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AEROSERVOELASTICITY

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Aeroservoelasticity

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Abstract

The paper describes recent accomplishments and current research projects along four main thrusts in aeroservoelasticity at the NASA Langley Research Center. One activity focuses on enhancing the modelling and the analysis procedures to accurately predict aeroservoelastic interactions. In the area of modelling, improvements to the minimum-state method of approximating unsteady aerodynamics are shown to provide precise, low-order models for design and simulation tasks. Recent extensions in aerodynamic correction factor methodology are also described. With respect to analysis procedures, the paper reviews novel enhancements to Matched Filter Theory and Random Process Theory for predicting the critical gust profile and the associated time-correlated gust loads for structural design considerations. In another activity, two research projects leading towards improved design capability are summarized. The first program involves the development of an integrated structure/control design capability; the second provides procedures for obtaining low-order, robust digital control laws for aeroelastic applications. Experimental validation of new theoretical developments is the third activity. As such, a short description of the Active Flexible Wing Project is presented, and recent wind-tunnel test accomplishments are summarized. Finally within the area of application, a study performed to assess the state-of-the-art of aeroelastic and aeroservoelastic analysis and design technology with respect to hot, hypersonic flight vehicles is reviewed.

Introduction

Aeroservoelasticity (ASE) is a multidisciplinary technology dealing with the interaction of the aircraft's flexible structure, the steady and unsteady aerodynamic forces resulting from the aircraft motion, and the flight control systems. Detailed and quite complex mathematical models are required to accurately predict "ASE interactions" and to design active control systems for flexible vehicle applications. Not long ago the only "ASE interactions" of concern to the aircraft designer were those that caused adverse effects on vehicle stability and performance. Recent examples include the YF-16 and the F-18 which exhibited adverse dynamic interactions between the airframe aeroelastic characteristics and their flight control systems, and the X-29 which was predicted to be unstable throughout a significant portion of its flight envelope if costly and time consuming flight control modifications were not accomplished in a timely manner.

There has been much progress made in the last few years by many researchers, too numerous to reference here, that demonstrated the usefulness of active controls technology for favorably modifying the aeroelastic response characteristics of flight vehicles. These demonstrations promise significant enhancements in aircraft performance and stability while reducing structural weight. Today, ASE is becoming a viable design consideration for meeting the minimum weight, optimized performance, and multimission requirements being imposed on future designs. It is apparent that the future will demand high-gain control systems and flexible structures, two ingredients requiring significant interdisciplinary communication not only to avoid adverse ASE interactions, but also to make maximum use of this promising technology. Furthermore, ASE is becoming even more multidisciplinary in that the ASE technologists must now interact and communicate with experts in structural fatigue, thermodynamics, and propulsion.

So that this technology can play an increasing role in the design of flight vehicles, ASE is the focus of a major research program underway at the NASA Langley Research Center (LaRC). The objectives of this research are: to improve the ASE modelling and analysis procedures; to develop design methodologies for integrating the important technical disciplines; to validate new software and hardware developments through experimentation; and to demonstrate the application of ASE principles using advanced flight vehicle concepts. The purpose of this paper is to briefly describe a sampling of these research activities.

Modelling Procedures

The availability of efficient linear system algorithms has provided a strong motivation to transform the frequency-domain aeroelastic equations of motion into linear, time-invariant, (LTI) state-space form. This section describes recent advancements in obtaining low-order rational function approximations (RFA) of the reduced-frequency dependent, unsteady aerodynamics to permit reasonable

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LTI transformations and reviews the development of aerodynamic "correction" factors derived using experimental or computational fluid dynamics (CFD) data.

Recent Extensions to the Minimum-State Method for Approximating Unsteady Aerodynamics

One procedure for obtaining time-domain ASE equations requires the use of rational functions to approximate the reduced-frequency dependent unsteady aerodynamic force coefficients in the frequency or Laplace domain. Several procedures for determining the RFA are available in the ISAC[1] code (Interaction of Structures, Aerodynamics, and Controls), a NASA tool for developing aeroelastic equations and performing ASE analyses. A disadvantage of using an RFA is that it can significantly increase the size of the state vector after transformation into state-space. This increase in size is referred to as the aerodynamic dimension. There is, of course, always a trade-off between how well the rational function approximates the aerodynamic forces and the desire to keep the aerodynamic dimension small. Figure 1 shows the general RFA form for each method in ISAC and the associated aerodynamic dimension. Of the three methods in ISAC, the Minimum-State Method[2] is the most computationally intense, but as Figure 1 indicates, this method provides the lowest aerodynamic dimension. Recent extensions to these approaches include the capability to enforce selected equality constraints on the RFAs and to optimize the denominator coefficients of the rational functions using nonlinear programming techniques[3].

Additional studies by Tiffany and Karpel[4] have shown that by using discretion in the selection of the denominator (lag) coefficients, choosing various equality constraints, and applying physical weighting to the various aerodynamic data terms according to their importance in subsequent analyses, the Minimum-State Method can provide very accurate, low-order ASE state-space models. The physical weighting procedure produces a measure of importance which allows the aerodynamic approximation to be improved at some reduced frequencies (at the possible expense of others) based upon physical properties without actually enforcing equality constraints at the specified points. The measure of importance is based upon partial derivatives of selected open-loop parameters with respect to the weighted term at a specified design flight condition. For the vibration modes, the weight at each value of reduced frequency is determined by the effective influence on the system flutter determinant; for control modes, by the effect on system gains; for gust modes, by the effect on the response to continuous gusts; and for hinge moment terms, by the hinge moment response to control surface or gust excitations. Using the Minimum-State Method and these techniques, the total size of a typical time-domain ASE model can be effectively reduced by 50 percent. In addition to significant computer time savings for control design and analysis tasks, lower-size models provide more realizable optimal control laws and facilitate near real-time simulations of ASE equations.

Unsteady Aerodynamic Correction Factor Methodology

In recent years much progress has been made in solving the nonlinear aerodynamic equations associated with complex aircraft configurations. Since CFD analyses are quite expensive for routine aeroelastic/ASE studies, linearized lifting-surface theories are still the most common method within the aerospace community for predicting the aerodynamic pressures or forces/moments. Linear theory, however, is based on small disturbance theory and limited to subsonic or supersonic flight conditions. There is the desire and need to extend such linear, inexpensive methods into areas in which they are currently known to be inaccurate, for example, the transonic regime. The application of factors based on steady aerodynamic test data or CFD codes to correct the linear-predicted aerodynamic forces is one reasonable approach for obtaining more accurate aeroelastic and ASE evaluations.

Enhancements to correction factor methodology have recently been accomplished by Wieseman[5]. These techniques are based on using steady experimental or CFD analytical pressure or force data to correct steady and unsteady aerodynamic calculations obtained by linear methods. Correction factors are multipliers which are applied to aerodynamic pressures or downwashes. Three approaches for developing the correction factors were investigated.

The first approach involves matching pressures or downwashes. The pressure (or downwash) correction factor associated with each individual box (or collocation point) is the ratio between the experimental (or CFD) lifting-pressure coefficient derivative (or downwash) and the corresponding analytical value. Pressure corrections have the effect of modifying only the pressure on the box to which they are applied, whereas a downwash correction factor on one box affects the pressures on all other boxes. The effect of pressure correction factors on unsteady pressures is to modify only the magnitude of the unsteady pressures. Downwash correction factors affect both the magnitude and phase of unsteady analytical pressure distributions.

The second approach develops a correction factor based on the ratio of one or more airfoil section properties. If only one section property is to be matched, the pressure correction factor is simply the ratio of the experimental to the analytical section property for each airfoil section. The same correction factor is applied to all the pressures at the aerodynamic boxes along a chordwise strip at the span location for which the section characteristics are valid. In most cases, however, it is desirable to match both lift and moment derivatives, simultaneously. One way this can be accomplished is by using correction factors which vary linearly along the chord section. Optimization techniques can also be used to calculate a set of correction factors which are different for each of the boxes along a chordwise strip. Instead of solving separate optimization problems for each strip, the correction factors for all the strips could be calculated simultaneously by summing the objective functions for each strip.

The third approach for obtaining correction factors is to match total forces, total moments, or integrated pressures with respect to angle-of-attack and control-surface deflections. This approach expands the work developed Giesing, Kalman, and Rodden[6]. Correction factors are obtained using the procedures described in the second approach and can be applied to either the aerodynamic box downwashes or pressures.

Analysis Methods

There is a continuing international effort to rationalize and improve the gust criteria applied by U.S. and European airworthiness authorities. The effort includes the investigation of candidate analysis methods for gust loads certification. The Federal Aviation Administration (FAA) Regulations require that, unless a more rational method is used, an airplane manufacturer must use the Power Spectral Density (PSD) Method to determine the dynamic response of it's airplanes to atmospheric turbulence. One alternate means with important advantages over the PSD Method involves the computation of time-correlated gust loads (time histories of two or more different load responses to the same disturbance quantity). This work is an application of Matched Filter Theory (MFT).

Matched Filter Theory

MFT was originally developed and applied in the field of signal processing for the design of an electrical filter that maximized the detection of a returning radar signal. In the current application[7] to linear aeroelastic systems, MFT is used to "design" a critical gust pattern (a time history of vertical gust velocity) that produces the worst-case deterministic response of a chosen load quantity and the time-correlated responses of other load quantities.

Figure 2 contains a signal flow diagram of the analytical steps necessary to generate the maximum dynamic response at some point in the aircraft structure using MFT. On the left, a gust pre-filter is excited by an impulse of unit strength to generate an intermediate gust impulse response which, in turn, is the excitation to the aircraft. Also shown are several output load responses to the impulse, one of which, y, is chosen for the maximization process. Response y is then normalized by its root-mean-square (RMS) value, reversed in time (analogous to convolution), and used as input to the system as shown on the right side of the figure. This normalized and reversed signal is referred to as the matched excitation waveform. Intermediate and final outputs due to the matched excitation waveform are the critical gust profile and the time correlated responses, including the maximum response of the system. It can also be shown that the time-correlated gust loads computed by MFT are theoretically identical to auto- and cross-correlation functions of Random Process Theory (RPT) obtained directly from response spectra. Thus, auto- and cross-correlation functions of RPT may be interpreted as time-correlated gust loads.

In addition, there is a relationship between time-correlated gust loads computed by MFT and RPT and Phased Design Load Analysis (PDLA)[8], a procedure commonly use in the aerospace industry. The relationship is as follows: Time histories of two time-correlated gust load responses, determined using either MFT or RPT, can be plotted as parametric functions of time and the resulting plot, when superimposed upon the PDLA design ellipse corresponding to the two loads, is tangent to the ellipse. The point of tangency corresponds to the design value of one load and the "phased" value of the other load. Figure 3 which illustrates this relationship, contains normalized wing-root-bending-moment and wing-root-torsion-moment responses due to an excitation matched to wing-root torsion for a typical MFT calculation.

As a result of this investigation, the analytical tools, knowledge, and options needed to calculate time-correlated gust loads in a quick and efficient manner are available for use by the aerospace community. If gust loads are found to be critical, MFT or RPT Methods can be used to provide accurate loadings for the limit and ultimate load cases to validate the aircraft strength design. In addition, the MFT and RPT approaches are general enough to be applied to other dynamic-response problems, including taxi, landing, and maneuver loads.

Synthesis Methodology

Two research projects associated with design are summarized. The first effort deals with preliminary design and the effort expended to include ASE considerations at that stage of flight vehicle development. At the present time, only the integration of structures and controls is considered. The second research activity has resulted in the development of procedures for obtaining low-order, robust, multi-input/multi-output (MIMO) digital control laws based on high-order dynamics for aeroelastic applications.

Integrated Structure/Control Law Design Methodology

The integrated structure/control law design methodology is based on hierarchal multilevel problem decomposition and optimization techniques (Figure 4). The hierarchal decomposition techniques allow for a natural ordering of design objectives into system level and subsystem objectives. This ordering provides a structure within a design methodology to trade off subsystem performance for improved system performance. The subsystem designs are obtained independently subject to a set of fixed design integration parameters, using existing design methods and tools. A rational means for making subsystem performance trade-offs is provided through the use of optimization techniques for subsystem design and the use of sensitivity of optimum solution concepts to obtain subsystem design sensitivity information. The subsystem design sensitivity information is used at the system design level to make decisions which influence the subsystem designs in such a way that overall system performance is improved.

As part of the design procedure, a method[9] for obtaining the analytical sensitivities of a control law solution to key system parameters has been developed for the linear system, quadratic cost, Gaussian (LQG) distributed disturbance optimal control law problem. The analytical sensitivity equations were derived by differentiating the necessary conditions of optimality for the LQG problem, thus eliminating the need for perturbed optimal control law solutions and finite difference derivative calculations.

The analytical sensitivity approach was evaluated by developing a control system to stabilize an unstable short period mode associated the DAST ARW II aircraft. The sensitivity of the optimized control law and the aircraft responses to various inputs were computed for several aircraft structural and configuration parameters. Time responses to control surface motions and discrete aerodynamic gusts, stochastic responses to random gust environments, closed-loop system eigenvalues, and open- and closed-loop frequency responses were considered during the design process. A typical sensitivity expression result[10] is shown in Figure 5. This figure shows the percentage error in predicting changes in mean square aircraft pitch rate response due to random gusts using the sensitivity results for parametric variations in the wing bending frequency (stiffness). In the hierarchal design method, the wing bending frequency parameter could be selected to improve the pitch rate response of the aircraft due to the gust environment. The parameter would influence both the structural and control law designs resulting in improved dynamic response characteristics of the aircraft.

Design Using Constrained Optimization with Singular Value Constraints

When the aeroelastic equations are transformed into LTI state-space form for control design tasks or for simulation, RFA of the unsteady aerodynamics is required resulting in a large order design model. A control law design for such a system is expected to satisfy multiple conflicting design requirements as described in Figure 6 and be robust to modelling uncertainty. Because the resulting control law is usually of the same order or higher than the design model, it is difficult to implement the control law on a digital controller for practical application.

A control law design algorithm[11] has been developed to obtain low-order, robust, MIMO digital control laws using a high-order dynamical system. The objective of the procedure is to reduce a large-order analog controller to lower order without sacrificing performance and stability robustness. The procedure begins by performing a singular value analysis of the full-order controller to determine its robustness and the significant states to be retained during the reduction process. Balanced truncation or residualization techniques are then used for control law order reduction. If the order reduction step results in loss of stability robustness or increased RMS response, a constrained optimization technique[12] may be used to improve the performance and stability robustness. The parameters of the reduced-order analog control law are used as the design variables. The design requirements, such as control surface deflection and rate limits and maximum allowable RMS responses, can be imposed as constraints. Constraints on the minimum singular value at the plant input and output can also be used to improve the robustness properties. The low-order analog equations can be easily converted into the digital domain using z transforms with zero-order hold or Tustin transforms.

Validation of Methods Through Experimentation

The ASE analysis and design methodologies that are now emerging offer the designers the capability to exploit the aircraft's aeroelastic characteristics to improve performance and stability while reducing structural weight. However, test demonstrations using actively controlled, aeroelastic wind-tunnel models are vital for the verification of these analysis and design methodologies. This section of the paper briefly describes the recent accomplishments and the status of the Active Flexible Wing (AFW) wind-tunnel test project.

Active Flexible Wing Program

In 1985 Rockwell International Corporation, the Air Force Wright Aeronautical Laboratories, and the NASA LaRC initiated the AFW program[13,14]. The goal of that program was to develop, demonstrate, and validate AFW technology, a multidisciplinary technology concerned with integrating active controls with a highly flexible, advanced aerodynamic wing design to produce enhanced aerodynamic performance and control. To extend the state-of-the-art in active controls into more challenging and rewarding areas of application, an agreement for continued AFW cooperation between the LaRC and Rockwell International Corporation was signed in 1987. The objectives of the ongoing AFW program[15] are to design digital MIMO active control concepts, develop near real-time simulation techniques, perform wind-tunnel experiments, demonstrate control of aeroelastic response characteristics, and validate current analysis and design methodologies. Control concepts being investigated include flutter suppression (FSS) and rolling maneuver load alleviation (RMLA).

AFW Wind-Tunnel Model. The model is an actively controlled, full-span aeroelastic wind-tunnel model of an advanced tailless fighter. Two leading-edge and two trailing-edge control surfaces driven by hydraulic actuators are available on each wing for open- or closed-loop test functions. Figure 7 shows a photograph of the sting-mounted model in the Transonic Dynamics Tunnel (TDT). The mounting scheme utilizes an internal ballbearing arrangement and a roll degree-of-freedom brake to allow the model to either roll about the sting axis or to be held fixed. In addition, an actuator located at the model center-of-gravity is available for remotely positioning the model angle-of-attack.

Wing Tip Ballast and Flutter Stopper. To perform FSS investigations, ballast was attached to the tips of each wing so that the model would flutter well within the operational capabilities of the TDT. The ballast is basically a hollow aluminum tube with added internal mass. Its effect is to increase the wing pitch inertia and the wing total mass such that the first wing bending and torsion modes coalesce earlier causing flutter to occur at a lower dynamic pressure than without the ballast present. In addition, the wing-tip ballast tubes were designed to improve model safety during flutter testing. The ballast tube is attached to the wing by a pitch-pivot mechanism that uses an internal hydraulic brake mechanism. When the brake is on for flutter testing the attachment between the wing and the ballast is essentially rigid ("stiff"); when the brake is off (either manually or automatically), a spring internal to the store provides a more flexible ("soft") pitch stiffness. This "soft" pitch stiffness essentially decouples the ballast pitch inertia from the wing at low frequencies.

Modelling. For subsonic flight conditions, the linear aeroelastic equations of motion were developed using the ISAC code and the doublet lattice unsteady aerodynamic method[16]; for supersonic flight conditions, a modified Woodward code was used to obtain the unsteady aerodynamics. All linear equations of motion were transformed into LTI state-space form for control system design functions and simulation activities. To more accurately represent the change of control-surface effectiveness with increasing dynamic pressure, control surface correction factors were employed. These correction factors were derived by comparing analytical predictions of lift force and rolling moments with experimental data. The correction factors brought the analytically-corrected control-surface effectiveness into close agreement with experimental data.

For transonic flight conditions, a nonlinear transonic flutter analysis was accomplished using the CAP-TSD (Computational Aeroelasticity Program - Transonic Small Disturbance) code[17]. A procedure[18] was developed to analyze situations where static aeroelasticity is important in determining the dynamic stability at transonic flight conditions. The analysis procedure determined the static aeroelastic shape of the AFW configuration resulting from certain flight and model conditions. Dynamic perturbation analyses were performed about the deformed shape to obtain the flutter characteristics. The results indicate the presence of a transonic flutter "dip" near Mach 0.95.

Active Flutter Suppression Design. The FSS design objective was to develop low-order, robust, discrete control laws for implementation on a digital computer. The goal was to increase the open-loop flutter dynamic pressure by about 20 to 30 percent in air at Mach 0.5 while maintaining control surface deflection and rate limits and reasonable gain and phase margin requirements over the entire dynamic pressure range. To accomplish this goal, two flutter modes of instability, one symmetric and one antisymmetric, had to be suppressed simultaneously. Three control law design approaches were investigated. These include: 1) an LQG Method[11,12] described earlier in this paper; 2) a sensor blending approach[19] which develops a signal that observes the modal velocities of the critical flutter modes; and 3) an eigensystem assignment technique[20]. The predictions based on the LQG design procedure and some practical observations are presented in Reference 21. A schematic of a candidate digital FSS is shown in Figure 8. Although not shown in the figure, the right and left wing sensor signals would be split into symmetric and antisymmetric components prior to entering the FSS controller. In addition, the right and left wing actuator feedback signals would be obtained by blending the symmetric and antisymmetric control law output components.

Rolling Maneuver Load Alleviation. The approach for roll control is to twist the flexible-wing structure into an optimum shape by actively deflecting multiple leading and trailing edge control surfaces on each wing panel. The RMLA objective is to maintain a fixed roll rate while reducing wing loads at multiple points by 20 percent using direct load feedback (strain-gage signals). A schematic of a RMLA system is shown in Figure 9. Multiple wing load sensors along with a roll rate sensor are differenced from like signals obtained from the "Command Generator." This difference is input into a forward path controller to produce control surface position commands. The "Controller" was designed using an LQG/LTR (Loop Transfer Recovery) Method[22] to provide robust stability and good tracking of the load and roll-rate commands. The load commands from the "Command Generator" were developed for several steady-state roll rates with mathematical optimization techniques to determine the minimum-load solution for a given roll rate using an analytical model of the vehicle. This optimal solution was constrained by control surface position and hinge moment maximums.

Digital Controller. To obtain both computational speed and system versatility, a Sun 3/160 Workstation was modified to include analog-to-digital (ADC) and digital-to-analog (DAC) conversion boards, a digital signal processing (DSP) board, and a floating point array-processing board. A schematic showing the NASA/Rockwell Interface Box which contains analog circuitry and the digital controller is provided in Figure 10. The figure illustrates how the host CPU (Central Processing Unit), the disk and tape drives, and the added boards communicate across the bus. During closed-loop operation the ADC boards convert analog sensor signals to digital data; the DAC boards convert digital actuator commands to analog signals; the host CPU and the user control panel provide user interface to the DSP board; the DSP board ("the controller") controls the real-time processing; and the array processing board performs floating-point calculations of the FSS and RMLA control laws.

Simulation. To test the functionality of the digital controller, a hot-bench simulation (Figure 11) was performed using the LaRC Advanced Real-Time Simulation (ARTS) System. The ARTS used a Cyber 175 computer to represent the symmetric and antisymmetric aeroelastic characteristics of the wind-tunnel model. The size of the mathematical model and the requirement of high frequency dynamics analysis prevented the simulation from being performed in actual real time on the Cyber. As a result, the Cyber was coupled to the Sun Workstation in synchronized "slow-time" with a time-scale factor of about 20:1.

Controller Performance Evaluation. Software was developed to evaluate the performance of the digital control systems and to provide, in near real-time, information necessary for making a reasonable decision to continue the test thereby improving model and wind-tunnel safety. The methodology, shown schematically in Figure 12, was derived based on multivariable control theory and implemented using the Sun Workstation and a Macintosh II computer. The procedure involved providing excitation to the open- or closed-loop wind-tunnel model, developing transfer matrices between the control surfaces and sensors, and calculating the return-difference matrix of the closed-loop system. This procedure was used to directly determine closed-loop performance and stability and to predict closed-loop characteristics from responses taken while the control system was open loop.

Wind-Tunnel Testing. The first wind-tunnel test series was completed in November 1989 resulting in the following accomplishments[23]: flexibilized stability derivatives were measured; the unaugmented aeroelastic flutter boundaries for "stiff" and "soft" tip ballast configurations were defined; wind-tunnel model hardware, digital computer hardware and supporting software, and the controller performance software were evaluated; the FSS open- and closed-loop behavior was measured; and an increase in flutter dynamic pressure of over 20% was achieved with FSS. Problems encountered during the open-loop RMLA tests prohibited further testing and evaluation of that concept. The next test is scheduled for the Fall of 1990.

Application

This section of the paper describes the status of a study to investigate hypersonic aircraft and thermal effects on aeroelasticity. The objective of the study is to: 1) identify deficiencies in aeroelastic and ASE methods with respect to hypersonic flight vehicles; 2) define the required enhancements; and 3) extend the appropriate analysis and design methodologies.

Generic Hypersonic Aircraft

Atmospheric flight at high speeds causes large thermal loads due to aerodynamic heating. These large thermal loads can destiffen the structure through changes in structural material properties with temperature and through material stress level changes caused by thermal gradients in built-up structural components. Increasing flexibility would be expected to significantly affect the vehicle flutter characteristics and aeroelastic response.

The goals of this research[24] were to develop appropriate aeroservothermoelastic (ASTE) analysis methods and apply ASE technology to reduce adverse aeroelastic changes caused by aerodynamic heating. The ASTE approach, shown schematically in Figure 13, includes: 1) the determination and application of thermal loads due to aerodynamic heating to the finite element model of the aircraft structure; 2) the assessment of the thermal effects on aircraft short period dynamics and flutter; and 2) the design of FSS and ride quality (RQ) improvement systems to overcome any potential adverse aeroelastic stability or response problems due to aerodynamic heating. For this study, the generic hypersonic aircraft configuration shown in Figure 14 was selected; only symmetric motion was considered.

The Hypersonic Arbitrary Body Program of the Aerodynamic Preliminary Analysis System[25] was used to provide the steady-state aerodynamic forces and heat loads for a Mach 4.0 flight condition. These heat loads were applied to a finite element structural model of the generic configuration resulting in changes in structural stiffness and material properties. Flutter predictions and aeroelastic response data were obtained for the hot configuration at Mach 2.0 (resulting from deacceleration from Mach 4.0) and Mach 4.0 flight conditions using piston theory unsteady aerodynamic forces.

For the FSS design, a full-order state estimator was used for compensation in the feedback loop. The controller was designed using LQG Methods with LTR to improve stability robustness. Normal acceleration at the pilot station and at a location very near the wing aileron were used as measurements for feedback to the compensator. As shown in Figure 15, the FSS control function not only recovered the lost flutter dynamic pressure of the hot structure, it increased the flutter dynamic pressure beyond that of the cold structure as well.

The RQ system was designed to reduce cockpit acceleration levels due to structural motion induced by encounters with turbulence. It was designed using a pole-placement technique to locate the closed-loop system eigenvalues to achieve the desired dynamic response. Full-state feedback was assumed, and normal acceleration at the pilot station was used as the figure of merit.

Besides reducing the peak amplitudes of the short period and elastic modes as shown in Figure 16, the RQ control function also achieved an overall 30% reduction in RMS normal acceleration response while maintaining acceptable control surface deflections and rates during random wind gust encounters.

Concluding Remarks and Recommendations

This paper briefly reviewed a sampling of recent ASE accomplishments and ongoing research at the NASA LaRC providing some insight as to the present state-of-the-art. However, high-gain digital control systems and flexible high-performance structures coupled with the desire to use multidisciplinary analysis and design tools requires continued aggressive research in ASE. In the area of modelling and analysis, enhanced computer capabilities and modelling techniques are a necessity to permit real-time simulation of the ASE equations of motion with a pilot and controller hardware in the loop. In the control law synthesis area, the need to integrate nonlinear, time-dependent unsteady aerodynamics into ASE analysis and design methodologies is essential if transonic flight and high maneuverability is required. Furthermore, the integration of structural optimization, aeroelastic tailoring of composite materials, smart structures, and controls into a meaningful design procedure is highly desirable. Finally, there is always a need to conduct wind-tunnel tests using simple models of known geometric, structural, and inertia characteristics to calibrate linear and nonlinear steady/unsteady aerodynamic theories, aeroelastic response methods, and ASE design procedures.

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Approximation Method	RFA	Aerodynamic Dimension
	$\hat{Q}(s) = A_0 + A_1 s + A_2 s^2 + \hat{Q}_{ij}$	
Least-Squares	Common denominator coefficients in each $\hat{Q}_{ij}$ $\hat{Q}_{ij} = \sum_{k=1}^{n_L} (A_{(k+2)})_{ij} \frac{s}{s + \beta_k \frac{V}{b}}$	$j * n_L$
Modified Matrix Pade´	Different number of and values for denominator coefficients for each column, Q_j $\hat{Q}_{ij} = \sum_{k=1}^{n_{L_j}} (A_{(k+2)})_{ij} \frac{s}{s + \beta_k \frac{V}{b}}$	$\sum_j n_{L_j}$
Minimum-State	Common denominator coefficients in each $\hat{Q}_{ij}$ $\hat{Q}_{ij} = \sum_{k=1}^{n} \frac{\{D_i\}[E_j]^s}{s + \beta_k \frac{V}{b}}$	n

Figure 1 Rational Function Approximation Matrix Formulations

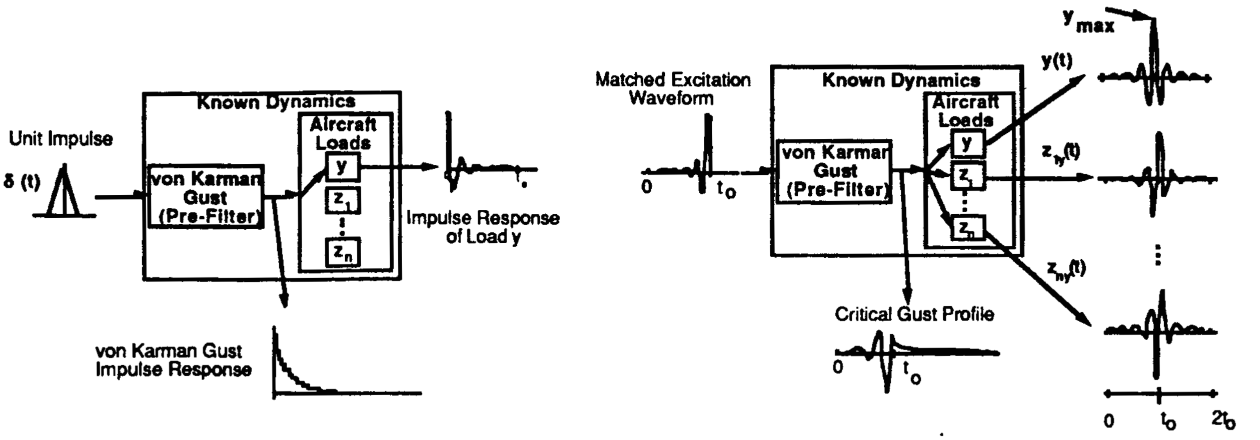

Figure 2 Signal Flow Diagram for MFT to Predict Time-Correlated Loads

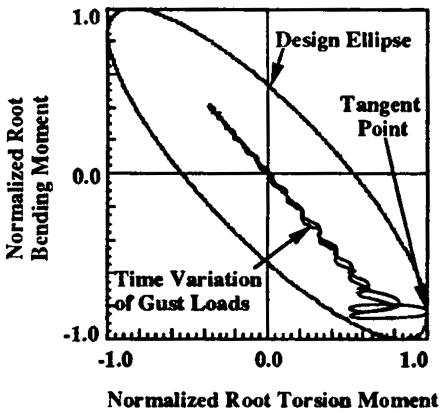

Figure 3 Phased Design Loads Analysis Design Ellipse with Normalized Parametric Loads

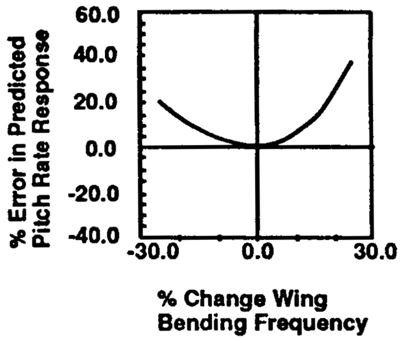

Figure 5 Predicted Response Based on Bending Frequency Sensitivity Gradients

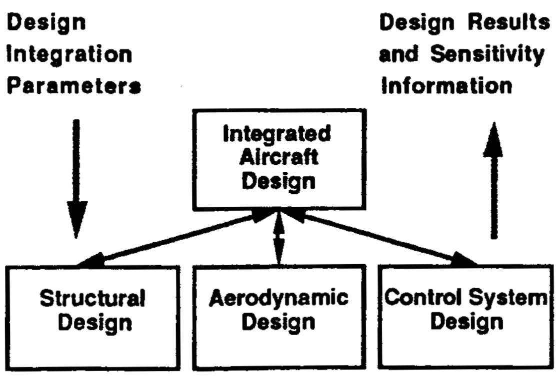

Figure 4 Schematic of Integrated Multilevel Structure/Control Design Procedure

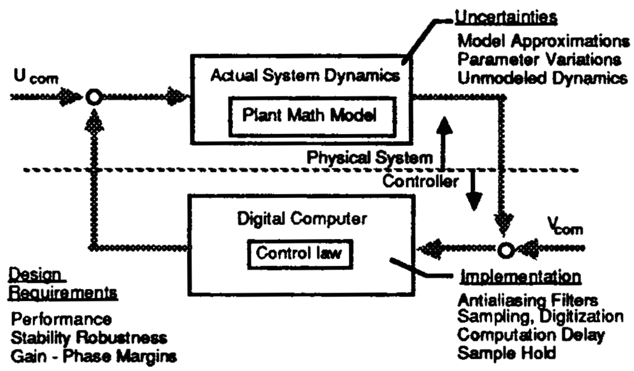

Figure 6 Design Considerations for a Multivariable Control System

Figure 7 Photo of AFW Model Mounted in the NASA Transonic Dynamics Wind Tunnel

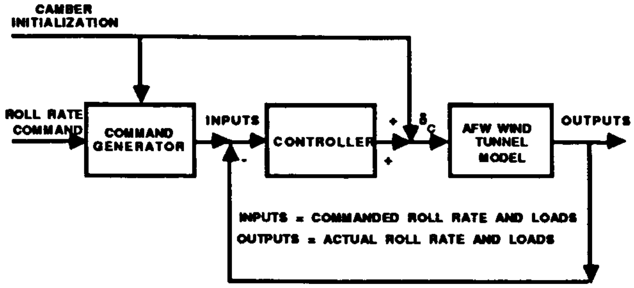

Figure 9 Block Diagram of a RMLA Control System

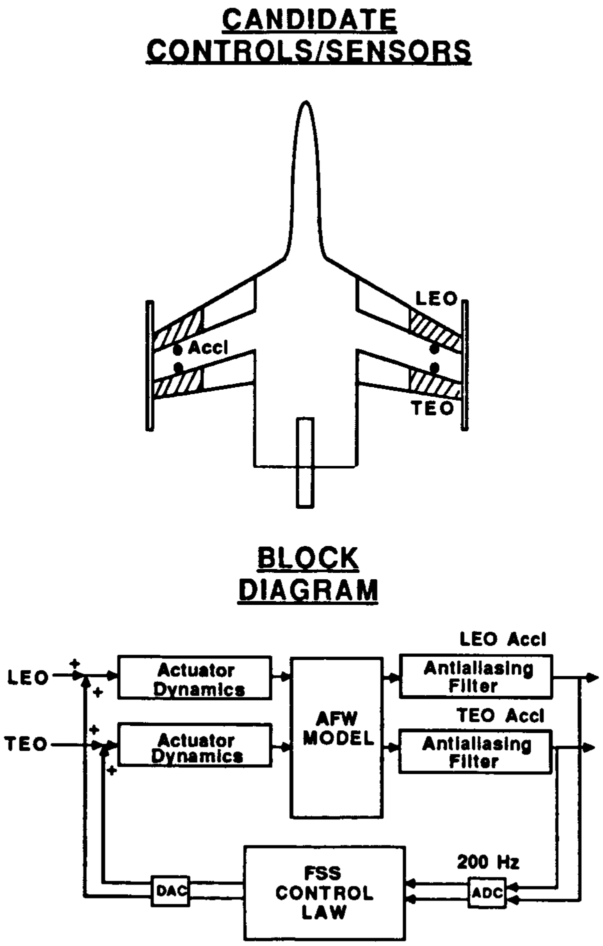

Figure 8 Schematic of a Generic Digital FSS Controller

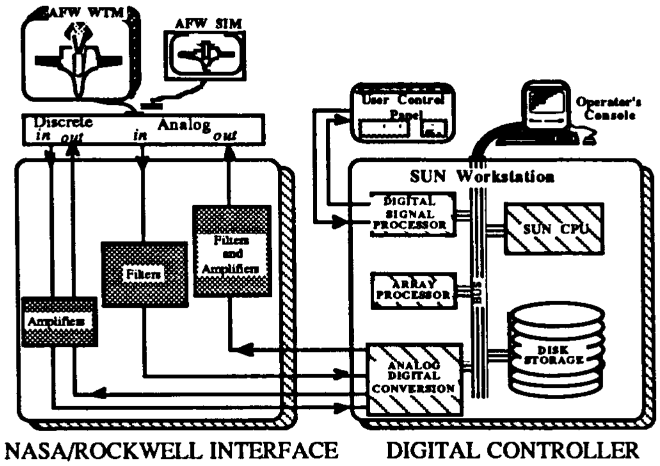

Figure 10 Schematic of the AFW Digital Controller

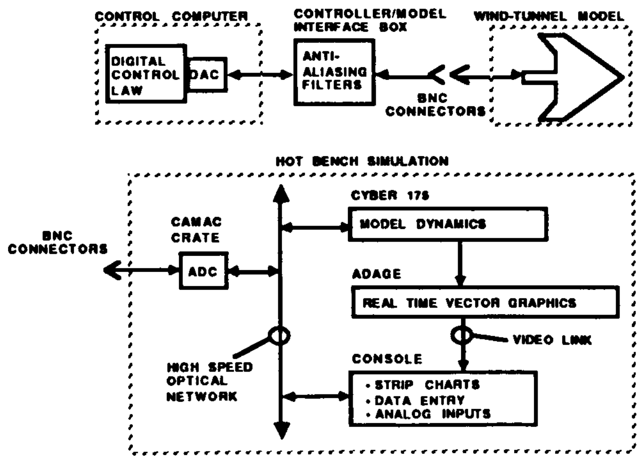

Figure 11 Schematic of Near Real-Time Simulator

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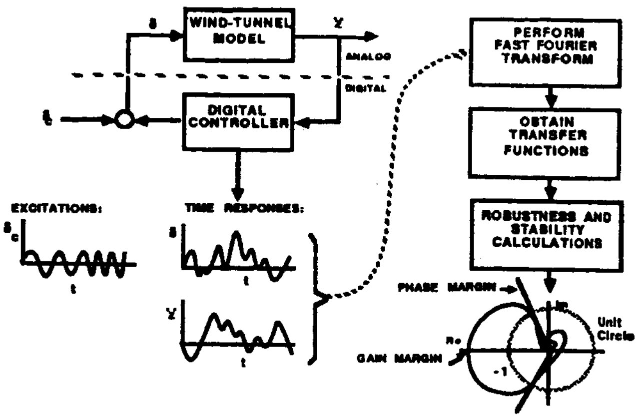

Figure 12 Real-Time Controller Performance Evaluation Procedure

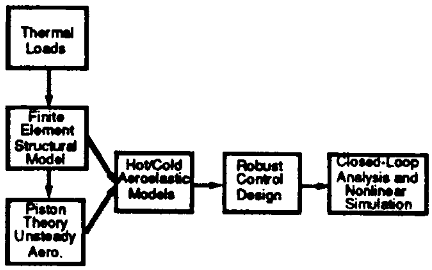

Figure 13 Schematic of Aeroservothermoelastic Analysis Procedure

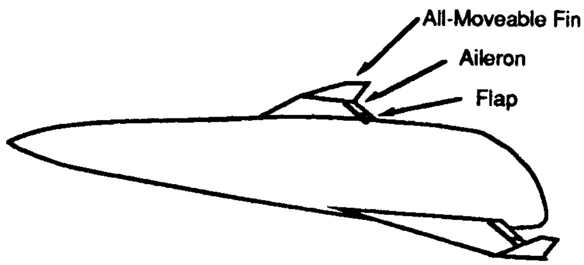

Figure 14 Generic Hypersonic Aircraft Configuration and Finite Element Model

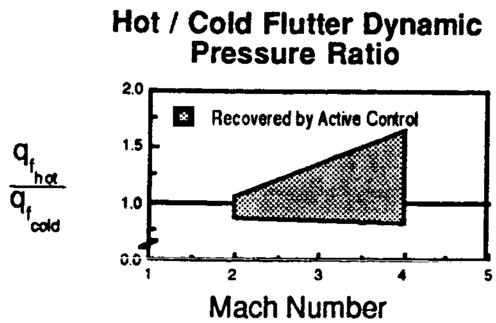

Figure 15 Flutter Suppression Results

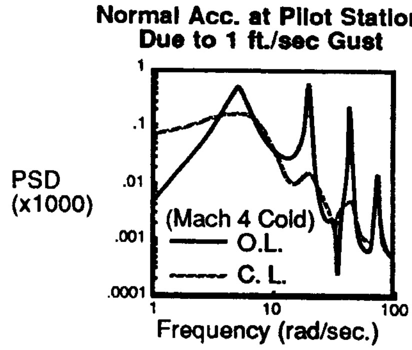

Figure 16 Ride Quality Improvements

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15. Supplementary Notes

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16. Abstract

The paper describes recent accomplishments and current research projects along four main thrusts in aeroservoelasticity at the NASA Langley Research Center. One activity focuses on enhancing the modelling and the analysis procedures to accurately predict aeroservoelastic interactions. In the area of modelling, improvements to the minimum-state method of approximating unsteady aerodynamics are shown to provide precise, low-order models for design and simulation tasks. Recent extensions in aerodynamic correction factor methodology are also described. With respect to analysis procedures, the paper reviews novel enhancements to Matched Filter Theory and Random Process Theory for predicting the critical gust profile and the associated time-correlated gust loads for structural design considerations. In another activity, two research projects leading towards improved design capability are summarized. The first program involves the development of an integrated structure/control design capability; the second provides procedures for obtaining low-order, robust digital control laws for aeroelastic applications. Experimental validation of new theoretical developments is the third activity. As such, a short description of the Active Flexible Wing Project is presented, and recent wind-tunnel test accomplishments are summarized. Finally within the area of application, a study performed to assess the state-of-the-art of aeroelastic and aeroservoelastic analysis and design technology with respect to hot, hypersonic flight vehicles is reviewed.

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