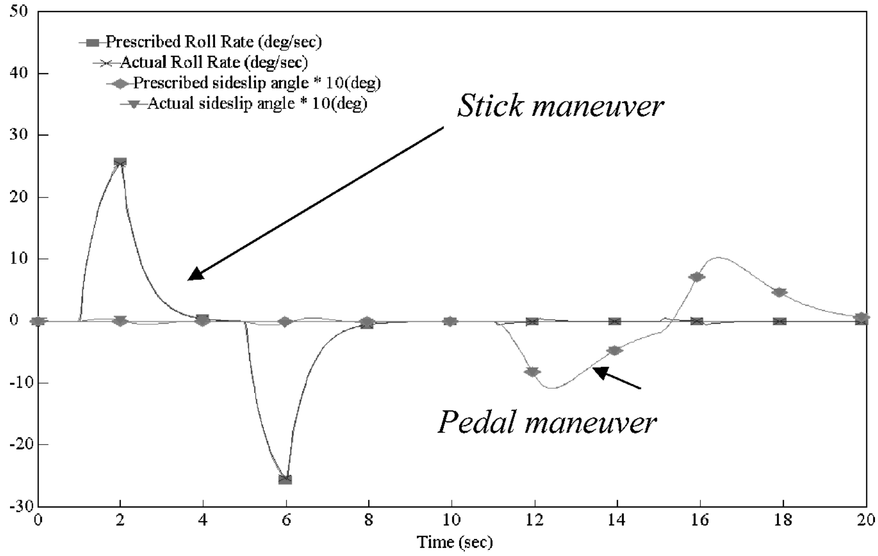

Fig. 2 Roll rate and sideslip responses.

$$K_{e0,p} = -\mu_p \varpi_p^2, \qquad K_{e1,p} = -1.4\mu_p \varpi_p - \varpi_p^2$$

$$K_{e2,p} = -\mu_p - 1.4\varpi_p - \omega_p \tag{18}$$

The motion to the subspace is chosen faster than the motion on the subspace because it is essential to achieve prescribed error response as quickly as possible. Values of $\mu_\beta = 15$ and $\mu_p = 25$ were chosen for the F-14 simulation.

F-14 Simulation Results

The scenario used in the previous work of Fialho et al.[1] was chosen to test the proposed controller design. Figure 2 shows the two simulated maneuvers. Two pairs of 1-s, 1-in. (2.54-cm) stick inputs to the left and then to the right are applied at 1 and 5 s followed by two pairs of pedal inputs at 11 and 15 s. The comparison of the roll rate response to the stick input with the "ideal" closed-loop response in Fig. 2 shows tracking performance slightly superior to the already very good result shown in Ref. 1. The very small peak sideslip error of 0.06 deg is far better than the 0.8-deg error obtained in Ref. 1. The response to pedal inputs achieved almost perfect tracking of the sideslip angle and a limited residual roll rate response of only 0.35 deg/s. This is much better than the 1 deg/s roll rate error presented in Ref. 1.

Conclusions

A linear-adaptive controller has been designed where disturbance estimators/observers provide a real-time estimate of the effects of all terms except the nominal control effects. The compensation of the generalized disturbance terms, based on real-time estimates provided by the observer, transforms the coupled and uncertain time-varying MIMO control problem into a pair of SISO control problems. The prescribed roll rate and sideslip responses for an F-14 were almost perfectly tracked with a nearly total decoupling of the two channels. This approach significantly extends the results obtained in Ref. 1.

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Employing Soft Computing Techniques to Study Stability and Control in Aircraft Design

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Nomenclature

$C_{L_{h\alpha}}$	=	a_t-lift curve slope of horizontal tail
$C_{L\alpha}$	=	lift curve slope of aircraft
$C_{m\alpha}$	=	$\mathrm{d}C_m/\mathrm{d}\alpha$
C_{m0}	=	coefficient of moment at zero angle of attack
$(C_{L\alpha})_{A-h}$	=	a_w-lift curve slope of aircraft without horizontal tail
$\bar{c}$	=	mean aerodynamic chord
$\mathrm{d}\varepsilon/\mathrm{d}\alpha$	=	downwash effect induced by the wing
l_t	=	horizontal tail arm, m
N_β	=	$\mathrm{d}N/\mathrm{d}\beta$
S	=	gross wing area, m^2
S_t	=	gross tail area, m^2
V_h	=	horizontal tail volume
W_0	=	gross weight, N
η_t	=	ratio of dynamic pressure at tail to the freestream dynamic pressure

Introduction

IT may be argued that one of the most well-known evolutionary algorithms is the genetic algorithm (GA) developed by Holland and his colleagues in the early 1970s (see Ref. 1). The GA capabilities of searching a vast search space using a population of search points, with multiple mixed parameter types, and at the same time

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employing many constraints made it more robust when compared to the traditional gradient-based optimization schemes. Subsequently, because the traditional gradient approach is restricted in domain and number of parameters used, it often falls into the trap of finding suboptimal solutions. On the other hand, GA belongs to a class of general-purpose (domain-independent) search methods that strike a remarkable balance between exploration and exploitation of the search space.[1] As a result, GA has the potential of solving numerous real world problems. This potential has already been recognized, and GA has been employed as a tool to obtain solutions to problems faced by researchers and engineers across the globe.

In aircraft design, it is a painstaking task to manipulate design parameters and to foresee the consequence of such manipulation on the entire design, and often expensive to readjust the initial change or other parameters to suit the required design objectives. It is from this standpoint that the GA's capability can be used to remove the latter difficulties.

The objective of this paper is to study the effects of longitudinal static stability and control, lateral–directional static stability and control, and longitudinal motion of open-loop dynamic stability, specifically longitudinal and lateral flying qualities, on the aircraft conceptual design process. The purposed methodology exploits the capabilities of a binary GA to study the effects of stability and control parameters on aircraft conceptual design. The objective function is geared toward weight (indicative of cost) minimization of a commercial aircraft with a manual control system, subjected to conceptual design constraints, as well as constraints in stability and control.

Genetic Algorithms

Genetic algorithms have proven to be very powerful search and optimization tools especially when only little of the structural data is known.[2] The power of GA lies in its ability to alter randomly and create combinations of variables that have the potential of moving up during the search, hence, leading to better designs.[3] The idea is that, given a certain problem representation, the GA is able through repeated use of genetic operators, that is, selection, crossover, and mutation, to combine those parts of a solution that are necessary to form a globally optimal solution.[2]

A GA searches and optimizes by means of multiple search points or solution candidates (population-based search). A GA starts with a population of strings and thereafter generates a successive population of strings. In GAs, each individual represents a certain solution to a given problem. The quality of this solution is expressed by a so-called fitness value. Consequently, the underlying principle of GAs is based on the mechanism of evolution.[3]

Further information and applications of GA to study complex design problems in the engineering industry can be found in Refs. 1–9.

Aircraft Conceptual Design for Minimum Weight

The objective of this study is to analyze the effect of stability and control on the aircraft conceptual design process using a binary-coded GA programmed in MATLAB®.[10] The objective function is geared towards weight minimization of a medium-size commercial aircraft with a manual control system, subjected to constraints in performance and geometric sizing, as well as stability and control.

Because some research has already been done on the Boeing 717, this aircraft was employed in the design criteria. In addition, some data for comparing and checking the validity and feasibility of the results were obtained from Ref. 11. Moreover, for this study, we were given a fitness module, which includes a sizing and constraint routine.

Design Criteria and Stability and Control Implementation

The design process first begins by setting down the particular mission profile for the Boeing 717 that is typical of a medium-size commercial aircraft. Some flight segments produce certain constraints that must be met by governing transportation rules. All imposed constraints are handled using the adaptive penalty approach.[4] In addition, other parameters that are required to meet the design objectives, such as the number of passengers, number and weight of crew, limit load factor, etc., are constant and are subsequently read into the program. The other 21 encoded aircraft design parameters that were adopted and optimized to study the aircraft evolutionary process are given in the leftmost column of Table 1.

With respect to stability and control, the design layout is important; for example, acceptable tailplane size, acceptable fore and aft center-of-gravity location, and overall configuration of the aircraft must be established. These factors will directly impact on the empty weight of the aircraft. A simple criterion for sizing the horizontal

Table 1 GA optimization results and comparison

Parameters	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	B-717
Crossover type	One point	Two point	Uniform	Uniform	Two point	One point	——
Selection type	Tournament	Tournament	Tournament	Roulette	Roulette	Roulette	——
Design variables							
W/S	4482.05	4166.52	5244.30	4482.05	4205.78	5034.10	5506.2
T/W	0.3	0.3	0.3	0.3	0.3	0.3	0.365
$C_{l\,\max}$	1.5	1.5	1.5	1.5	1.5	1.5	1.4
AR_w	6	6	6.05	6	6.14	6.8	8.7
λ_w	0.3	0.41	0.38	0.32	0.31	0.3	0.38
Λ_w, deg	27.98	26.517	26.32	28.28	30.82	0.1	26.9
t/c	0.11	0.11	0.11	0.11	0.13	0.1	0.11
AR_{ht}	4.68	3.13	3.77	3.52	4.68	3	5.21
λ_{ht}	0.28	0.23	0.47	0.41	0.47	0.57	0.4
Λ_{ht}, deg	25.47	27.04	36.18	19.80	32.72	15.08	36.87
T_{type}	T tail	Conventional	T tail	Conventional	Conventional	Conventional	T tail
AR_{vt}	2	2	2	2	2	2	1.05
λ_{vt}	0.38	0.38	0.32	0.65	0.40	0.49	0.8
Λ_{vt}, deg	35	41.67	39	43	37.68	39	41
N_{eng}	2	2	2	2	2	2	2
Material[a]	1	1	1	1	1	1	1
N_{seats}	5	5	5	5	5	5	5
l_t	22.23	22.78	20.60	22.82	22.52	22.69	——
S_t	19.55	18.67	19.17	18.85	18.90	18.63	——
$C_{h_{\delta e}}$	−0.28	−0.22	−0.22	−0.22	−0.22	−0.22	——
l_v	22.49	22.69	17.50	22.27	22.65	19.26	——
W_0	462,549.1	468,509.9	461,352.5	462,500.1	471,165.6	463,598.9	511,566
Constraint violation, %	10.21	9.42	9.26	9.92	9.24	10.4	——

[a] 1 means composite and 0 means conventional.

tail was undertaken by assuming that the stick fixed static margin is of some specified minimum value. For a commercial aircraft, a static margin of at least 5% is needed.[12,13] The neutral point was then related to the aerodynamic center of the aircraft, without the tail plane, by the following relationship:

$$\frac{X_n - X_{ac}}{\bar{c}} = \frac{C_{Lh\alpha}}{C_{L\alpha}}\left(1 - \frac{d\varepsilon}{d\alpha}\right)V_h\eta_t \tag{1}$$

where

$$C_{L\alpha} = (C_{L\alpha})_{A-h} + C_{L_{h\alpha}}\frac{S_t}{S}\left(1 - \frac{d\varepsilon}{d\alpha}\right)\eta_t \tag{2}$$

Note that these expressions are valid in the absence of compressibility effects.[14]

The aerodynamic center of the aircraft, that is, $X_{ac}/\bar{c}$, is greatly influenced by the wing shape; however, other contributions due to fuselage and nacelles must also be taken into account. The latter can be found from empirical correlations.[15] Note that the aerodynamic center of the wing–fuselage combination is sensitive to pressure distribution and not the lift forces, and therefore, it is difficult to predict accurately.[13] The distance that the aerodynamic center is ahead of the center of gravity is

$$(X_{cg} - X_{ac})/\bar{c} = (X_n - X_{ac})/\bar{c} - (X_n - X_{cg})/\bar{c} \tag{3}$$

where $(X_n - X_{ac})/\bar{c}$ is found via Eq. (1) and $(X_n - X_{cg})/\bar{c}$ is the known static margin.

Finally the aft center of gravity location was obtained as follows:

$$X_{cg}/\bar{c} = X_{ac}/\bar{c} + (X_n - X_{ac})/\bar{c} - (X_n - X_{cg})/\bar{c} \tag{4}$$

At this point it may be instructive to introduce two crucial constraints that will be necessary and sufficient in ensuring that the aircraft is statically stable in pitch. These are

$$C_{m0} > 0, \qquad \frac{dC_m}{d\alpha} < 0$$

A detailed analysis such as the one described is repeated for static stick free stability and longitudinal maneuverability with the control stick both fixed and free, as well as some aspects of dynamics behavior.

The aircraft must also possess positive static directional stability. This implies that the slope of the yawing moment curve is

$$\frac{\partial N}{\partial \beta} = N_\beta > 0$$

The vertical tail is not normally sized by the consideration of static directional stability. Instead, a minimum vertical tail size is determine by controllability in the event of an asymmetric engine failure or flying qualities related to dynamic motion. Consequently, a broad design criterion for sizing the vertical tail is adapted from Ref. 13.

The rudder and aileron effectiveness was also analyzed to ensure controllability of the aircraft in the event of an engine failure. Using statistical data provided in Refs. 12, 14, and 15, rudder and aileron sizing was undertaken.

The overall dynamics longitudinal motion of an aircraft can be divided into the short period (SP) oscillatory mode and the long period or phugoid mode. From this, a direct relation can be made to the flying qualities of the aircraft. This relation is based on the opinions of pilots, who after some simulation testing, expressed their views on the Cooper Harper scale. The aircraft characteristics are regarded as satisfactory within a specific region of the plotted linearized equation of motion for the longitudinal SP oscillation.

To find the damping ratio ξ, the stability derivatives were calculated and then analyzed. In this analysis some parameters, such as the elastic behavior of the control system, and aeroelastic effects, such as flutter, were ignored because they are small or they are difficult to determine at this stage of the design process. Consequently, Ref. 14 was followed in the analysis of stability derivatives. However, for a more detailed analysis, see Refs. 15–17.

After the stability derivatives were determined, the equation of longitudinal motion represented by a set of three simultaneous, linear, differential equations were solved. The roots of the aforementioned equation aid in the prediction of the normal modes of longitudinal motion and determine if the motion is stable or not. In addition, the results from this analysis were used to determine the forward center of gravity limit as a function of stick fixed maneuver margin and the attributes of the flying qualities.

The subject of dynamic lateral stability is generally not included in the preliminary design process because of the lack of data and the absence of qualitative design criteria. Note that the coefficient of roll moment for the entire aircraft is greatly affected by the dihedral of the wing, and because this parameter can be varied without greatly affecting the general arrangement, some flexibility is available to the designer at the later stages of the design.[13]

The preceding stability and control criteria and the conceptual design of aircraft flow control implementation into the GA, from the various aircraft design disciplines, are shown in Fig. 1. The aircraft design parameters are given in leftmost column of Table 1 and were encoded into a binary string, indicative of one aircraft design. A fixed population of aircraft designs was then randomly generated to begin the GA design evolution.

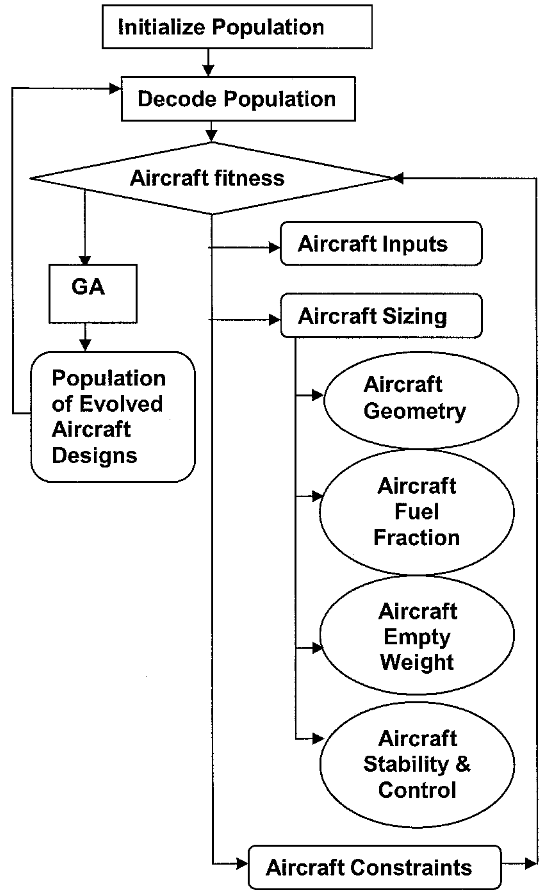
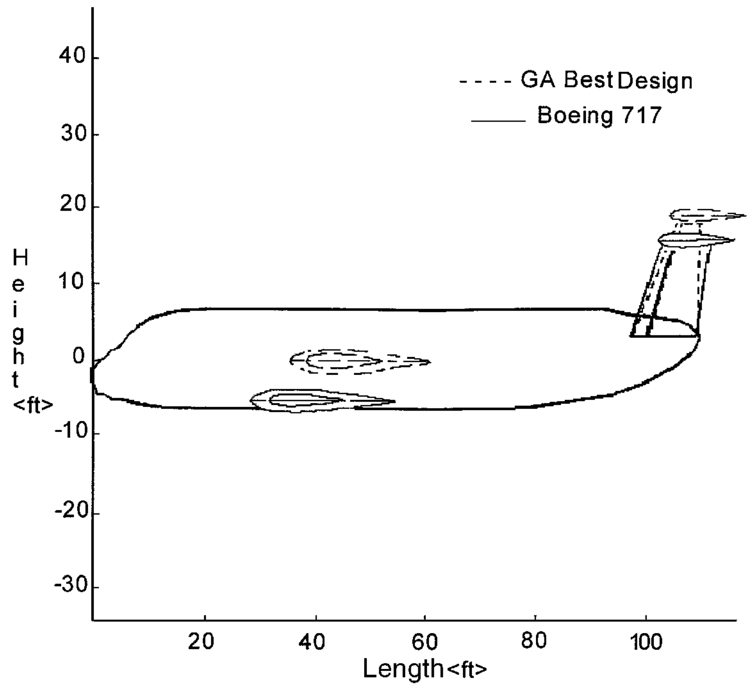


Fig. 1 Flow chart of stability and control implementation into GA.

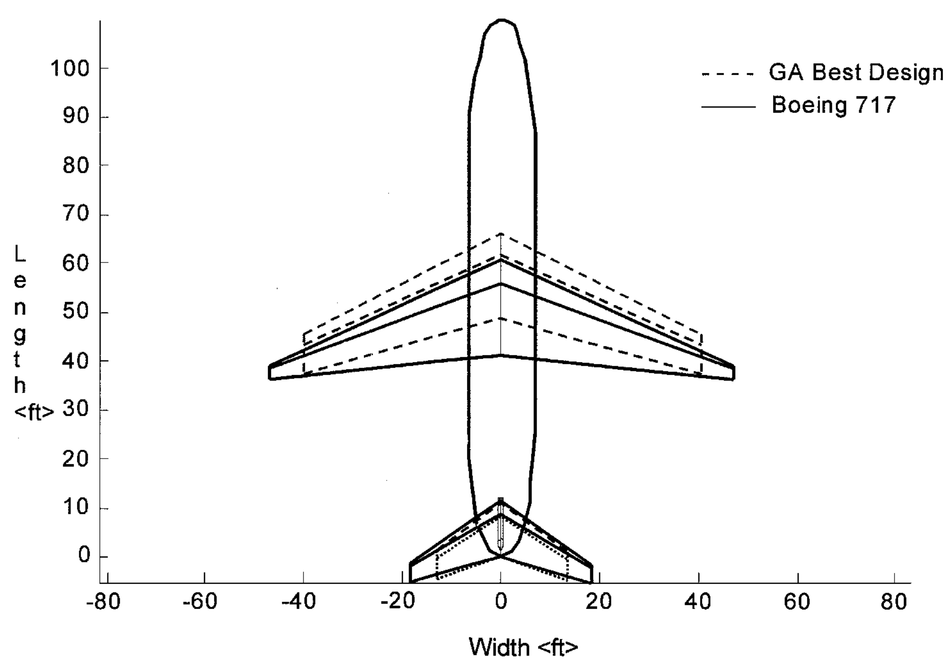
Designs with the Inclusion of Stability and Control

The results shown in Table 1 are based on a population size of 40 with 200 generations employed at each run. A fixed probability of crossover and mutation of 0.08 and 0.01, respectively, was employed. Roulette selection and tournament selection effects on the GA's evolutionary process were also studied. In addition, elitism strategy was used, and an inverse scheme was adopted to scale the fitness values. The results indicated that uniform crossover coupled with tournament selection proved to be the best genetic operators for the GA to find feasible aircraft designs. Results also revealed that uniform crossover encouraged the greatest information exchange between designs, whereas tournament selection played a major role of closely imitating mating competition in nature. One-point and two-point crossover schemes although useful, were not too effective in quickly exploiting and exploring the search space. This is partly because the bit string that represented each design was large, and consequently, there was not enough information exchange facilitated by these genetic schemes. This sometimes results in suboptimal rather than optimal solution due to speedy convergence.

The roulette selection scheme fused with any crossover scheme was also not too effective in finding optimum results. This is mainly because roulette selection has some undesirable features in that there is a tendency for a few superchromosomes to dominate the selection process; in later generations, when the population is largely converged, competition between chromosomes is less strong, and a random search behavior will emerge.[4] Nonetheless, the effect of the inverse scheme employed in the GA clearly indicated its capability of quickly exploring a broader search space. In addition, although generally increasing the population size improves the performance of the GA, all runs illustrate that even at a lower population size, the GA employed to conduct this study was capable of finding reasonable solutions with low constraint violation. The constraint violation is the percentage difference between the fitness value and the objective value. The fitness value is the sum of the objective function value and a value that is equivalent to the amount of violation of all



Side view



Top view

Fig. 2 Comparison of Boeing 717 with optimized aircraft found by the GA.

constraints. Hence, a low degree of constraint violation is indicative of a reasonable design. From Table 1 it can be gleaned that, with respect to fitness and constraint violation, the GA used in this study is both robust and efficient.

A graphical comparison of the side and top view of the best design found in run 3 with the existing aircraft is shown in Fig. 2. The fuselage dimensions are similar to the existing aircraft because the number of seats found by the GA was identical. Significant changes in horizontal and vertical tail arm and a subsequent reduction in tail area should be given attention. Note also the substantial decrease in wing and horizontal tail span and increase in both the vertical and horizontal tail arm. The low aspect ratio can be attributed to the failure of incorporating second-segment climb constraints. Nonetheless, the GA was capable of finding reasonable aircraft designs in an affordable time, thus aiding in reducing the time required by designers to complete the conceptual design process. The GA-generated designs are uniquely different from the existing Boeing 717 design; these differences usually provided a favorable combination of design variables that lead to a lighter aircraft. Consequently, the GA can be used as a tool to initialize the aircraft conceptual design process to meet design objectives in the event of reduced time frame, which is the main goal of conceptual design.

Conclusions

The capabilities of the GA to handle a population of designs, in a single generation, under the consideration of stability and control, is without question. Consequently, the consideration of stability and control on the aircraft conceptual design did prove to have an impact, resulting in a lower weight and feasible designs in most test runs. Accordingly, the GA was capable of varying design parameters in ways that other design tools cannot. Thus, the problems of interdependency of parameters in design, and the consequences of changing these parameters during designing, or, moreover, forseeability, are eradicated. It is from this standpoint that serious consideration should be paid to the designs found in this and other research utilizing GAs.

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Flutter Supression Using Linear Optimal and Fuzzy Logic Techniques

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I. Introduction

RECENTLY, NASA Langley Research Center, as part of the Benchmarks Models Program, developed a Benchmark Active Control Technology (BACT) wind-tunnel model.[1,2] Among other objectives, the BACT system provides an active control testbed for evaluating new and innovative control algorithms for flutter suppression. Several control approaches were developed including classical Nyquist methods (see Ref. 1), linear quadratic Gaussian (LQG) (see Ref. 1), H_∞, μ-synthesis[3] generalized predictive control,[4] minimax approach,[1] passivity-based robust control,[2] and others.

The BACT wind-tunnel model is a rigid rectangular wing with a NACA 0012 airfoil section. The wing is equipped with a trailing-edge control surface and upper and lower surface spoilers that can be independently controlled via hydraulic actuators. For simplicity, this research effort was restricted to a single input/single output formulation. Hence, we consider the trailing-edge control surface as the only means to control the system. Accelerometers are the primary sensors for feedback control. We assume a single accelerometer located at the wing shear center. The wing is mounted to a device called the pitch and plunge apparatus (PAPA),[2] which, in principle, is designed to permit motion in two modes: rotation (or pitch) and vertical translation (or plunge). The combination of the BACT wing section and PAPA mount will be referred to as the BACT system.

In this effort, three flutter suppression control laws for the BACT problem are developed: 1) full-state LQG, 2) reduced-order LQG, and 3) fuzzy logic techniques. The system dynamics varies with the dynamic pressure. Here, 24 working points have been considered, each one representing a different dynamic pressure (some stable and some unstable). The design criteria of the desired controller correspond to stability, settling times, and control effort for each of the working points.

The paper is organized as follows: The next section descibes the aeroservoelastic (ASE) modeling and the open-loop flutter analysis. The first two controllers, based on linear optimal theory, are presented in Sec. III, and the fuzzy logic controller is developed in Sec. IV. Finally the conclusions are given in Sec. V.

II. ASE MODELING

The ASE formulation in this section follows the state-space formulation of Ref. 5, where models for stability and response analysis are constructed from the separate models of the aeroelastic system, the sensors and actuators, and the control system, all expressed in state-space form. The control system includes the control surfaces

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