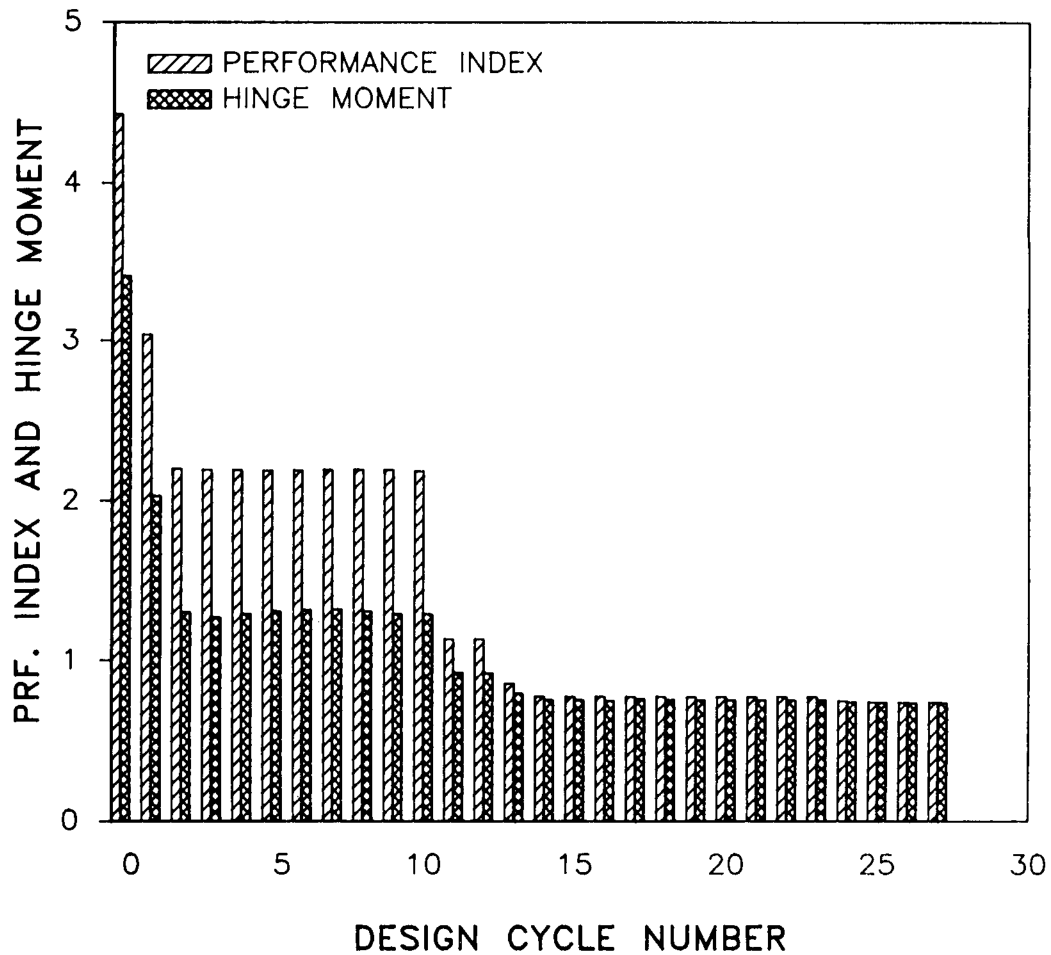


Figure 7

LAMINATE PLY ANGLE BEHAVIOR DURING OPTIMIZATION

All 3 plies began the optimization search oriented 20 degrees forward of the swept span reference line. During the design process they acquired different orientations, but finally became nearly equal as more design cycles occurred. The final design was a wash-in design with the design plies at about 30 degrees aft of the reference axis (Figure 8)..

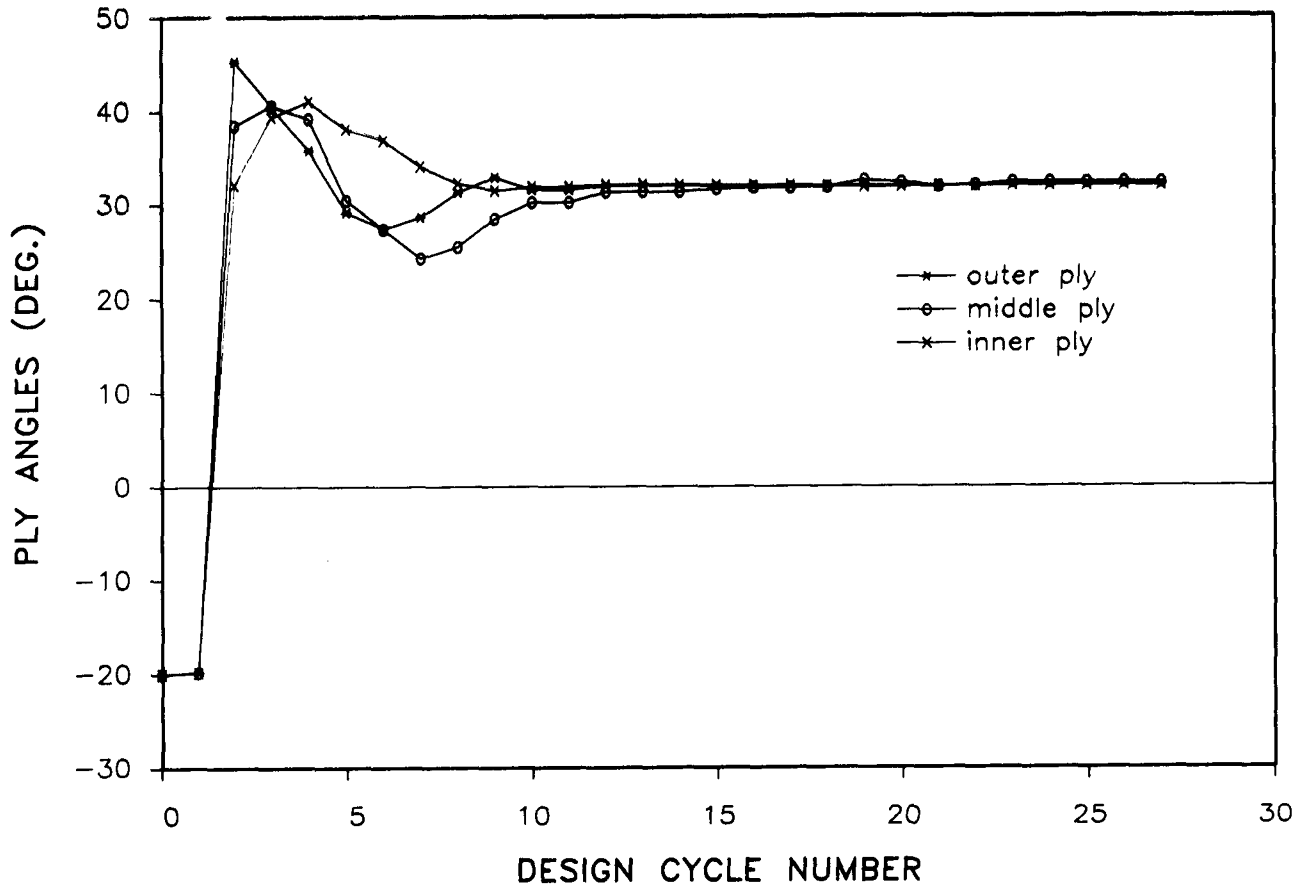


Figure 8

OPTIMAL SPANWISE AILERON POSITION

While the laminate plies are re-orienting themselves, the aileron is moving along the span to try to relieve the load on the hinge, while at the same time maintaining performance. Figure 9 shows the design history of this movement. The aileron begins near the 3/4 span position, moves inward slightly, and then proceeds to move outward to the 8/10 span position.

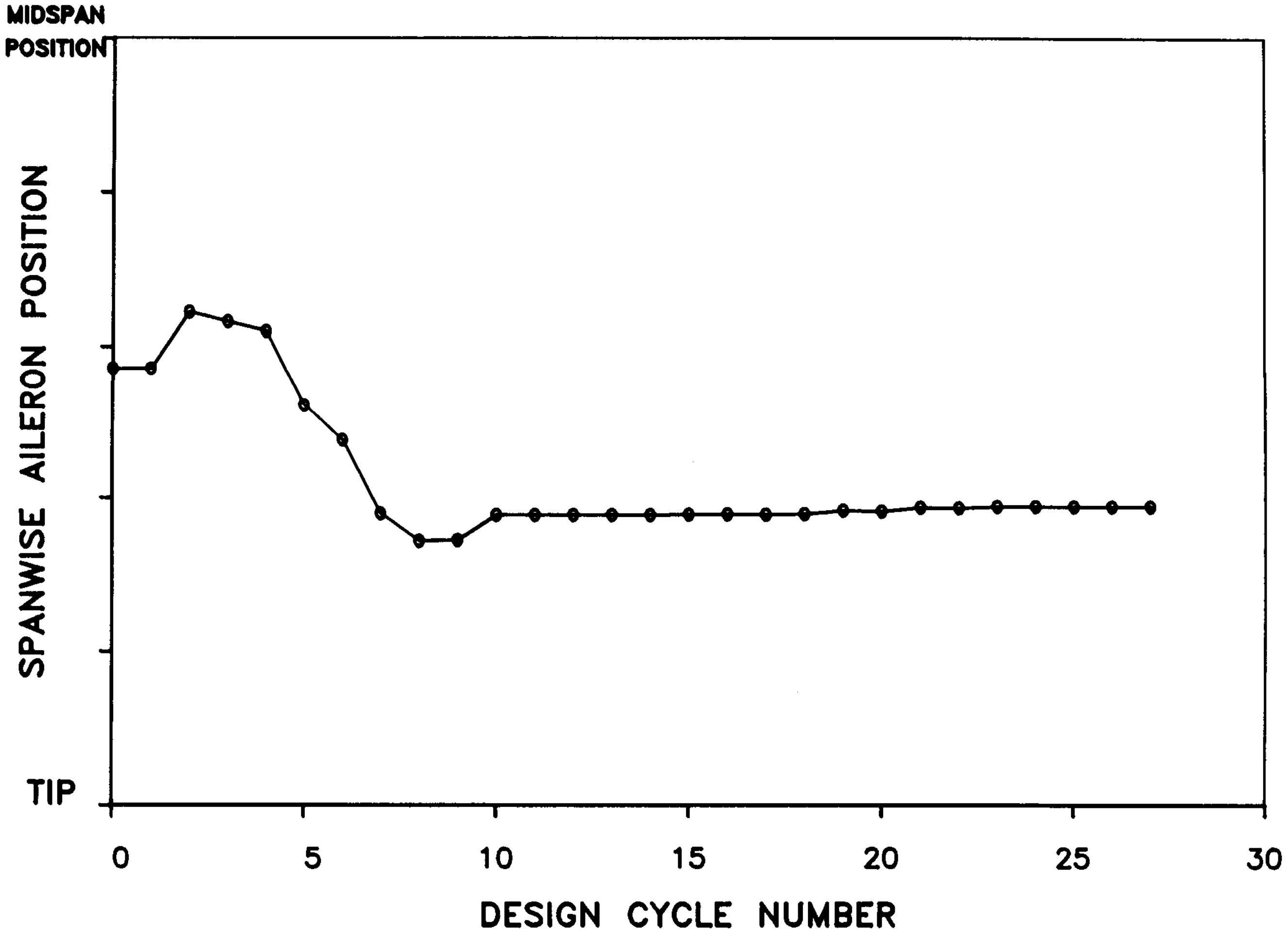


Figure 9

FLAP-TO-CHORD RATIO DESIGN HISTORY

The history of the value of aileron flap-to-chord ratio is shown in Figure 10. Because of the model used, this ratio tries to become as small as possible, but is not allowed to become less than 0.075. When other initial starting point designs were input to the procedure, the final result was essentially the same.

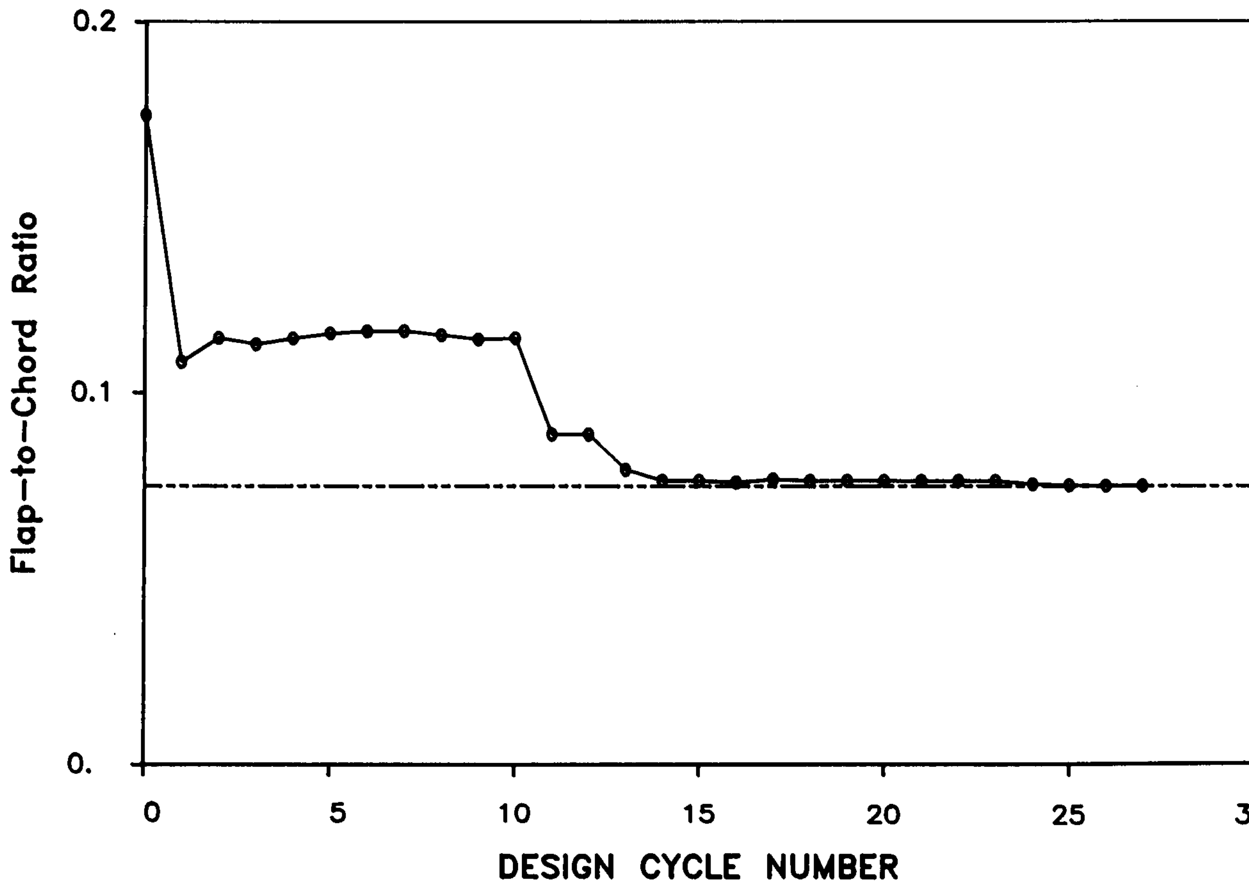


Figure 10

SUMMARY OF RESULTS AND OUTLOOK FOR THE FUTURE

This design optimization problem indicates the advantages of simultaneous consideration of structural design and control design. The performance index, the aileron hinge moment, has appeal to both groups, and because of the actuator weight associated with it, appeal to all. Besides the numbers generated, the interesting aspect of the problem is that it indicates that there is a trade-off between large values of rolling power and low damping-in-roll of the wing surface itself. The method used was made efficient by using subroutines that computed design sensitivity derivatives directly from analytical expressions obtained by algebraic manipulation. Present efforts have been directed towards including wing taper ratio as a design variable to further control damping-in-roll and including wing sweep angle itself to control aileron effectiveness and damping-in-roll.