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INTERACTIVE AIRCRAFT FLIGHT CONTROL AND AEROELASTIC STABILIZATION

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Summary

This report covers research performed under sponsorship of NASA/Langley Grant NAG-1-157 during the period 1 November 1984 through 30 April 1985. An analytical model of a 3-D airfoil was used to study an optimization procedure formulated to enhance stability of an airfoil through integrated structural and control synthesis. This procedure is discussed in this report, together with preliminary results. These results show that a sensitivity derivative approach utilizing structural parameters, weighting matrix parameters and optimal control parameters (in this case, the design airspeed) is effective in determining the "best" structural/control design.

Two trips were taken during this reporting period. The first trip was taken 28-29 January 1985 to visit Langley Research Center to present a research progress report. The second trip was taken from 1 April to 3 April 1985 to attend the Second International Conference of Aeroelasticity and Structural Dynamics in Aachen, West Germany. A paper was presented at this conference. A trip to MBB Aircraft in Munich was also included from 4 April to 5 April 1985 to discuss common research efforts. A trip summary is included in this report.

Discussion

The objective of the current work was to develop and to demonstrate a procedure to ensure aeroelastic stability of an airfoil up to and including a target airspeed. To accomplish a portion of this objective, optimal control techniques were used to design the active control system. In addition, sensitivity derivatives were computed to assess how changes in system parameters affect the optimal control law design. In addition to control parameters such as the elements of the state weighting matrix (the [Q] matrix) and the design speed at which the control law is formulated, denoted as $\overline{U}_{Des}$, the position of the shear center, expressed as a parameter a_e, was used as a design variable. $\overline{U}$ is a nondimensional airspeed, while a_e is a nondimensional coordinate described below.

The objective of the new procedure is to define a control law such that the aeroelastic system is stable at all speeds below a certain airspeed, called $\overline{U}_s$. A problem that arises with the use of optimal control techniques to define such a control law is that the system may be stable at the airspeed at which the control law is formulated, but may be unstable at lower airspeeds. As a result the design airspeed for the control law does not necessarily correspond to the maximum airspeed to be reached before aeroelastic stability is encountered. Conversely, $\overline{U}_{Des}$ may be used as a parameter in the stability augmentation problem.

Similarly, the elements of the state weighting matrix $[Q_{ij}]$ used for optimal control synthesis are arbitrary. However, the choice of these Q_{ij} elements affects the control law and the off-design performance of the active control. Setting these parameters in an "optimal" manner is also advantageous. Therefore, the Q_{ij} elements become design parameters.

The structural design affects the behavior of the flexible structure. The example chosen for the current research is a 3-degree of freedom, typical section model as shown in Figure 1. The degrees of freedom are airfoil pitch, α, airfoil plunge, h, (bending) and control surface rotation, β. In particular, for this 3-DOF model, the position of the shear center affects the aeroelastic stability of the airfoil.

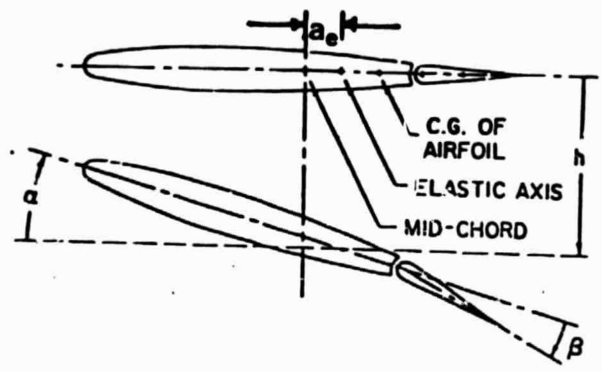

Figure 1 - Three-degree-of-freedom typical section airfoil.

In reality, the airfoil skin thicknesses, span areas and locations all affect the shear center location. A parameter, a_e, is used to denote shear center position. The parameter a_e is the nondimensional position (position divided by semi-chord) of the airfoil shear center with respect to the airfoil midchord. As a result, $a_e = 0$ represents the shear center position at the airfoil midchord, while $a_e = -0.50$ corresponds to a shear center placement at the airfoil quarter chord. For this study we have assumed that there is no weight variation (penalty) to be incurred when the shear center is moved. Furthermore, the sectional center of mass is held fixed as a_e is changed. These restrictions do not invalidate the results to be discussed nor the procedure used to generate these results.

The shear center location has a substantial effect upon the "open-loop" aeroelastic stability of the 3-DOF airfoil. The shear center position also has a substantial effect upon the value of the "cost function" used to generate control laws using full-state feedback with optimal, steady-state, linear-quadratic-regulator theory (LQR theory).

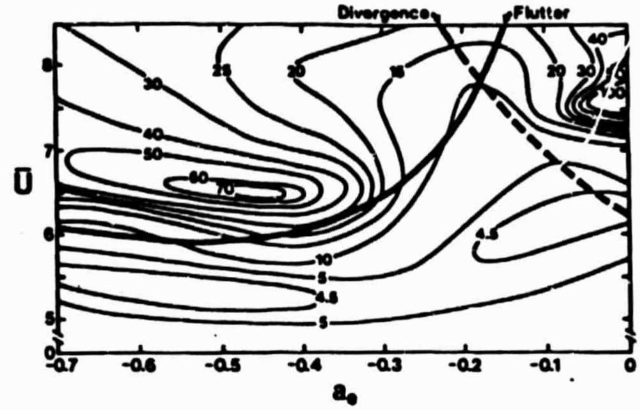

Figure 2 - Constant optimal control cost contours for an actively controlled 3-DOF typical section as a function of $\overline{U}_{Des}$ and a_e.

In Figure 2 the effect of the parameter a_e upon the standard LQR cost function J for different values of $\overline{U}_{Des}$ is indicated. The open-loop flutter and divergence speeds, as functions of a_e, are indicated as bold solid and dashed lines, respectively, in Figure 2.

If $a_e = -0.20$ and $\overline{U}_{Des} = 6.0$ an optimal control law may be designed such that closed-loop stability is ensured at $\overline{U} = 6.0$. As seen in Figure 2, the cost, J, is approximately J = 10. If $\overline{U}_{Des}$ is fixed at 6.0, but a_e is changed to equal -0.4 (a forward shear center movement), stability of the closed-loop system is still ensured at $\overline{U} = 6.0$. However, the "cost" has increased to J = 20. While the control cost can not be directly translated into real costs, the implication here is that the system requires more effort to control. This is due to the close proximity of the open-loop stability boundary when $a_e = -0.40$.

Next, let us examine the closed-loop behavior of this system. To generate Figure 3, active control laws were formulated, using LQR theory with $\overline{U}_{Des}$ fixed at 6.0, and at several different values of a_e. Both open-loop and closed-loop instability speeds are shown in Figure 3.

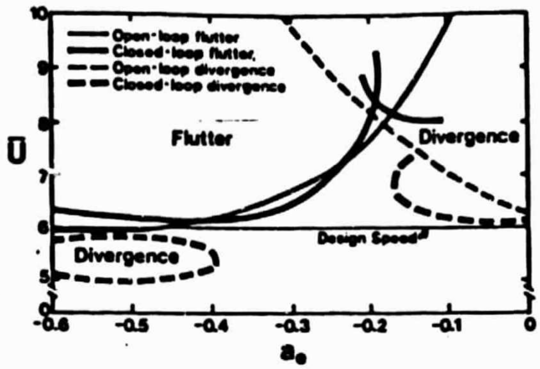

Figure 3 - Closed-loop stability boundaries for an actively controlled 3-DOF typical section. The design airspeed is $\overline{U}_{Des}$ = 6.0 while control laws are formulated as various values of a_e.

With $\overline{U}_{Des}$ fixed at 6.0 the closed-loop stability behavior may be degraded for one of two reasons. First of all, the open-loop stability boundary may be degraded at speeds above $\overline{U}_{Des}$ = 6.0 when active control is added. This is seen to be the case when a_e is in the vicinity of -0.30. In a second case, when a_e is less than -0.40, a low-speed instability region appears due to the addition of feedback control.

Notice also, that if one were to fix $\overline{U}_{Des}$ and maximize the airspeed at which closed-loop aeroelastic instability occurred, this maximum would occur near a_e = -0.20. This value is slightly less than the maximum obtained using passive means (change in a_e only).

In summary, the choice of both a_e and $\overline{U}_{Des}$ has a substantial effect upon closed-loop system stability. In addition, low values of the LQR cost function, J, do not necessarily lead to acceptable dynamic response at all speeds below the instability speed. As a result of these observations a modified procedure was investigated to both take advantage of LQR theory, optimization theory and optimal sensitivity derivatives. This method was proposed by Mr. T.A. Zeiler who has included work by Mr. M.G. Gilbert to produce a hybrid scheme for selecting the best structural/control design.

An Integrated Design Synthesis Scheme

Let us define as our design objective the increase in the aeroelastic instability speed (either flutter or divergence) to a certain value, $\overline{U}_s$. This increase will be accomplished by utilizing two sets of design variables, those involving structural parameters (in the present case, only a_e) and those involving active control law parameters. The optimal control design airspeed $\overline{U}_{Des}$ does not necessarily correspond to the design objective airspeed, $\overline{U}_s$. We also require closed-loop system stability at all airspeeds below $\overline{U}_s$.

At $\overline{U}_s$ or at any other airspeed below $\overline{U}_s$, the closed-loop system will yield eigenvalues of the form

$$\lambda_i = \sigma_i + j\omega_i \tag{1}$$

Our design objective requires that all values of σ_i be negative (in the left half-plane) at speeds below $\overline{U}_s$. A function, F_s, may be defined such that

$$F_s = \frac{1}{\rho} \ln[\sum_{i=1}^{N} e^{\rho\sigma_i}] \tag{2}$$

F_s is called a cumulative constraint function. In Eqn. 2, ρ is a constant chosen to scale the problem while N corresponds to the number of distinct values of σ_i obtained from the closed-loop eigenvalue analysis. It can be shown (see Sobieski, et al., AIAA Paper No. 83-0832-CP) that F_s is bounded as follows:

$$\sigma_i(\max) \le F_s \le \sigma_i(\max) + \frac{1}{\rho} \ln N \tag{3}$$

Thus if at a given airspeed, $\overline{U}$, F_s is negative, then $\sigma_i(\max)$, the largest value of σ_i at this airspeed, $\overline{U}$, is also negative and the system is stable.

What happens if, at $\overline{U}_s$ or some other airspeed $\overline{U}_j$, the value of F_s is found to be positive? How do we modify the system control law and structure to reduce the value of F_s to an acceptable value in an "optimal" manner? Certainly we could rely exclusively upon active control. However, situations such as shown in Figure 3 might arise, for which "sub-critical" instabilities appear.

Let us designate F_s as being a function of a set of "design" parameters, p_i, in this case a_e, $\overline{U}_{Des}$ and Ω_{ij}. The functional F_s is also a function of the control, u.

First, we select a finite set of airspeeds at intervals up to $\overline{U}_s$; call these airspeeds $\overline{U}_j$. These speeds are chosen to monitor system stability at "sub-critical" airspeeds. At each airspeed except $\overline{U}_s$, the actively controlled closed-loop eigenvalues λ_i yield functionals F_j such that

$$F_j < 0 \quad \text{at } \overline{U}_j \tag{4}$$

where the form of F_j is the same as that indicated in Eqn. 2. At our aeroelastic design airspeed $\overline{U}_s$, $F_s > 0$. We wish to choose a new set of design parameters, p_i, in such a way that we minimize F_S while keeping $F_j < 0$. In addition we require that the LQR cost function J be a minimum with respect to a choice of control, u at $\overline{U}_{Des}$. Changes in the parameters p_i to reduce F_s so as to stabilize the system at $\overline{U}_s$ will, in general, change the values of F_i at the intermediate design airspeeds. This will occur because of reshaping of the root locus curves for the closed-loop system.

The procedure to be used to optimize the actively controlled system is a modification of the multi-level, linear decomposition procedure suggested by Sobieski and co-workers. In the present case the system is decomposed into a structural subsystem and an active control subsystem. Let us first discuss the active control subsystem.

At the active control level, the subsystem optimization is the solution to the optimal steady-state LQR problem,

$$\min_u J = \int_0^{\infty} [X^* C^* QCX + u^* Ru]dt \tag{5}$$

with

$$\dot{X} = AX + Bu \ , \tag{6}$$

The solution is:

$$u = GX = -R^{-1}B^*PX \ , \tag{7}$$

where P is the solution to the steady-state matrix Riccati equation. The change in J with respect to design parameters is achieved through differentiation of the necessary conditions satisfied at the minimum J, known generally as Kuhn-Tucker conditions. The results of interest are derivatives of the optimal feedback gain matrix with respect to the design parameters, (assuming $B \neq B(p)$)

$$\frac{\partial G}{\partial p} = -RB^* \frac{\partial P}{\partial p} \ . \tag{8}$$

That is, the derivatives are constrained to describe how the <u>optimal</u> gains change with changes in parameters. Thus, the control-augmented state matrix (denoted as A_+) derivatives are written as:

$$\frac{\partial A_+}{\partial p} = \frac{\partial A}{\partial p} + B \frac{\partial G}{\partial p} \ . \tag{9}$$

Eigenvalue sensitivity derivatives are found from

$$\frac{\partial \lambda_i}{\partial p} = \mathrm{DIAG}[E^{-1} \frac{\partial A_+}{\partial p} E] \,, \tag{10}$$

where, λ_i = diagonal matrix of system eigenvalues; E = eigenvector matrix of A_+.

These derivatives describe how the eigenvalues of the optimally controlled system change with changes in the design parameters. The real parts of the eigenvalues and their sensitivity derivatives,

$$\frac{\partial \sigma_i}{\partial p} = \mathrm{Re}\, (\frac{\partial \lambda_i}{\partial p}) \,, \tag{11}$$

are then used in the system level optimization. At this point we can change parameters p_i such that we still have an optimally controlled system, that is, at a minimum control "cost".

For this example there is no structural cost, that is, no additional weight is associated with changes in a_e.

At the system level, the optimization problem can be written in linearized form as:

$$\min_{\Delta p_i} F_s = F_{so} + \sum_{i=1}^{m} \frac{\partial F_s}{\partial p_i} \Delta p_i \tag{12}$$

subject to

$$\text{(a)} \quad F_j = F_{j_o} + \sum_{i=1}^{m} \frac{\partial F_j}{\partial p_i} \Delta p_i < 0 \tag{13}$$

$$\text{(b)} \quad J = \min_u J$$

$$\text{(c)} \quad \dot{x} = Ax + Bu$$

where m = the number of active design parameters. Note that constraints (b) and (c), representing the subsystem optimization, are implicitly satisfied since optimal sensitivity derivatives of the eigenvalue real parts are used in construction of the Taylor series approximations to the cost function F_s and constraints. The derivatives in Eqns. 12 and 13a are given as:

$$\frac{\partial F_s}{\partial p} = \frac{\sum_{i=1}^{N} e^{\rho\sigma_i} \frac{\partial \sigma_i}{\partial p}}{\sum_{i=1}^{N} e^{\rho\sigma_i}} \tag{14}$$

To test this procedure a "simplex" algorithm adapted from linear optimization was used. The parameters $p_1 = a_e$ and $p_2 = \overline{U}_{Des}$ were chosen as design parameters. An initial design with $a_e = -0.4$ and $\overline{U}_{Des} = 6.0$ was chosen. In this case the closed-loop system was unstable at $\overline{U} = 7.0$. The objective was to stabilize the system at $\overline{U}_s = 8.0$ in an optimal manner. To do this, the functional associated with $\overline{U}_j = 7.0$ was first reduced. Then the functional associated with $\overline{U}_j = 8.0$ became $\overline{U}_s$ and it was reduced.

Figure 4 shows the history of a_e and $\overline{U}_{Des}$ versus number of design cycles, together with the values of F_s and F_j. After seven iterations, no meaningful stability improvements were possible. Figure 5 shows the system root locus for the final design. The final design appears to be a compromise between flutter of the closed-loop system in two different modes, that is, a cusp in the flutter boundaries such as shown in Figure 3.

Figure 6 shows a plot of pole-zero "migrations" with airspeed for a fixed value $a_e = -0.4$. At this value of a_e there is close pole-zero proximity (not exact cancellation) for an unstable mode. This may account for the fact that the control designed at this point does not produce superior stability boundaries. However, the process of reducing F_s moves the system away from this divergence region.

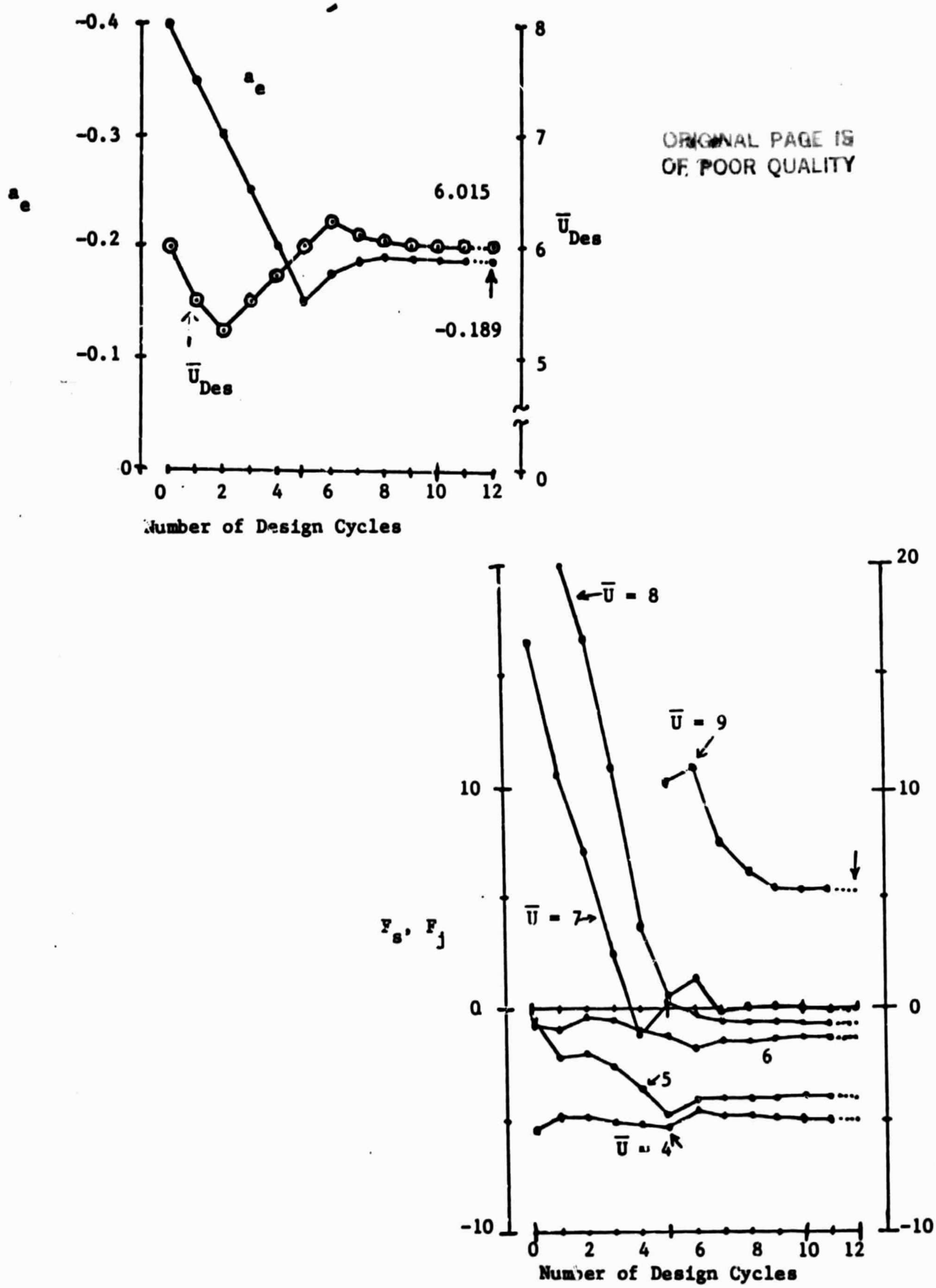

Figure 4 - Values of a_e and $\overline{U}_{Des}$ versus design cycle iteration number. Also shown are the values of the cumulative constraint functions F_s and F_j for each design cycle. Integer numbers refer to associated values of $\overline{U}_j$.

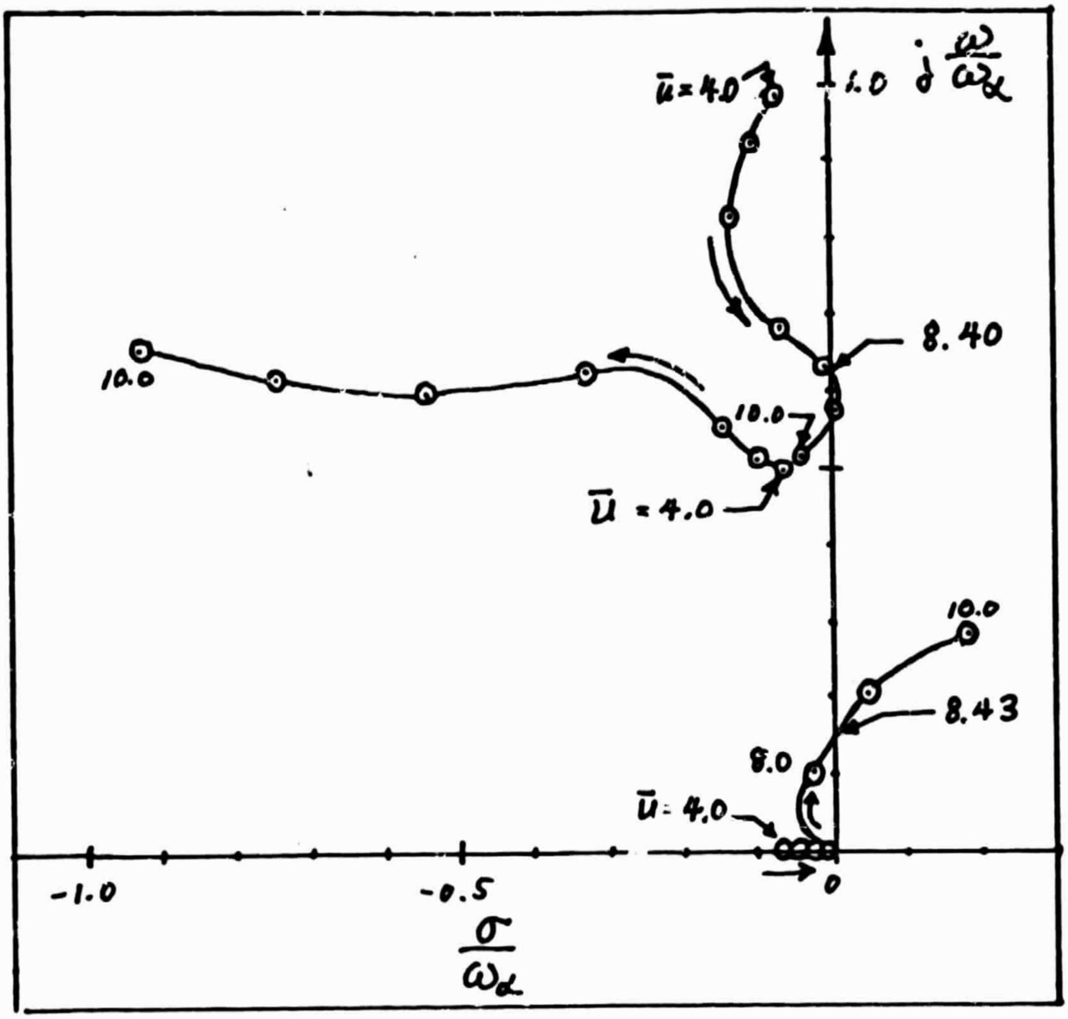

Figure 5 - Root locus plot for final design cycle, a_e = -0.189 and $\bar{U}_{Des}$ = 6.015. Note that instability occurs at $\bar{U}$ = 8.40 and $\bar{U}$ = 8.43.

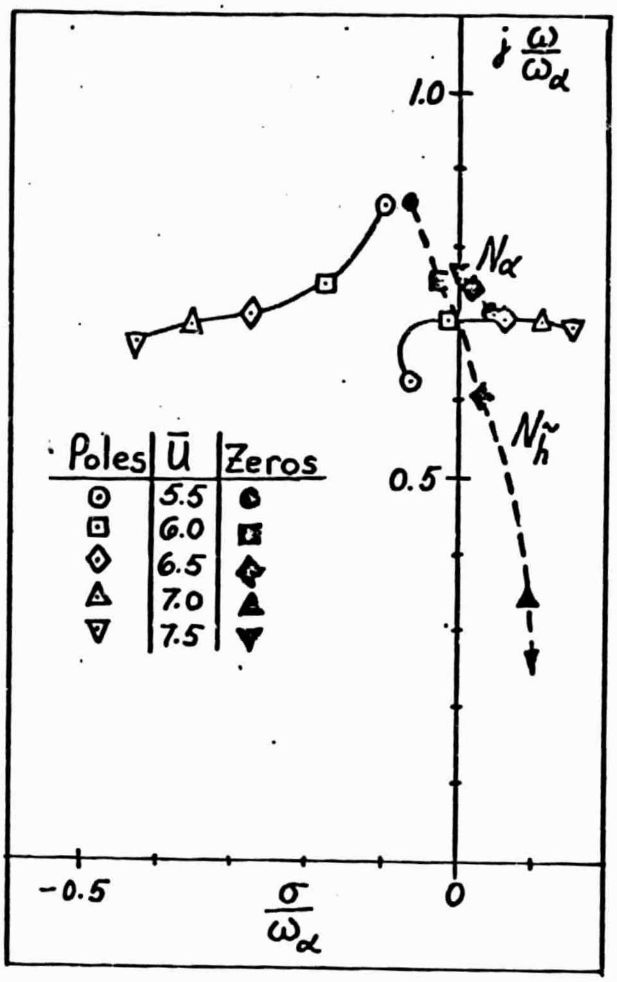

Figure 6 - Plots of actively controlled system poles and zeroes as a function of airspeed for a 3-DOF model with $a_e = -0.4$. Real axis poles and zeroes are not shown.

Figure 7 shows the pole-zero migration as a function of $\overline{U}$ for a configuration close to the final design. This figure shows that the problem of unstabilizability (uncontrollability of an unstable mode) is avoided by stabilization of the unstable mode through structural modification. There does appear to be some additional pole-zero separation, representing enhancement of controllability (as opposed to avoidance of incontrollability).

In addition to the above study, an investigation was made of the effects of changing the diagonal elements of the output weighting matrix, Q_{ij}. All previous studies had taken $[Q_{ij}]$ to be an identity matrix. Figure 8 shows stability boundaries versus a_e for $\overline{U}_{Des} = 6.0$ and airfoil pitch weighting of $Q_\alpha = 100$. With this weighting, the closed-loop divergence region for large negative values of a_e that exists when $[Q_{ij}]$ is an identity matrix is eliminated. (Compare Figure 8 with Figure 3.) However, the flutter boundaries and the divergence boundary when a_e is near zero are unaffected by this change. The closed-loop divergence boundary appears to be associated with the control deflection and, in fact, merges with the flutter boundary just above it. Figure 9 shows stability boundaries for the control deflection weighting, $Q_\beta = 100$, with all other diagonal elements equal to unity. The divergence boundary for large negative a_e is again eliminated while the main flutter boundary is only slightly affected. The divergence and flutter boundaries for a_e near zero are shown to be more heavily influenced by changes in Q_β.

Summary of Results and Future Work

During the past six months a procedure has been developed to

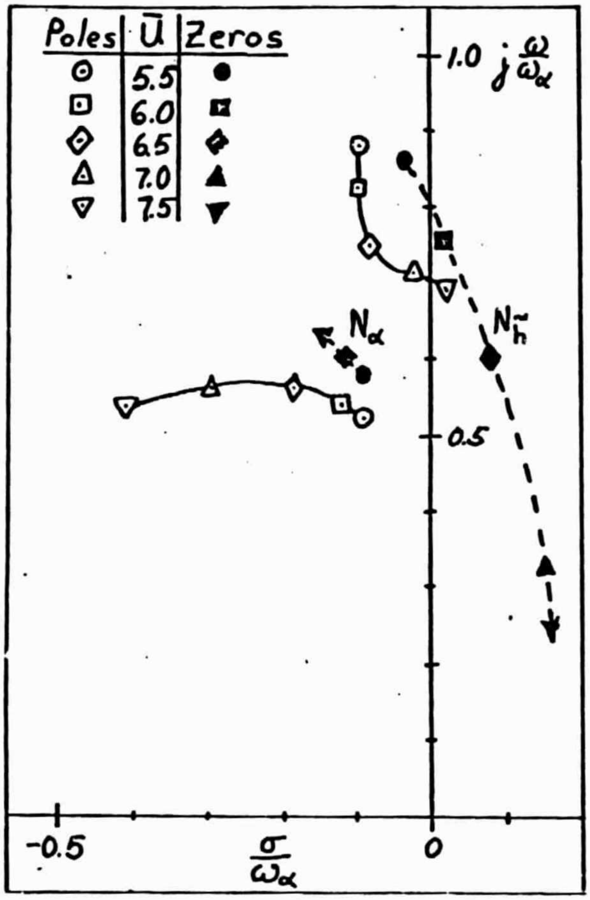

Figure 7 - Plots of actively controlled system poles and zeroes as a function of airspeed for a 3-DOF model with a_e = -0.2. Real axis poles and zeroes are not shown.

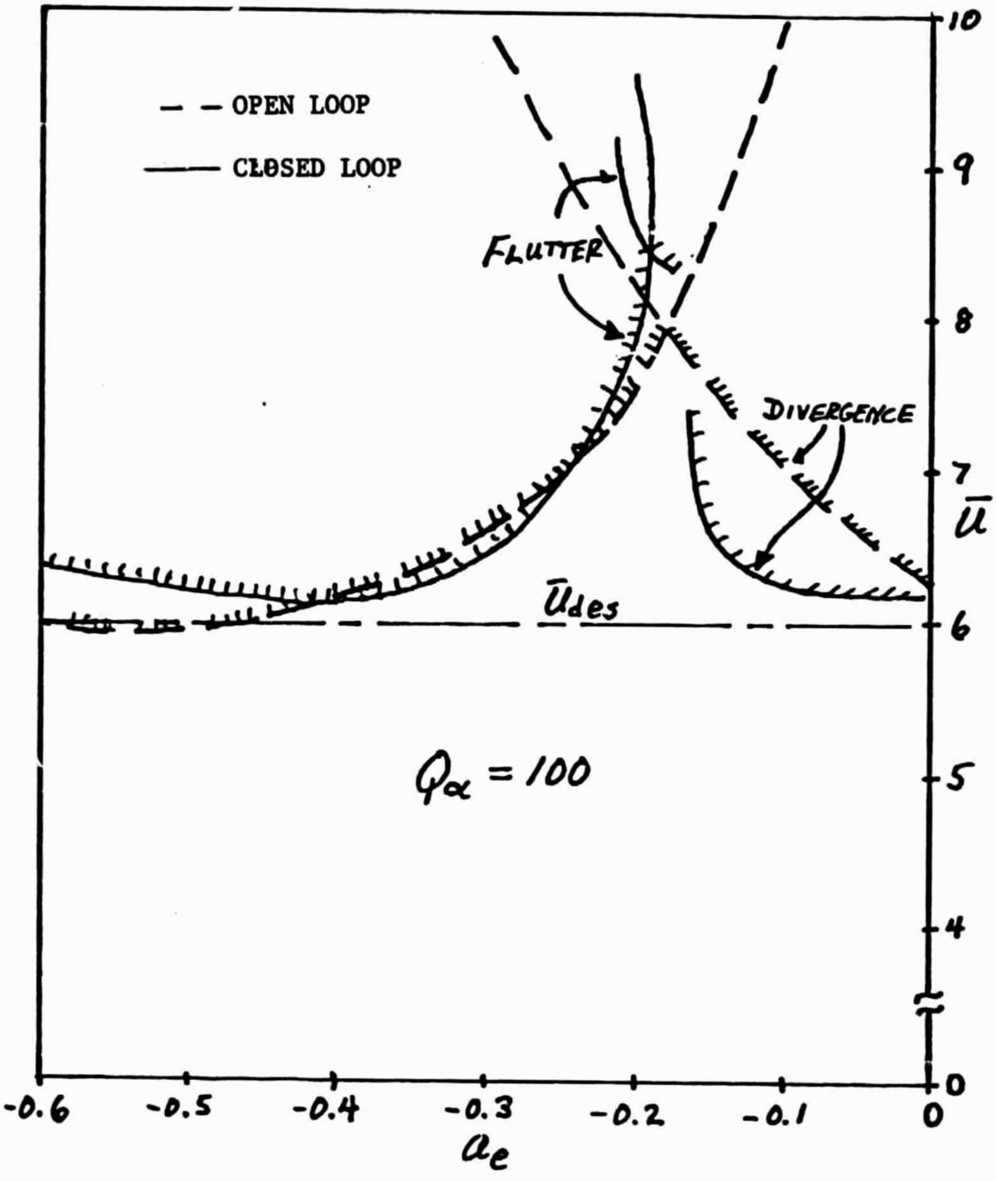

Figure 8 - Open-loop and closed-loop stability boundaries with $Q_h = 1$, $Q_\beta = 1$, $Q_\alpha = 100$, $Q_{ij} = 0$, $i \neq j$ for an actively controlled system at various values of a_e.

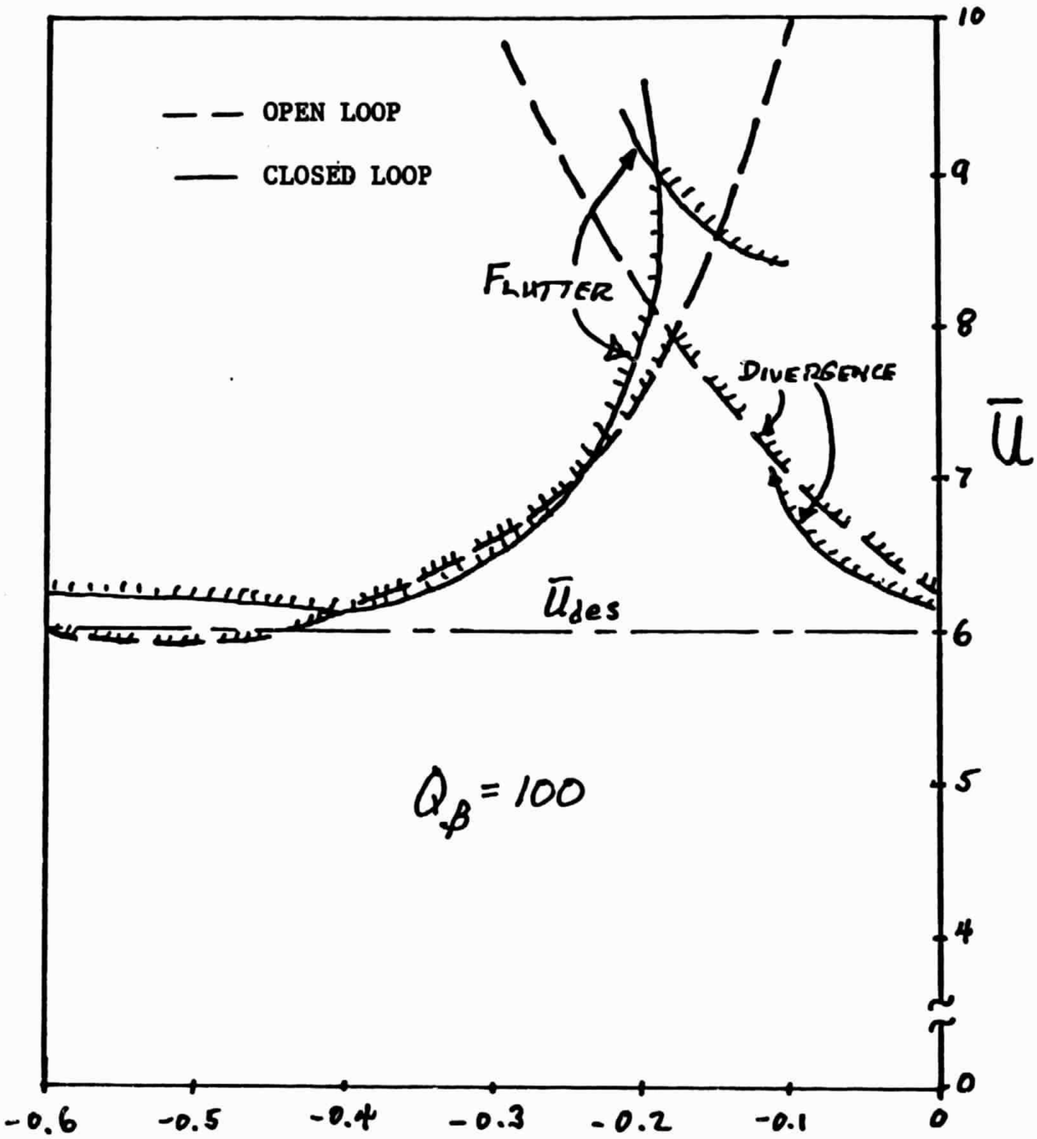

Figure 9 - Open-loop and closed-loop stability boundaries with $Q_h = 1$, $Q_\beta = 100$, $Q_{ij} = 0$, $i \neq j$ for an actively controlled system at various values of a_e.

redesign the structure and the control system to augment the aeroelastic stability of a idealized aeroelastic system. A number of problems remain to be resolved and some procedures need to be formalized. However, it appears that a major step toward the integration of the structural/control optimization has been accomplished.

Future efforts will be directed towards exercising the method further on the 3-DOF model as well as the 4-DOF model with "fuselage" pitch freedom.

Work will also begin on more realistic models that incorporate multi-mode, laminated composite structures. A Master's degree student, Mr. V.J. Sallee will begin a 10 week residency at Langley Research Center in mid-May 1985 to learn to operate the ISAC code so that these new thrusts can begin.

Trip Report

Second International Conference on Aeroelasticity and Structural Dynamics, Aachen, West Germany, 1 April through 3 April 1985.

A trip was made to this conference to present a paper entitled "Tailoring for Aeroelastic Stability and Lateral Control Enhancement". The conference was well-attended by European specialists in this area of research and technology. In the field of aeroelastic tailoring the presentations were for the most part not state-of-the-art as we know it in the USA. Personal discussions with engineers from the German aircraft establishment lead one to believe that their capabilities and interest are much greater than conference presentations would indicate. Some mention was made of the aeroservoelastic tailoring problem although ideas about how to approach the subject were not forthcoming. The Israeli aircraft engineers and researchers seem also to have a submerged interest in tailoring.

A visit to MBB, Munich was made on April 4 and 5. Mr. Otto Sensburg was the host for this visit. During this visit there was a keen interest expressed by the Germans in innovative technology. I was briefed on their design for a tailored composite vertical stabilizer and planned scale-model tests. They also plan active control testing. A lasting impression was that of a highly trained and qualified group of German engineers with many new ideas, not all of which they were willing to discuss.