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Active Aeroelastic Wing Flight Research Program: Technical Program and Model Analytical Development

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The Active Aeroelastic Wing (AAW) Flight Research Program's (Pendleton, E., Griffin, K., Kehoe, M., and Perry, B., "A Flight Research Program for Active Aeroelastic Wing Technology," AIAA Paper 96-1574, April 1996 and Pendleton, E., Bessette, D., Field, P., Miller, G., and Griffin, K., "The Active Aeroelastic Wing Flight Research Program," AIAA Paper 98-1972, April 1998) technical content is presented and analytical model development is summarized. Goals of the AAW flight research program are to demonstrate, in full scale, key AAW parameters and to measure the aerodynamic, structural, and flight control characteristics associated with AAW. Design guidance, derived from the results of this benchmark flight program, will be provided for implementation on future aircraft designs.

Introduction

ACTIVE aeroelastic wing (AAW) technology is multidisciplinary in that it integrates air vehicle aerodynamics, active controls, and structural aeroelastic behavior to maximize air vehicle performance. The concept uses wing aeroelastic flexibility for a net benefit and enables the use of high aspect ratio, thin, swept wings that are aeroelastically deformed into aeroelastic shapes for optimum performance. This makes it possible to achieve the multipoint aerodynamic performance required of future fighters.[1]

During initial sizing studies, traditional air vehicle design approaches treat wings and control surfaces as rigid components and treat aeroelastic response as a negative that must be overcome. Traditionally, control surfaces are employed to produce control force by changing the net camber of the lifting surface. Wing flexibility, in high-performance aircraft, causes adverse aeroelastic twist that degrades control effectiveness at high aerodynamic pressures. Control surfaces must be located inboard to preserve some control effectiveness and to avoid roll reversal. Traditional high-performance aircraft wing designs are, therefore, stiffer to reduce the adverse twist. This adds significant structural weight and drag penalties.

AAW technology employs wing aeroelastic flexibility for a net benefit through the use of multiple leading- and trailing-edge control surfaces activated by a digital flight control system. At higher dynamic pressures, AAW control surfaces are used as aerodynamic tabs that promote a favorable wing twist instead of the reduced control generally associated with aileron reversal caused by trailing-edge surfaces. The energy of the airstream is employed to twist the wing with very little control surface motion. The wing itself creates the control forces. An AAW wing is expected to experience less twist than a conventional wing, which twists in opposition to the control force generation.[2]

Overall benefits of AAW technology to future systems include substantially increased control power, reduced aerodynamic drag, reduced maneuver loads, and reduced aircraft structural and takeoff gross weight. The use of AAW technology in a design approach increases design latitude in terms of wing span, sweep, and thickness and expands air vehicle design latitude by allowing configurations with higher aspect ratio, thinner wings.

The development of AAW technology through full-scale aircraft flight research will result in design guidance in the form of comparisons between design methods and tools, scaled wind-tunnel measurements, and full-scale experimental data. Design studies, performed to demonstrate the design process for AAW and to determine the sensitivity of AAW benefits to conceptual design parameters and design requirements, will also be valuable for future systems design. Flight research data and design guidance emanating from full-scale research will change the design paradigm for wing structures by allowing the design of wings that are lighter and more aerodynamically efficient. Depending on mission requirements, these benefits should mean significant reductions in air vehicle takeoff gross weight and production costs.

Background

During the period from 1984 through 1993, AAW technology has been shown during several wind-tunnel test programs[1,3,4] to provide large amounts of control power across the aircraft envelope. This control power can be used to twist and camber the wing into shapes that minimize drag at multiple flight conditions, to reduce structural loads, and to provide control power for rolling or pitching the air vehicle. A typical plot for control effectiveness shows rolling moment coefficient as a function of dynamic pressure, as shown in Fig. 1.

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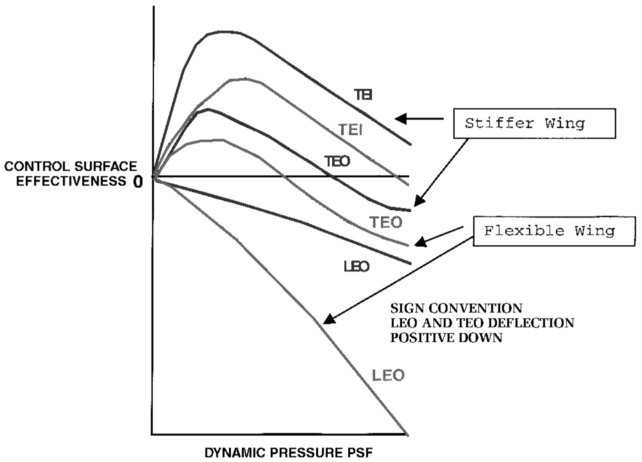

Fig. 1 Typical effectiveness of control surfaces as a function of dynamic pressure.

AAW technology can be applied to high-performance aircraft required to operate in a broad range of subsonic, transonic, and supersonic conditions. AAW design techniques have been applied to several fighter concepts during design studies and have been shown to reduce aircraft takeoff gross weight by 5–20% (Refs. 1 and 5).

In 1995, a flight research program[6] was initiated to demonstrate key parameters associated with the AAW concept using a full-scale crewed fighter aircraft. Aerodynamic, structural, and flight control characteristics associated with AAW will be measured during flight testing. Following flight test data reduction and interpretation, design guidance will be developed for use during future aircraft design initiatives.

Several aircraft candidates were considered as host aircraft in terms of cost/benefit combination for AAW modification, operation, and potential for research data. Two of these were the F/A-18 and the F-16.

Potential research program design studies were conducted to identify modifications and costs associated with making the F/A-18 or the F-16 aircraft suitable as AAW research testbeds.[6]

Early in full systems development (FSD) flight testing of the F/A-18, the aircraft exhibited poor roll performance at high speeds due to the wing outboard ailerons' loss in effectiveness and subsequent aeroelastic reversal at approximately Mach 0.7 at sea level. The requirement to correct the roll performance deficiency caused by the thin flexible wing dictated both structural and flight control system modifications. The structural modifications included adding more plies of composite skin, adding material to the aft spar, and increasing the area of the aileron. Flight control modifications involved incorporating asymmetric deflection of both leading- and trailing-edge flaps at high-subsonic and supersonic Mach numbers. These improvements, referred to as roll modifications I and II, allowed the aircraft to meet roll specifications. The wing incorporating these modifications is currently used on A–D versions of the F/A-18.

In 1995, McDonnell Douglas and Rockwell, North American Aircraft[7] conducted a testbed modification study. This study was done to determine modifications to make the F/A-18 suitable for full-scale AAW technology research. Two wing planforms, the F/A-18 production wing and a preroll modification (PRM) wing, were evaluated. The AAW testbed design study of the F/A-18 evaluated several combinations of control surface usage and effectiveness on both the PRM and production wings. A goal of the study was to find the best flight combination of control surface usage and associated modification costs. New actuation techniques were also identified for the leading- and trailing-edge outboard surfaces. For both the pre- and post-roll modification (roll mod)-wings, control surface usage strategies evaluated included employment of trailing-edge surfaces activated independently and symmetrical leading-edge control surface activation, as well as asymmetric leading-edge activation.

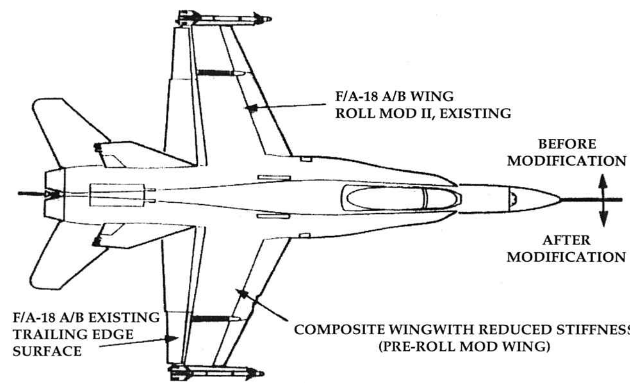

Fig. 2 F/A-18 AAW modification concept.

The study evaluated a fourth combination for the PRM wing in which both trailing-edge surfaces were activated independently with outboard leading-edge surfaces activated asymmetrically and inboard leading-edge control surfaces fixed. In this case, the span for the outboard aileron was increased to that of the production wing. Figure 2 shows this modification option using the PRM wing and the existing F/A-18 trailing-edge outboard control surface. Static aeroelastic control effectiveness analyses and flight tests conducted on the F/A-18 PRM wing together showed that an F/A-18 modified with a PRM wing could serve effectively as a testbed for an AAW flight research experiment.

Flight Research Program

Following cost feasibility studies, the flight research program was initiated to flight test some of the key aspects of AAW technology. Goals of the initiative are to develop full-scale flight data that demonstrate and measure the physics of AAW in a low-cost, effective manner. The flight research program will evaluate the concept in full scale, measure its physics on a crewed supersonic flight vehicle, and provide benchmark design criteria as guidance for future aircraft designs.

Full-scale flight testing of AAW technology must be conducted to evaluate the effects of full-scale Reynolds numbers, Mach numbers, angles of attack, and elevated aircraft maneuver accelerations. The flight test will also be conducted using an active aeroelastic wing with representative wing stiffness, wing aeroelastic hysteresis, actuation responses, and actuation hysteresis and lags.

The program will be conducted to establish guidelines for the designer's toolbox. It is a government-led contracted effort, responsible for determining the flight-test requirements, aircraft modification, and flight research to mature the AAW concept.

Joint U.S. Air Force/NASA/Industry Program

The AAW flight research program is a joint U.S. Air Force/NASA flight research program using the integrated product and process development approach. An integrated product team consisting of personnel from the U.S. Air Force Research Laboratory Air Vehicles Directorate, NASA Dryden Flight Research Center, NASA Langley Research Center, and the contractor have been assembled to perform the program.

In early 1996, a program research and development announcement initiating the program was released by the U.S. Air Force's Wright Laboratory. An airframe team of McDonnell Douglas (MDA) and Boeing North American was selected to conduct the design, modification, and flight research testing of a modified AAW F/A-18. Subsequently, Boeing acquired MDA, and the contractor team is now consolidated into one company, The Boeing Company Phantom Works. The aircraft wings selected for modification come from the NASA F/A-18 formerly operated as the High Angle-of-Attack Research Vehicle, shown in Fig. 3. These wings will be modified and then reinstalled on an F/A-18 fuselage. Under subcontract, Moog was selected to develop an outboard leading-edge flap drive system for the testbed and Lockheed Martin Control Systems was selected to develop the flight control computer.

Fig. 3 AAW technology F/A-18 testbed prior to modification.

The aircraft design/modification effort began in August 1996. Preliminary design was completed in late 1997. Completion of the modification is scheduled in late 1999. Ground and flight tests follow and are scheduled to be complete in mid-2001. Briefings to industry and an AAW symposium are planned to follow flight testing. The tasks outlined for the AAW flight research program are as follows: task 1, concept/preliminary flight planning; task 2, structural analysis and development, and AAW flight control law development; task 3, fabrication/modification, and delivery; task 4, ground tests; task 5, flight tests; and task 6, ground/flight-test data reduction and correlation, technology transition and future aircraft design guidance.

Research Objectives

A set of prioritized, research objectives were established jointly by the AAW team. The research objectives were categorized in three levels with the highest level as priority 1. The priority 1 objectives were defined as significant to the fulfillment of information needed for the future employment of AAW technology. These objectives are to 1) demonstrate that AAW technology can be safely implemented and evaluated including the safe transition between research control laws and reversion control laws; 2) evaluate the weight savings of AAW technology with the F/A-18A as the benchmark; 3) evaluate the wing hysteresis effects of AAW technology as implemented on the F/A-18A; 4) determine the static and dynamic high acceleration effects of AAW technology; 5) evaluate, if present, the effect of any unusual elastic coupling; 6) correlate flight-test data with static and dynamic predictions; 7) evaluate time-dependent internal loads; 8) correlate between flight-test data and predicted values of loads and aircraft stability and control; 9) evaluate the ability of AAW technology to implement maneuver load control; 10) evaluate the control improvements provided by AAW technology; and 11) evaluate control system stability (open- and closed-loop flight control system characteristics).

Testbed Modifications

F/A-18 test-bed modification[8] consists of modification to the wing skins, the addition of a wing leading-edge flap drive system, flight computer modifications, development of a set of AAW research flight control laws, and the addition of test instrumentation. Test instrumentation will include aircraft rate and control surface position sensors, a wing deflection measurement system, and strain gauges and accelerometers located at critical places throughout the aircraft.

The wing stiffness characteristics of an F/A-18 preproduction aircraft will be modified to a stiffness level suitable for demonstration of AAW technology. This will be accomplished by replacing the current set of stiffened aft upper and lower wing cover panels with a more flexible set, as shown in Fig. 4. The current panels are made of solid composite skin. The location and corresponding thickness of each graphite–epoxy panel currently in use is shown in the top set of data in Fig. 4. The new panels will be constructed of thinner composite skins with honeycomb substructure. The location and thickness of each new aluminum panel is shown in the bottom set of data in Fig. 4. These new panels will return the wing stiffness to the F/A-18 original prototype (PRM) wing stiffness level. Figure 5 shows the AAW F/A-18 wings during the modification. The areas where panels have been removed are the locations of the aft wing panels. The mass (and weight) of the aft spar material associated with the original modification from PRM to roll mod will not be removed.

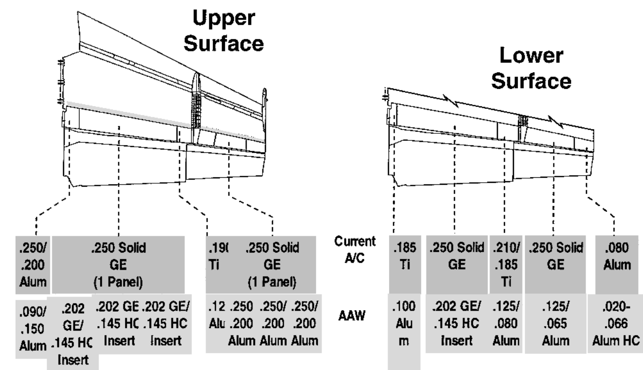

Fig. 4 AAW wing stiffness modification.

Fig. 5 Wing modification/leading-edge flap drive location.

The leading-edge flap drive system will be modified to permit the portion of the flap outboard of the wing fold to operate independently as a maneuvering control surface. New actuation capability to enable the leading-edge outboard control surfaces to deflect independently of the inboard surfaces will be installed. The outboard surface torque tube/transmission assembly will be decoupled from the inboard torque tube/transmission assembly in the wing leading edges. Two new independent hydraulic drive units, utilizing fixed displacement motors, will be installed to drive the outboard transmissions independently. The outboard power drive unit and associated control units will be mounted just forward of the front spar and just inboard of the outboard transmission, as shown in Fig. 5. Inboard actuation rate will remain at 15 deg/s, the outboard rate will increase to a nominal rate of 45 deg/s. Control surface travel limits will also be modified. Leading-edge outboard travel limits will be modified from -34 deg down and $+3$ deg up, to -34 deg down and $+10$ deg up. Leading-edge inboard travel limits will be modified from -34 deg down and $+3$ deg up, to approximately -34 deg down and $+5$ deg up.

A set of AAW flight control laws will be developed for approximately 20 transonic and supersonic test points. The control law point designs will be coded into an upgraded 68040-flight control computer that will replace the aircraft's current 1750A computer. The advantage of the existing digital flight control architecture on the testbed aircraft is its ability to provide flexibility at lower risk because the F/A-18's baseline 701E flight control computer is operated in parallel, as shown in Fig. 6. The baseline computer retains all input and output signal management. When engaged, actuator commands computed by the AAW flight control computer replace the aircraft's baseline flight control computer. When disengaged due

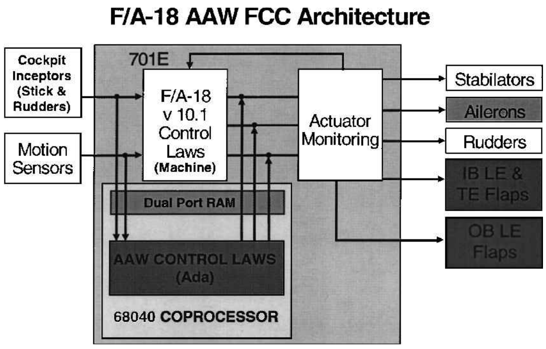

Fig. 6 Flight control computer parallel hardware path.

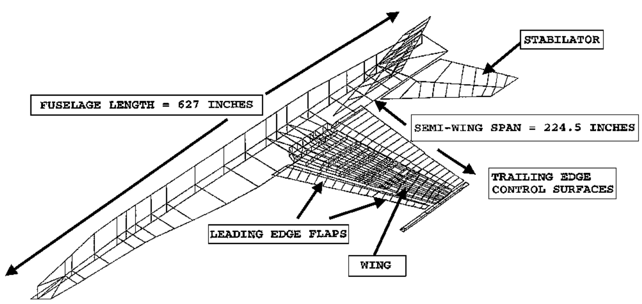

Fig. 7 AAW F/A-18 FEM.

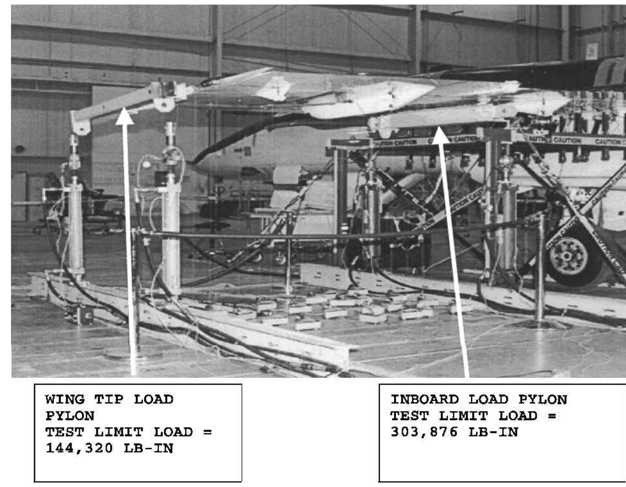

Fig. 8 AAW F/A-18 wing stiffness test.

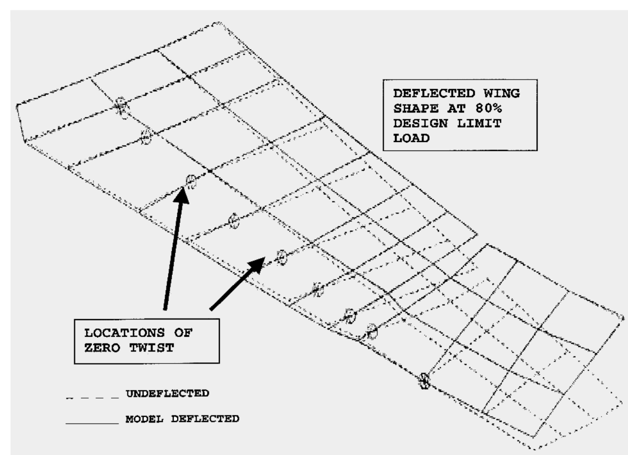

Fig. 9 Wing stiffness/AAW FEM prediction comparison.

to aircraft or system fault, transition logic reverts flight control back to the baseline flight control computer and the baseline F/A-18 flight control laws.

Structural Development and Analysis

As part of the design process, The Boeing Company has developed corrections to baseline F/A-18 databases for aerodynamics, structures, and controls models to account for the increase in wing flexibility. These include flex-to-rigid corrections to F/A-18 aerodynamic databases, aeroelastic loads databases, and to the wing structure developed for the AAW F/A-18 finite element model (FEM). The FEM developed for the AAW program was developed for use in the structural analysis tool MSCNASTRAN. The model was derived from geometry and stiffness properties obtained from Boeing's F/A-18 detailed stress model and mass properties obtained from the F/A-18 beam rod flutter model. The model, shown in Fig. 7, consists of approximately 3000 degrees of freedom and models the wing using primarily rod, shear, and composite quadrilateral elements. Final correlation between model predictions and wing stiffness test and ground vibration test data was accomplished through minor adjustments to the bending and torsional stiffness distributions.

In late 1996 at NASA Dryden Flight Research Center, a wing stiffness test was conducted on the F/A-18 testbed aircraft to accurately determine the wing's flexibility characteristics. The aircraft is shown undergoing wing deflection testing in Fig. 8. For this test, the aircraft was supported at the main landing gear trunnions and at the arresting hook by support fixtures. Test fixtures were installed at two spanwise locations on the left wing. Fixtures were installed at the outboard pylon attachment points and at the wing tip so that vertical loads could be applied in both directions. Test loads, simulating up to 90% of design limit load, were applied via hydraulic cylinders to the load fixtures, and deflection data were measured using high-resolution digital dial gauges. Wing deflection data were taken at 12 spanwise and 4 chordwise locations. The deflection data generated were considered to be accurate and showed no evidence of free play. The data did show a significant wing hysteresis loop and some load stiffening. The reduced test data were used to compare with analytical results from the FEM developed specifically for this program. Figure 9 shows the FEM profile before loads are applied and two deflected wing profiles. One deflection profile shows the wing deflected due to test loads, and the second shows the wing FEM deflected by theoretical loads. Circles and asterisks denote locations where there is no deflection or twist on the respective profiles. Comparison between test and theoretical profiles shows very close agreement. Figure 10 shows a comparison of flexibility for three different wing stiffness cases. The differences between deflections of front and rear spars (delta deflection) are plotted vs wing spanwise stations for each wing case. The baseline data show the spanwise stiffness test results for the baseline F/A-18 wing. The panels off data show the spanwise stiffness test results for the baseline F/A-18 wing with the aft box panels removed. The AAW panels data show the projected spanwise stiffness for the F/A-18 wing modified with more flexible aft skin panels. Figure 10 shows the AAW wing is approximately 17% more flexible than the baseline wing.

The FEM was also used to conduct flutter analyses. The analyses projected flutter velocities to be outside the AAW F/A-18 testbed envelope with margins exceeding 15%. This compared favorably with previous reported flight results from F/A-18 preproduction flight testing.

Figures 11 and 12 show the results of roll control effectiveness analyses using linear aerodynamics for various control surfaces including the leading-edge flaps, the trailing-edge flap, and the aileron. Figure 11 shows control effectiveness analyses for Mach 0.85 and 0.95 at 5,000, 10,000, and 15,000 ft. Figure 12 shows control effectiveness analysis for Mach 1.1 and 1.2 from 10,000 to 20,000 ft. Figures 11 and 12 show the leading-edge surfaces on the AAW F/A-18 become effective at Mach numbers greater than 0.95. The aileron is somewhat effective at lower Mach numbers and shows reversal occurring from about Mach 0.9 to 1.05.

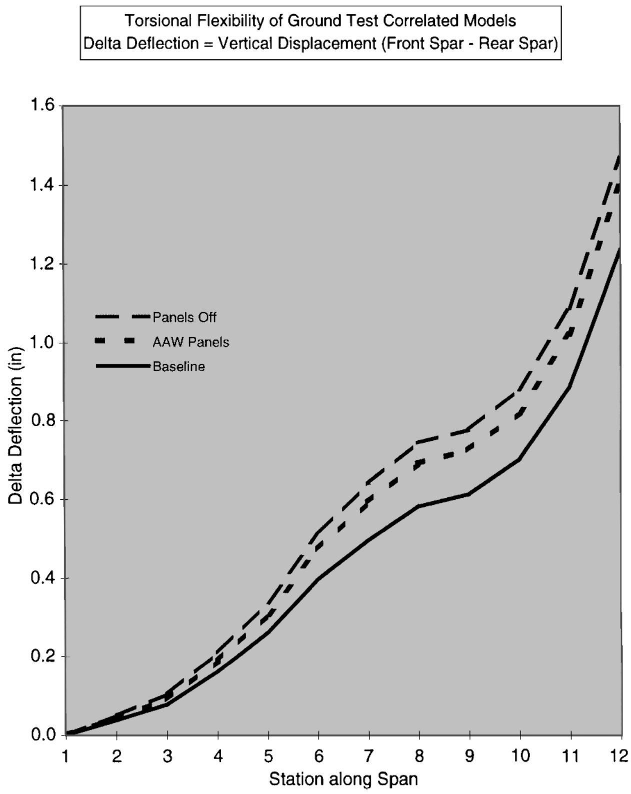

Fig. 10 Wing flexibility comparison: AAW testbed vs baseline F/A-18.

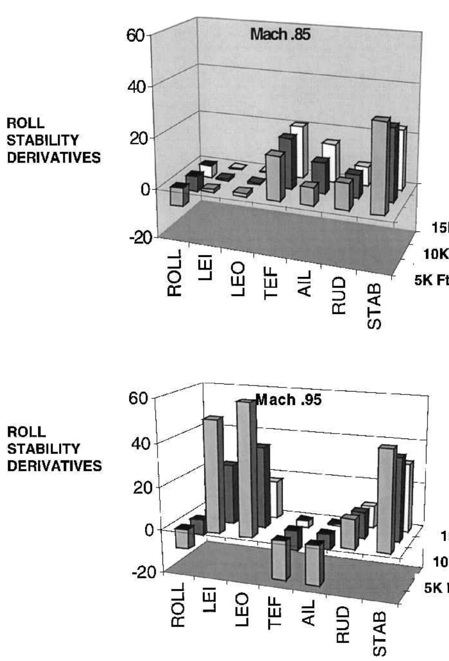

Fig. 11 Predicted roll control effectiveness using linear subsonic aerodynamics (5000–15,000 ft).

AAW Flight Control Law Development Approach

The Boeing Company has developed a set of AAW control laws for flight research evaluation. The control laws were developed using the integrated structure maneuver design (ISMD)[9,10] procedure and MATLAB®. ISMD is an analysis tool that determines optimized control surface trim settings and corresponding wing net external loads to minimize structural weight, aerodynamic drag, and maneuver loads. The ISMD optimization problem satisfies the quasi-static equations of motion for the pitch, lift, and roll axis. These quasi-static equations are represented as equality constraints. Structural

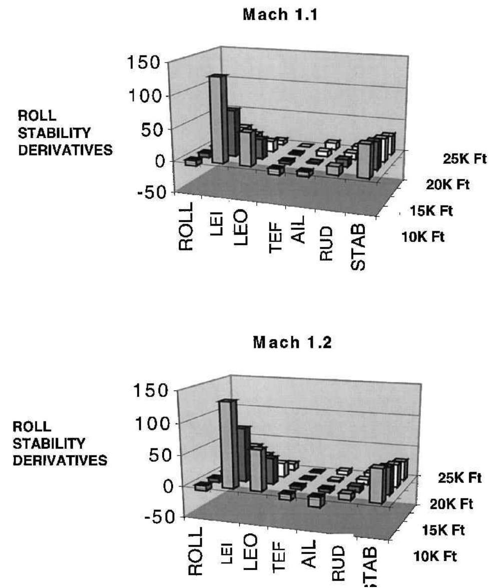

Fig. 12 Predicted roll control effectiveness using linear supersonic aerodynamics (10,000–25,000 ft).

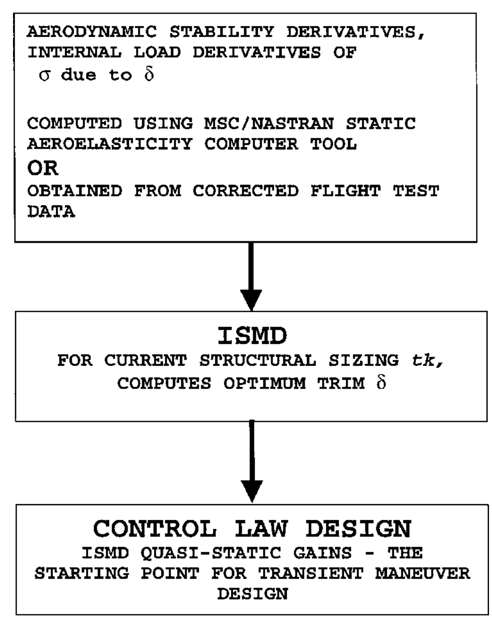

Fig. 13 AAW optimization process for an existing Aircraft.

load limits are represented as inequality constraints to the optimization problem. The ISMD optimization procedure uses these mathematical equations for the optimization algorithm. The objective function is a cumulative summation of induced drag and structural internal loads and is given by Eq. (1) and the matrix of equations (2) (to follow).

Figure 13 shows the optimization process for the AAW testbed aircraft. Aerodynamic stability derivatives and internal load derivatives can be determined from previous F/A-18 flight test database or from using NASTRAN and the FEM shown in Fig. 7. ISMD uses the aerodynamic stability derivatives and internal load derivatives to compute optimal trim settings:

$$\sum_{i=1}^{n\,\text{case}} WD^i \times D^i + WS^i \times (\sigma^i + B^i) \tag{1}$$

where

n case = total number of maneuever conditions
WD^i = weighting factor to be applied to drag coefficient D formaneuver i

WS^i = weighting factor to be applied to stress and buckling$(\sigma^i + B^i)$ for maneuver i

The variables on the right-hand side of the equations are the control surface deflections and twist and camber shape. The constraints shown in the matrix of equations (3) are trim equilibrium for all maneuvers where total lift, pitch, and roll are satisfied:

$$\begin{Bmatrix} D^1 \\ \sigma^1 \\ B^1 \\ D^2 \\ \sigma^2 \\ B^2 \\ D^i \\ \sigma^i \\ B^i \end{Bmatrix} = \begin{bmatrix} D^1\delta_j^1 & 0 & 0 & D^1 t \text{ and } c \\ \sigma^1\delta_j^1 & 0 & 0 & \sigma^1 t \text{ and } c \\ B^1\delta_j^1 & 0 & 0 & B^1 t \text{ and } c \\ 0 & D^2\delta_j^2 & 0 & D^2 t \text{ and } c \\ 0 & \sigma^2\delta_j^2 & 0 & \sigma^2 t \text{ and } c \\ 0 & B^2\delta_j^2 & 0 & B^2 t \text{ and } c \\ 0 & 0 & D^i\delta_j^i & D^i t \text{ and } c \\ 0 & 0 & \sigma^i\delta_j^i & \sigma^i t \text{ and } c \\ 0 & 0 & B^i\delta_j^i & B^i t \text{ and } c \end{bmatrix} \times \begin{Bmatrix} \delta_j^1 \\ \delta_j^2 \\ \delta_j^i \\ t \text{ and } c \end{Bmatrix} \qquad (2)$$

satisfied the constraints

$$\begin{Bmatrix} L^1 \\ M^1 \\ 1^1 \\ L^2 \\ M^2 \\ 1^2 \\ L^3 \\ M^3 \\ 1^i \end{Bmatrix} = \begin{bmatrix} L^1\delta_j^1 & 0 & 0 & L^1 t \text{ and } c \\ M^1\delta_j^1 & 0 & 0 & M^1 t \text{ and } c \\ 1^1\delta_j^1 & 0 & 0 & 1^1 t \text{ and } c \\ 0 & L^2\delta_j^2 & 0 & L^2 t \text{ and } c \\ 0 & M^2\delta_j^2 & 0 & M^2 t \text{ and } c \\ 0 & 1^2\delta_j^2 & 0 & 1^2 t \text{ and } c \\ 0 & 0 & L^i\delta_j^i & L^i t \text{ and } c \\ 0 & 0 & M^i\delta_j^i & M^i t \text{ and } c \\ & & 1^i\delta_j^i & 1^i t \text{ and } c \end{bmatrix} \times \begin{Bmatrix} \delta_j^1 \\ \delta_j^2 \\ \delta_j^i \\ t \text{ and } c \end{Bmatrix} \qquad (3)$$

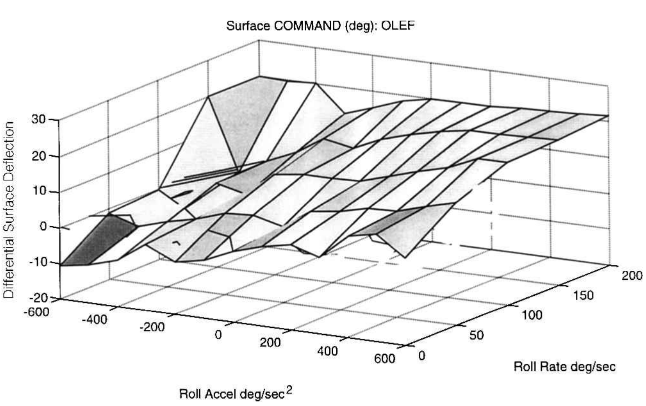

Fig. 14 Leading-edge outboard surface deflection as a function of roll rate and roll acceleration at Mach 1.2, 15,000 ft.

The control surface trim results obtained from ISMD are used to guide the development of a set of AAW flight control law gains. MATLAB is used to produce surface plots of the ISMD generated optimal trims. The ISMD trims are plotted in three dimensions in terms of roll rate, roll acceleration, and deflection. Figure 14 shows the surface plot for a case at Mach 1.2, 15,000 ft for the leading-edge differential command, where sign convention is Left-Right and units are in degrees. Figure 15 shows the surface plot for a case at Mach 1.2, 15,000 ft for the trailing-edge inboard differential command.

To achieve constant gains, a best-fit flat plate is fit to the surface plot data to give a smooth slope and capture first-order AAW effects. The slopes of each surface constitute the AAW gains. The constant gains are appended into closed-loop flight control architecture and constitute gearing functions that command the control surfaces to optimum positions as a function of Mach number and dynamic pressure. The constant gain approach was selected to minimize control law complexity and to obtain the best possible flying qualities. The gearing functions represent the optimal distribution of rolling, pitching, and lift forces and moments to the aircraft control surfaces.

The AAW flight control laws are designed to command all eight F/A-18 wing control surfaces to twist the wing aeroelastically at high dynamic pressures into optimal shapes for generating wing control power. Lateral directional flight control laws govern the roll mode of the aircraft and provide maximum roll rate sufficient to satisfy the research goals of the AAW program. The control laws also command load factor Nz in the longitudinal axis and control the short-period motion of the aircraft. Disengage logic will be incorporated to revert the flight control system to the baseline control laws if the aircraft deviates from specified flight conditions, side-slip limits, or load allowables, or by prescribed amounts determined during simulation. A manual pilot disengage feature will also be present.

Performance metrics for the control laws are straight forward. Roll authority will be attained using the wing and its control surfaces. The horizontal stabilator will not be differentially commanded. The AAW control laws are designed to produce roll rates and flying qualities similar to the current F/A-18, including maximum rolling rates. In terms of safety, the control laws must not permit the aircraft to exceed any structural load limits under normal operations, or during reversions to the baseline flight control laws. MIL-SPEC 9490 specifications requiring 6-dB gain and 45-deg phase margins are used as guidelines for determining stability with respect to uncertainties.

Results

By the use of the described design process, control law gains were generated for each flight-test point using flight-test corrected aerodynamic stability and internal load derivatives. Linear aircraft models combined with the flight control laws were evaluated against the stability requirements. The requirements were satisfied at all planned flight conditions.

Figure 16 shows a simulation time history of a roll doublet using AAW control laws with the linear aircraft model at Mach 1.2, 15,000 ft. Figure 16 shows the AAW F/A-18's leading-edge

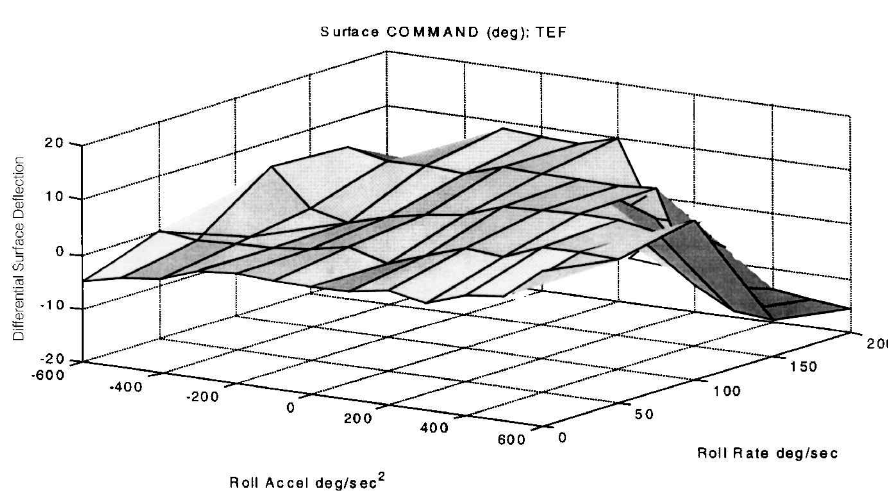

Fig. 15 Trailing-edge inboard surface deflection as a function of roll rate and roll acceleration at Mach 1.2, 15,000 ft.

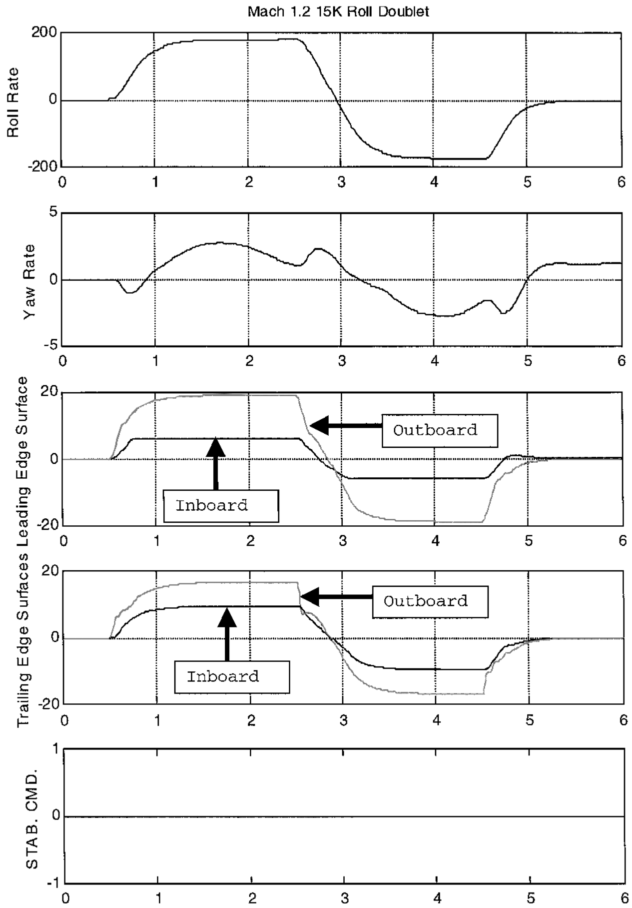

Fig. 16 Roll simulation time histories due to doublet input at Mach 1.2, 15,000 ft.

outboard control surfaces moving to 20-deg differential, the inboard leading-edges moving to 6-deg differential, the trailing-edge inboard surfaces moving to 10-deg differential, and the trailing-edge outboard surfaces moving to 18-deg differential. These control surface deflections result in an aircraft roll rate just below 200 deg/s with no roll input by the horizontal stabilizer. During the design phase, gains were generated for all planned flight-test points and similar simulations were conducted.

Ground Tests

Following modification, the aircraft wings with the AAW leading-edge flap drive system installed, and modified flight control computers will be shipped from The Boeing Company Phantom Works to NASA Dryden Flight Research Center. Following wing reinstallation on the fuselage at NASA Dryden Flight Research Center, a battery of ground tests will be performed. These include a postmodification stiffness test, a ground vibration test, and an aero-servo-elastic interaction test. Hardware-in-the-loop simulation tests and load calibration tests will also be performed.

Following comparison between ground and analytical model development results, the AAW control laws will be updated to reflect the actual aircraft test responses. The updated AAW control laws will then undergo final simulation evaluation. NASA Dryden Flight Research Center will conduct a verification and validation of the AAW control system prior to flight readiness review.

Flight-Test Approach

Key technical issues, important in the understanding and validation of AAW technology, involve a wide variety of structural, aerodynamic, and flight control parameters. The flight research program will strive to address and characterize as many of the flight research issues as practical. The key issues are embodied in the program research objectives. These have been prioritized based on their difficulty as a flight research topic, their importance in design applications, their risk in a flight research environment, and their cost.

Aerodynamic issues to be characterized include full-scale Reynolds and Mach number effects, especially with respect to shock movement due to dynamic aeroelastic motion. The effects of high angle-of-attack flow separation, especially when the wing is near stall, will need to be measured. In addition, flight-test aerodynamic data will need to be correlated with available wind-tunnel and aerodynamic performance predictions.

Among the structural characteristics to be evaluated are the wing's time-dependent aeroelastic twist and bending responses and associated strain fields due to aerodynamic forces, control forces, and high gravitational acceleration maneuvers. Wing aeroelastic characteristics need to be compared with aeroelastic predictions. Wing twist hysteresis will be assessed. The effects of elastic mode coupling with flight control rigid-body control responses must be minimized.

Aircraft maneuvering performance in terms of roll, yaw, and pitch rate must be measured as well as the flight control system (FCS) open- and closed-loop characteristics, especially as they change at high dynamic pressures. An estimation of acceleration and time lags present in the FCS due to AAW dynamic control inputs must be made. Flight control rigid-body coupling response also will need to be evaluated. Finally, force and deflection frequency responses for each control surface will need to be measured and all FCS flight parameters need to be compared with ground measurements for improved simulation modeling. These FCS-modeling issues must all be addressed prior to application of AAW to a new configuration. This flight research program will provide the vital experimental flight response benchmarks for comparison with analyses.

AAW technology flight testing will commence in three general phases to ensure a safe, thorough evaluation that addresses the research objectives. Phase I includes first flight and functional test flights. These flights will verify the baseline control law's ability to fly the aircraft. The functional flights will also ensure all aircraft systems and instrumentation systems are functioning. During phase I, a failure mode evaluation will be conducted to verify that sufficient control power exists to fly the F/A-18 at approach speeds with one leading-edge outboard control surface failed while deflected up. Results of this evaluation may (but are not likely to) result in a limit imposed on leading-edge control deflection limits. Phase II includes flight control computer reversion test flights and test envelope expansion. During test envelope expansion, AAW systems failure will be checked out, and initial parameter identification flights will be conducted. Phase III will demonstrate the ability of the AAW flight control laws to maneuver the aircraft.

Flight testing will be accomplished using an integrated test block approach. Each integrated test block consists of partial and full stick deflection reversion checks accompanied by a battery of 1 g, 15-, 30-, 45-, 90-, 360-, and 390-deg rolls. Lateral characteristics at elevated gravitational acceleration and angle-of-attack conditions will be evaluated through rolling pull out consisting of 2, 3, and 4 g turns with a 180-deg roll.

Parameter identification (PID) flights, envelope expansion flights, and reversion flights are all part of phase II flight testing. Flight control reversion tests will be incorporated into each integrated test block to verify safe reversion to the baseline computer without unwanted transients. Reversion tests will be accomplished for each control law update and for flight conditions below and above aileron reversal. Envelope expansion tests will verify previously cleared loads and aero-servo-elastic margins using an onboard excitation system. PID flights will be used to confirm analytical models used to develop initial AAW control laws. During PID flights, each flight control surface will be excited by the AAW onboard excitation system using sinusoidal sweeps from 0 up to 50 Hz. Transfer functions obtained from these sweeps will be compared with those obtained from simulation results to verify the aerodynamic database.

Phase III will demonstrate the ability of the active aeroelastic wing to provide large amounts of control while minimizing loads during maneuvers. Initial flights will test AAW control laws developed in the design phase. These flights will be flown at a set of transonic and supersonic flight conditions. Figure 17 shows the

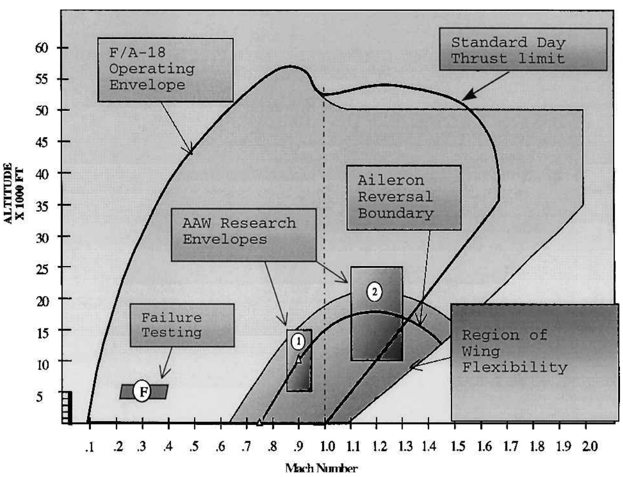

Fig. 17 AAW testbed operating envelope.

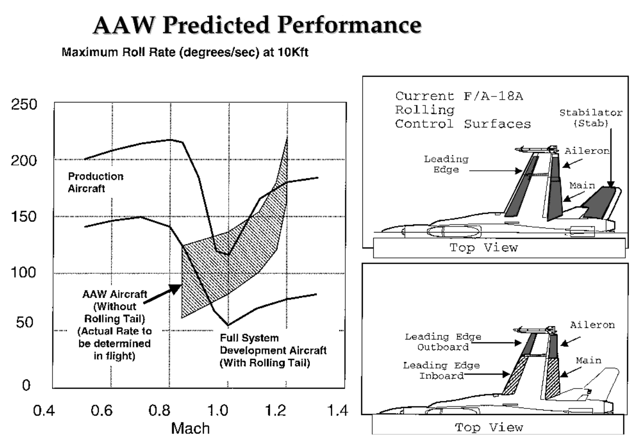

Fig. 18 Predicted AAW performance compared with baseline F/A-18 performance using linear aerodynamics (10,000 ft).

F/A-18 flight envelope with the AAW transonic and supersonic test envelopes marked by boxes. The box marked F denoted the range where functional flights will be used to check the ability of the aircraft to be controlled with the leading-edge outboard control surface stuck at 10 deg. Within box 1, 12 transonic test points exist at Mach 0.85, 0.9, and 0.95 at four altitudes. Within box 2, nine supersonic test points exist at Mach 1.1, 1.2, and 1.3 at three altitudes. Following evaluation, the AAW control laws will be updated to increase leading-edge outboard control surface deflection limits and usage and flown again.

Predicted Flight-Test Results

Results from the flight testing are expected to show the AAW testbed aircraft can roll at rates near current F/A-18 roll rates, but using wing control power alone without the use of the horizontal tail. Handling qualities have been shown in manned simulation to be comparable to those of the current F/A-18. Control surface usage and deflection amplitudes will be limited to show current F/A-18 performance levels and handling qualities.

Current predictions, shown in Fig. 18, project AAW roll rates at 10,000-ft mean sea level, which are similar to those the F/A-18 A-B baseline aircraft attained. Three sets of data are shown. The lowest set of roll rates were those the PRM (FSD) aircraft attained during flight tests. The FSD F/A-18 used the differential stabilator and both trailing-edge surfaces to roll the aircraft. The second set of roll rates are those attained by the current F/A-18 A/B aircraft. The F/A-18 A/B uses the entire wing leading edge, both trailing-edge control surfaces, and differential stabilator. The third set is the predicted AAW roll rates. These roll rates are indicated by a cross-hatched region due to uncertainty in the aerodynamic and loads for the modified aircraft. The analysis used to predict AAW roll rates used all wing leading- and trailing-edge control surfaces, no differential tail. Actual roll rates will be determined during the flight program.

Conclusions

AAW technology is a multidisciplinary, synergistic technology that integrates air vehicle aerodynamics, active controls, and structures advanced technology together to maximize air vehicle performance. The technology uses wing aeroelastic flexibility for a net benefit and takes advantage of high aspect ratio, thin, swept fighter wings that are aeroelastically deformed into shapes for optimum performance. Application of the technology in design studies has shown significant weight and performance benefits and is considered by the authors as the next step in the evolution of wing design.

This paper describes a flight research program initiative to test key aspects of AAW technology on an F/A-18 testbed. In the early 21st century, the technology will be developed and tested during this full-scale flight research program. This program began in late 1996. Flight data from the project should be available to the aircraft design community in mid-2001.

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