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Mission Adaptive Wing System for Tactical Aircraft

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The aerodynamic cruise efficiency of the supercritical airfoil in the transonic range is well known. Adaptation of this technology to a multirole tactical aircraft system requiring Mach 2+ maximum speed and 7+ *g* maneuver capability is enhanced by airfoil modification capabilities. This paper describes the hardware design and development of a mission adaptive wing system utilizing smooth, variable camber leading- and trailing-edge mechanisms to optimize wing airfoil camber for all flight conditions. Development included design and manufacture of a full-scale wing test component to demonstrate system capability and reliability.

Introduction

DEVELOPING a mission adaptive wing (MAW) system was the object of a General Dynamics funded effort that led to a proposal to the U.S. Air Force to equip an F-111A supercritical wing test aircraft with MAW capability. This paper describes the hardware design and development leading to that proposal.

Definition

A "mission adaptive wing" is defined as a wing having the ability to actively modify airfoil camber, spanwise camber distribution, and wing sweep in flight, while maintaining a smooth and continuous airfoil surface. This ability produces a near-optimum wing configuration for the entire flight spectrum as well as providing control function performance.

Features of a MAW include:

1) Variable camber: L/D optimization (decamber supercritical airfoil for efficient supersonic flight).

2) Roll control: integral aileron action.

3) Maneuver load control (MLC): spanwise control of the aerodynamic center for wing root moment reduction at high load factors.

4) Direct lift mode (DLM): increased lift without increased angle of attack.

5) Gust load alleviation (GLA): quick response camber variation to avoid gust impulse loads.

The flight envelope of Fig. 1 illustrates several of these MAW features.

Ground Rules and Objectives

The obvious restrictions of a rigid wing-box structure prevents full wing chord contour variation. Therefore, this effort focused on development of leading- and trailing-edge systems to mount on the variable sweep F-111 wing providing mission adaptability.

The objectives in development of the MAW system were:

1) Continuous contour: minimum of spanwise and chordwise joints; surface curvature to be a continuous mathematical function for all deflections.

2) Automatic control: airfoil optimization at all flight conditions through active flight control.

3) Serviceability: low maintenance requirements.

4) Nondedicated system: one system performs all wing control functions.

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Benefits

Aerodynamic benefits afforded by the supercritical airfoil mission adaptive wing include improved drag polar shapes and increased $C_{L_{max}}$ resulting in significant performance gains (139% F-111 high-altitude supersonic mission radius increase is predicted at constant penetration distance). However, a particular benefit of great impact to the hardware design is the effect of maneuver load control (MLC). As illustrated by Fig. 2, the ability to shift the aerodynamic center inboard during pull-up maneuvers results in an increased load factor capability approaching 1 *g* while maintaining a constant maximum wing root moment. The MAW accomplishes this by automatically decreasing airload at the tip (decamber) and simultaneously increasing airload inboard (increased camber).

Many other improvements are available from the MAW features:

1) Terrain following and weapon delivery: vertical maneuvering can be accomplished without change of pitch attitude by direct lift mode.

2) Radar cross section: smooth, continuous contours are desirable for reducing radar cross section.

3) Parasite drag improvement: the presence of slots, gaps, fixed geometry shapes, and misalignment of components generates aerodynamic drag. Maintenance of a smooth continuous contour increases overall aerodynamic efficiency.

Aircraft System Description

The MAW development is baselined for an F-111A test aircraft. The wing surface is continuous and smooth with no discontinuities (with the exception of the transition root section on the trailing edge). Figure 3 illustrates the four variable geometry functions of the wing operation.

The variable sweep feature of the F-111 is automated for the MAW. The leading edge has the capability of uniform spanwise deflection for the forward 20% of the wing chord, −5 deg (up) to +30 deg (down). The glove leading edge deflects to follow the wing. The trailing edge (aft 40% wing chord) has the capability of several deflection modes. Views 3 and 4 in Fig. 3 show the maximum surface spanwise twisted deflection capabilities. The surface is capable of any constant or twisted deflection between −7.5 and +25 deg (5 deg at the surface upper and lower extremes is reserved for roll control). The only limit on twisted deflections is a 1 deg/ft of span maximum twist. Even double-curvature trailing-edge spanwise shapes can be produced, but straight-line twist deflections have been found to be adequate. These deflections can be combined with variable sweep to provide many of the previously mentioned flight system features.

Full deflection of the leading or trailing edge is restricted to less than 28 deg wing sweep. Aileron function is limited to a maximum of 40 deg wing sweep with only the horizontal tail operating beyond 40 deg (similar to the basic F-111).

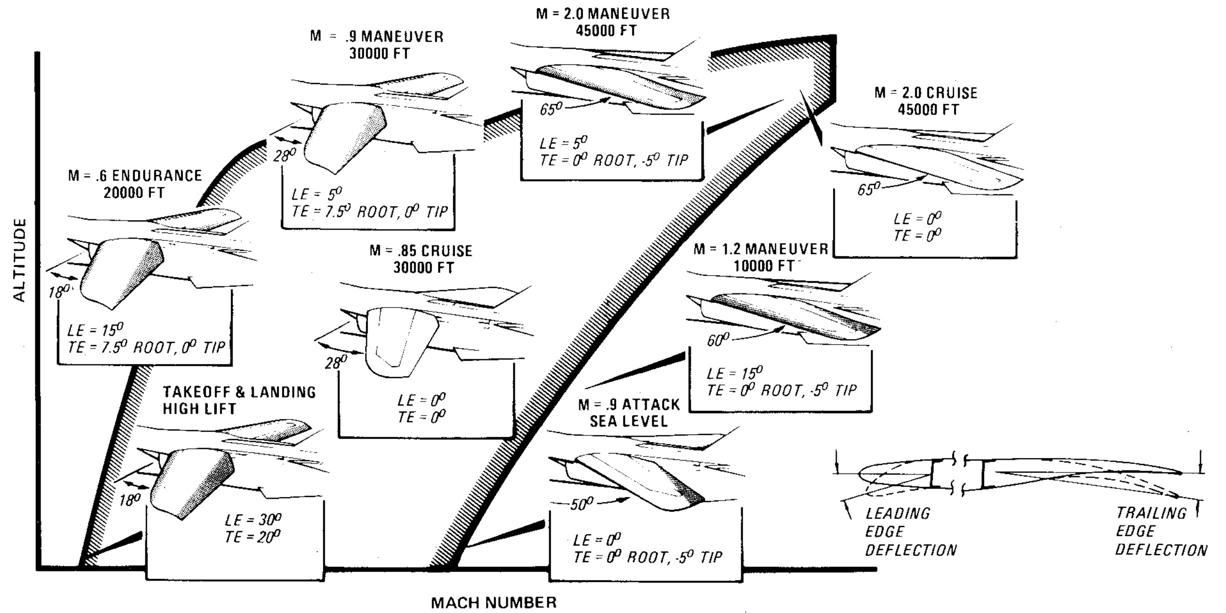

Fig. 1 Mission adaptive wing improves full envelope performance.

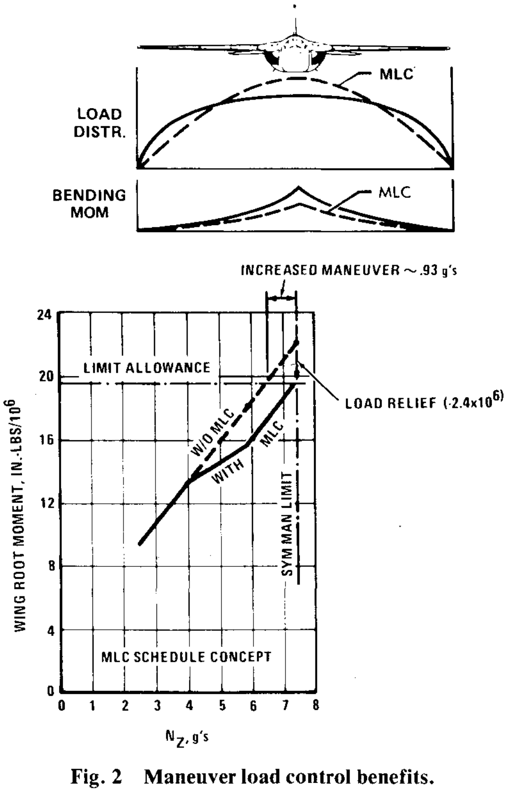

Fig. 2 Maneuver load control benefits.

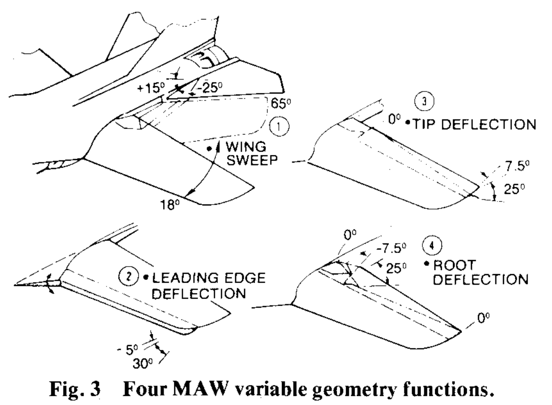

Fig. 3 Four MAW variable geometry functions.

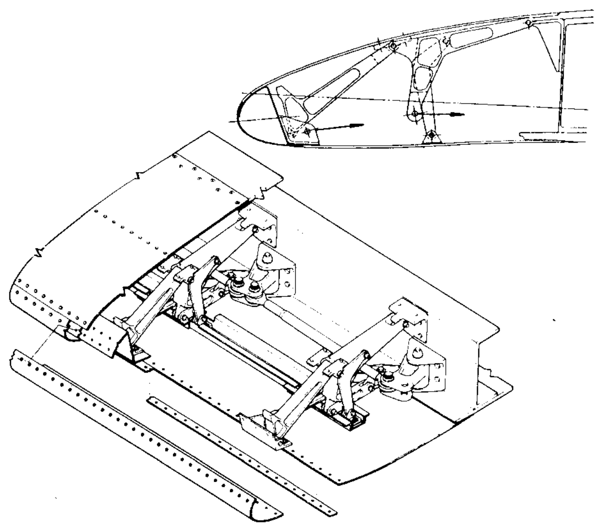

Fig. 4 Leading-edge mechanisms concept.

The variable camber leading-edge concept is shown in Fig. 4. The leading-edge system incorporates seven linkages per wing half-span and is driven by one linear actuator per side. Each control linkage consists of a main drive bellcrank driven by actuator push rods and connected to two control links. One of the control links is connected to and controls the forward bay of the linkage, and the other control link is connected to and controls the aft bay of the linkage. The two-bay linkage system supports a rigid aluminum nose cap and upper and lower flexible skins. The fiberglass skins are designed to permit smooth contour deflection of the leading edge from the supersonic cruise position to the fully deflected high lift position. No sliding joints or gaps exist on the leading-edge nose or upper surface. A faired sliding joint exists on the lower surface at the front spar in a region of positive pressures and minimum velocities. All movable joints and wear surfaces are designed to have permanent lube-type surfaces. With this system, the completed leading-edge assembly is capable of lasting the service life of a production fighter airplane without requiring routine lubrication or maintenance.

The variable camber trailing-edge concept is shown in Fig. 5. Seven mechanisms per wing halfspan are required for the MAW wing. Each mechanism may be driven by its own integrated servo actuator utilizing tandem hydraulic motors and a planetary gear reduction. All 14 actuators (full span) are independently controlled by the flight control computer. Each

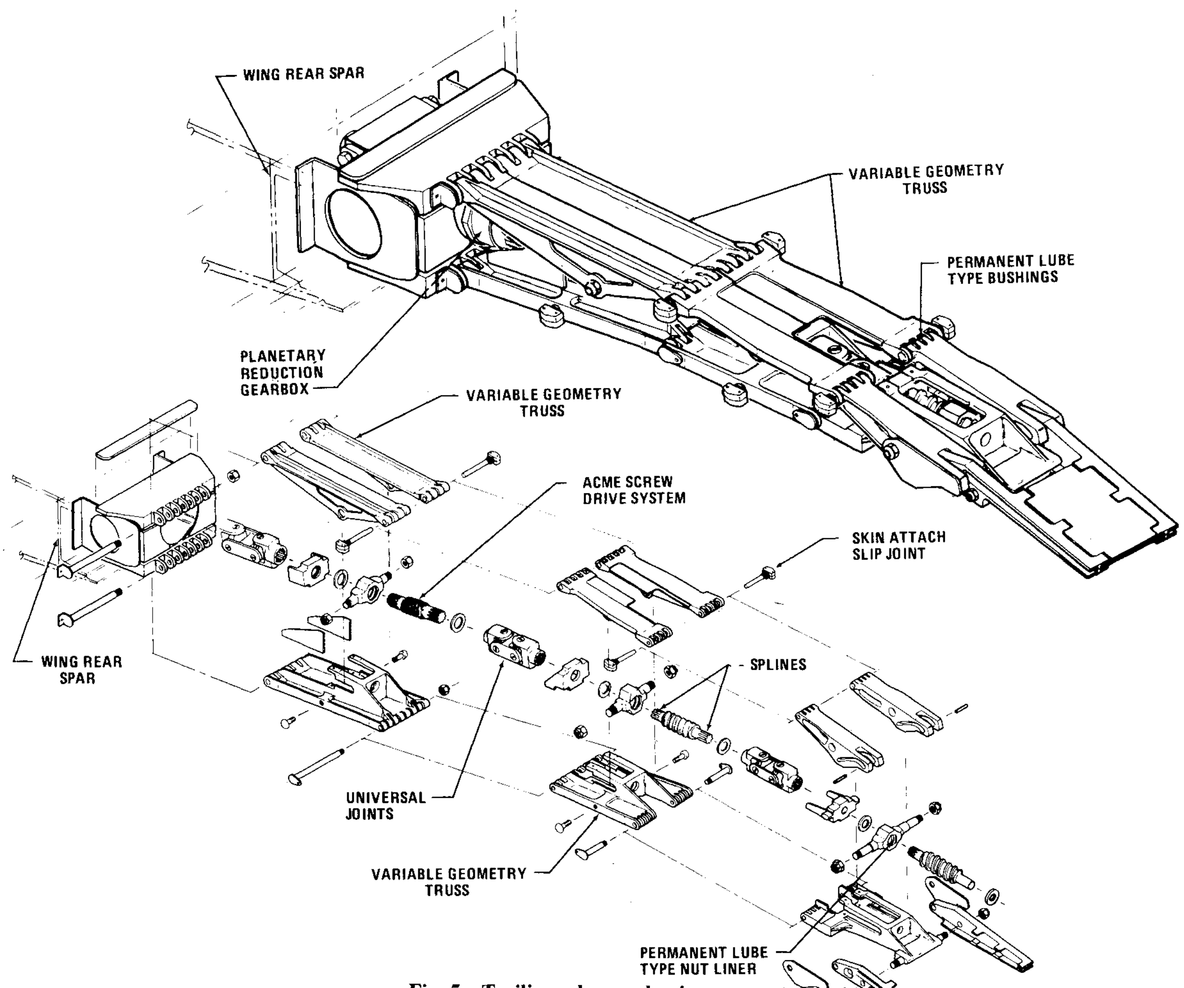

Fig. 5 Trailing-edge mechanism concept.

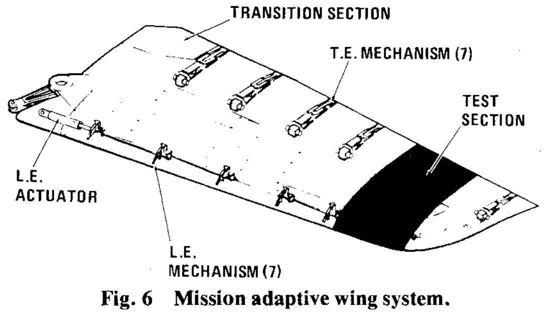

Fig. 6 Mission adaptive wing system.

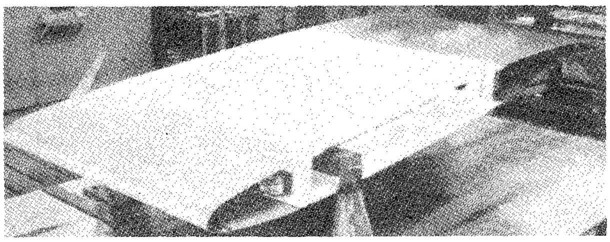

Fig. 7 MAW test component.

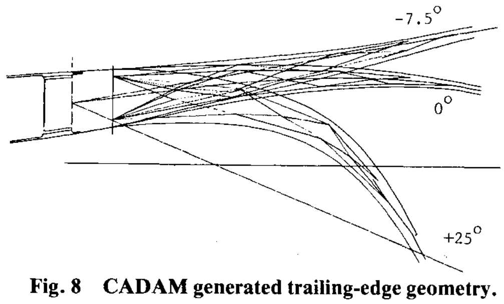

Fig. 8 CADAM generated trailing-edge geometry.

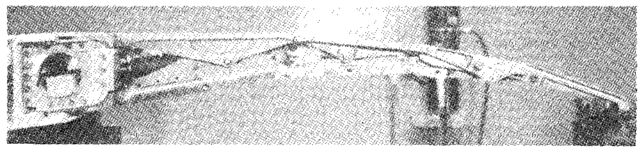

Fig. 9 Trailing-edge mechanism.

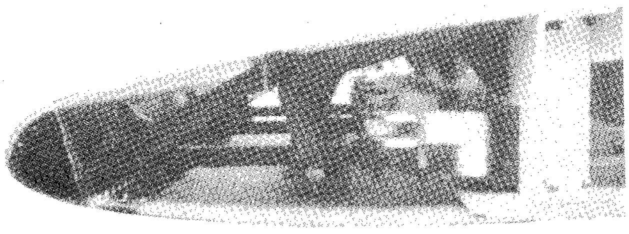

Fig. 10 Leading-edge mechanism.

mechanism is a three-bay variable geometry truss. Each of the three truss bays consists of triangular-shaped upper and lower truss members joined at the centroid of the truss by means of a triple-thread acme screw and nut combined with a slide arrangement. The forward ends of the forward truss bay upper and lower chord members are pivoted off of the rear spar and interconnected to the other bays at pivots adjacent to the skins. Acme screws in each bay of the truss are connected in series. The forward end of the drivelines are connected to the actuators. Screw and nut lead varies in each bay of the truss to produce the desired deflected airfoil camber.

The upper and lower skins are continuous (root to tip) glass-reinforced plastic with no sliding joints on the upper or lower contour. A slip joint is provided at the trailing edge. The skins are supported on spanwise-oriented beams. The ends of the skin support beams are supported at each mechanism control station by means of a slide block and ball joint arrangement. This skin support system allows the skins to pick up only normal air load and local bending (transferring that air load to the spanwise support beams). All movable joints and wear surfaces in the trailing-edge mechanism are designed to have permanent lube-type surfaces. Figure 6 shows the complete mission adaptive wing.

Development of Test Component

An important part of the MAW development was the design and manufacture of a wing section test component. This constant section wing segment was 42 in. in span (located at F-111 wing station 286.0) and full chord, leading edge to trailing edge. The component was designed and constructed full scale to realistic flight loads, material properties, and safety-of-flight requirements. The component included three leading-edge mechanisms and two trailing-edge mechanisms. The relationship of the test component to the AFTI-111 wing is shown in Fig. 6 and the component is shown in Fig. 7.

Structural and Mechanical Design

Mechanism geometry development and kinematic studies were accomplished with the aid of computer-aided design and manufacturing (CADAM) techniques. Figure 8 shows CADAM-generated overlay plots of the trailing-edge geometry. Iterative geometry development resulted in a 1:2:3 ratio of the three screw thread leads, producing the desired mechanism deflection shapes. For high system mechanical efficiency, leads of the trailing-edge drive screws were designed as long as possible consistent with acceptable torque load levels in the driveline. Mechanism geometry, long screw lead, and the effect of actuating along the neutral axis (small amounts of free play at the neutral axis produce large amounts of rotational free play about hinge line) dictated extremely tight dimensional tolerances. Thread tolerances were set at: ± 0.002 on thread lead, $+0.000/-0.002$ on screw thread diameters, and $+0.002/-0.001$ on nut thread diameters. Figure 9 shows the trailing-edge mechanism.

As mentioned earlier, all rotation surfaces were installed with bearings lined with Teflon-impregnated fabroid. This included the drive nuts on the acme thread screws of the trailing edge. These nuts were shipped to a vendor for lining with a material similar to that used in MIL-81934 sleeve bearings.

The leading edge was designed with an all-aluminum structure. The skins were standard aircraft grade woven cloth fiberglass. The material fibers were oriented ± 45 deg to the chord axis to provide maximum chordwise flexibility due to the high curvatures experienced by the leading-edge skins at $+35$ deg (down) deflection. Figure 10 shows the test component leading-edge system.

Due to the large air loads experienced on the 40% chord trailing edge (created by the supercritical airfoil pressure distribution), PH13-8MO H1000 stainless steel (201 ksi F_{t_u}) was required for the trailing-edge mechanisms. As well as possessing good strength and durability properties, this material can be polished to maintain the fine finish (8 rms) required for running surfaces on the fabroid bearings. The trailing-edge skins were designed using the same woven cloth fiberglass as the leading edge but the warp axis was oriented chordwise to provide maximum bending strength for air load beaming.

Structural Analysis

The structure was sized in accordance with material allowables and loads typical of a production fighter. Reduced material properties were used to size elements of the functional demonstration model. The ultimate design allowables reflected a reduction of more than 30% from MIL Handbook 5 properties; and this reduction was expected to preclude fatigue and damage tolerance problems. The reductions were made based on recent experience where durability allowables were calculated for these materials under similar load spectrums. Subsequent analysis would be based on design allowables calculated per MIL-STD-1530, the MIL-A-8860 series specifications, and MIL-A-83444.

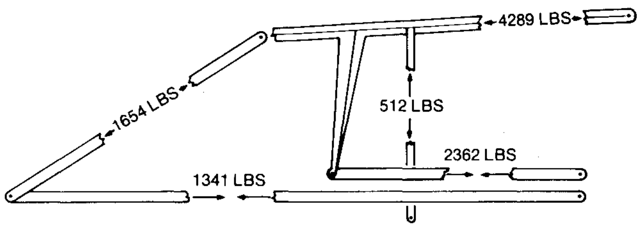

Fig. 11 Leading-edge internal design loads.

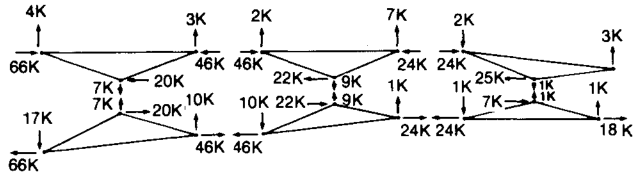

Fig. 12 Trailing-edge internal design loads.

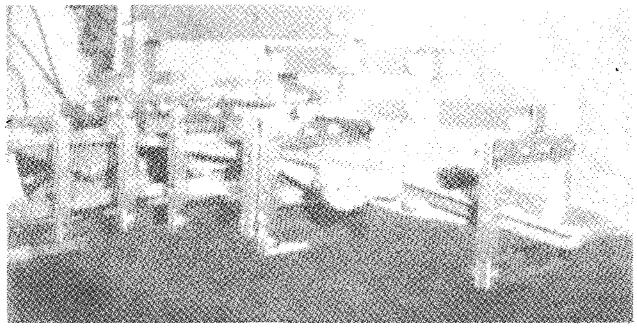
Fig. 13 Trailing-edge mechanism in load fixture.

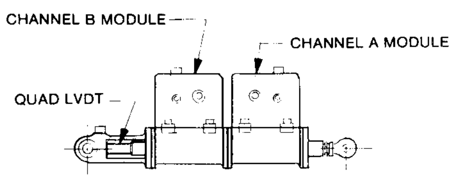

Fig. 14 Leading-edge actuator.

Finite-element models of the leading- and trailing-edge skins were used to obtain stresses induced by imposed deformations. Finite-element modeling was also used to obtain trailing-edge mechanism stiffnesses and internal loads while leading-edge mechanism loads were calculated manually. Figures 11 and 12 illustrate the internal design loads of the leading- and trailing-edge mechanisms.

Both trailing-edge mechanisms from the functional demonstration model were successfully tested to a limit load of 10,305 lb. This load corresponds to a 7.33 g rolling pullout maneuver. Strains, deflections, and actuation torques were measured. Figure 13 shows the trailing-edge mechanism in the load fixture.

Deflections at the trailing edge at limit load were higher than what was calculated for the mechanism, apparently due to deflection of fabroid bearing surfaces. The deflection of the mechanism, based on metal deformation, was calculated to be 1.00 in. at the limit load at the trailing edge. The test measurement for the mechanism was 1.70 in.; however, the deflected shape belonged to the same family of aerodynamic shapes as the calculated one. Actuation torques were lower than the design values by approximately 30% due to conservative estimates of friction coefficients.

Table 1 Flight control system requirements

		Trailing edge (TE)[b]			Leading Edge (LE)		
Flight phase	Mode	Max deflect, deg	Rate, deg/s	Hinge moment, ft-lb	Max deflect, deg/s	Rate, deg/s	Hinge moment, ft-lb
Cruise, maneuver[a]	Roll-MLC	7.2 up	20	19,700-12,800	—	—	—
	Constant camber	6 down	10	19,700-46,900	5 up, 15 down	17	—[c]
	Roll-MLC	5 down	20	22,000-27,000	—	—	—
	Gust alleviation	±2	40	21,700-17,800	—	—	—
Approach	Takeoff and landing-DLM	20 down	2	—[d]	35 down	5	—[c]
	Roll	25 down	20	—[d]	—	—	—

[a] Based on 0.9 Mach at 10,000 ft $\Lambda = 26$ deg.
[b] Differential surface deflections between adjacent trailing-edge mechanisms having 30 in center-to-center separation shall not be in excess of 1.41 deg.
[c] Loads assumed not to be in excess of one-third the TE hinge moments.
[d] Loads considered to be less critical than for cruise condition.

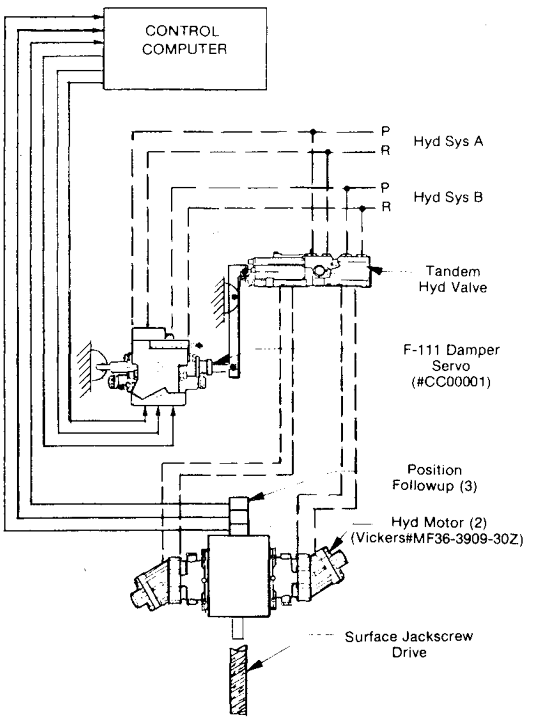

Fig. 15 Trailing-edge actuation system.

Flight Control

Control system concerns in design of the mission adaptive wing system were: space limitations, the suitability of existing state-of-the-art actuator equipment to satisfy performance requirements, and available aircraft hydraulic power. Table 1 presents the basic control system design requirements for the MAW test component.

The leading-edge actuator for the test demonstrator is shown in Fig. 14. One actuator (similar to this but with greater capacity) would be required per wing to actuate bellcranks and linkage to deflect the leading-edge surface. Each actuator operated on an active/standby principle. The actuator normally operated on one hydraulic system unless a failure (either electric or hydraulic) occurred. When the failure was detected by the logic circuitry, the standby channel would be switched into operation.

The actuator is shown with two control modules, one for each channel. These modules contained the actual electrohydraulic servovalve plus the hardware necessary for failure monitoring and redundancy management. Each of the modules was capable of approximately 2 gal/min maximum flow. Each actuator had a 2.4 in. stroke and was capable of 14,000 lb load on each hydraulic system.

The actuator loop was closed electrically in the computer and the overall actuation loop gain gave a bandwidth of 20

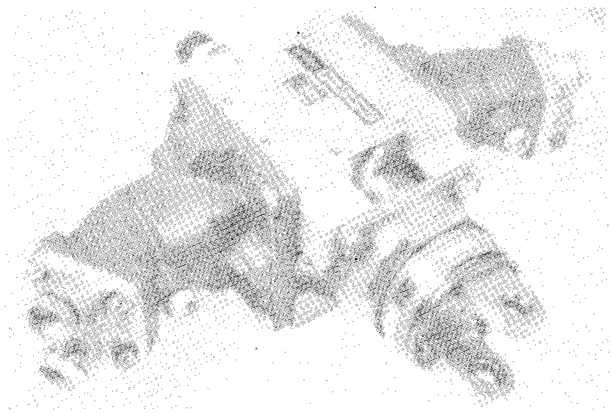

Fig. 16 Trailing-edge motor/gearbox.

rad/s. Transducers which measured the output of the second-stage servovalve spool provided signals that were demondulated and compared to the output of a servovalve model. If the difference between these signals, after being processed by a threshold and lag network, was larger than a predetermined value, a failure was assumed and the standby channel was engaged. The actuator used on the test demonstrator was a "hogged-out" prototype design utilizing existing servovalve modules with the included logic necessary to test redundancy management and failure transient effects.

The actuation system for the trailing edge is shown in Fig. 15. The motor/gearbox (Fig. 16) is representative of an aircraft configuration. The F-111 damper servo/tandem valve combination, however, does not physically reflect an airborne configuration. None the less, it was functionally adequate and was used in the definition of the demonstrator because an off-the-shelf integrated servo was not readily available. Both the damper servo and the tandem valve were located below the wing box of the test component demonstrator. In an airborne configuration, the integrated units would be packaged and installed aft of the rear spar.

The F-111 damper servo contained three separate electrohydraulic servovalves. These servovalves would receive the three channel commands from the computer and handle the redundancy management associated with signal failures and servovalve failures. The output of the damper servo actuated a bellcrank which in turn was connected to the input of the tandem valve. Stroking of the tandem valve provided equal hydraulic flow to each of the axial piston-type motors. These motors drove through a force-sharing arrangement to provide torque to the surface jackscrew drive. Each hydraulic motor operated off of a separate hydraulic system to provide hydraulic redundancy. The gear box included a takeoff for three follow-up potentiometers which provided redundant position signals to the computer for servo loop closure. The loop parameters of the servosystem were designed to achieve a 20 rad/s bandwidth.

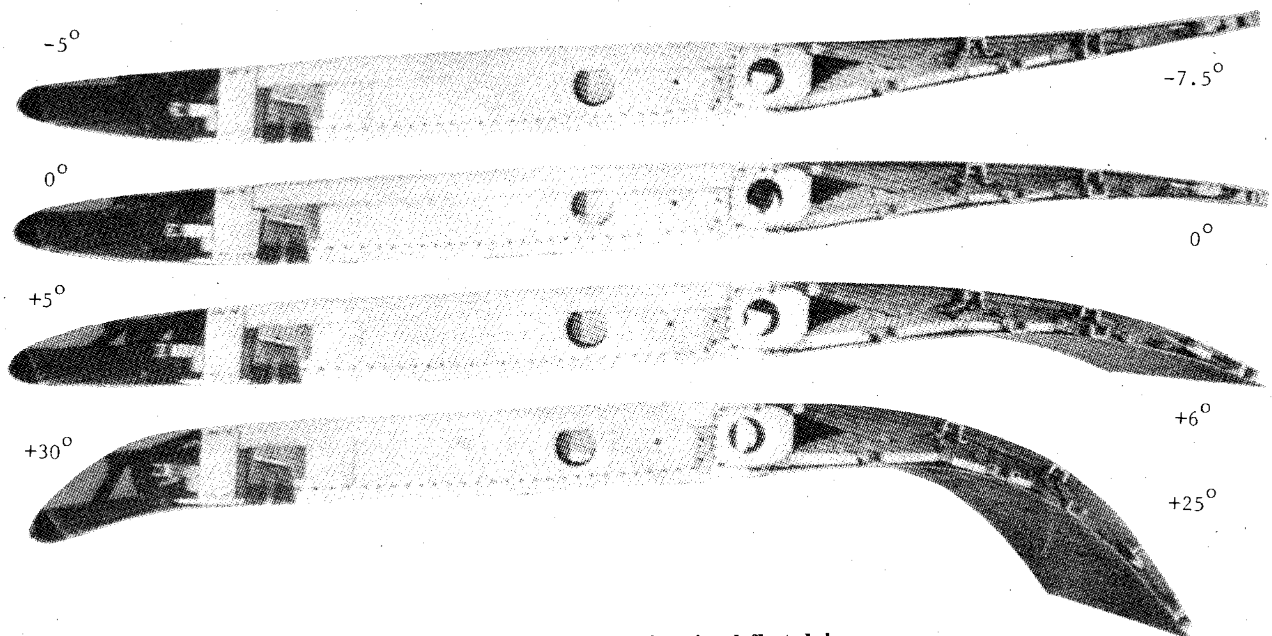

Fig. 17 Mission adaptive wing deflected shapes.

The failure monitoring and failure correction algorithms required with the presented independent actuation system would be quite complicated, requiring a digital auxiliary computer. Later in development, a simpler system utilizing mechanical interconnections between each jackscrew drive from an inboard power drive unit was conceived and developed. This system simplified the failure monitoring and increased the system reliability to the point that an analog auxiliary computer was deemed to be sufficient to handle all MAW command tasks.

Results

The test component was completed as described and demonstrated that implementation of a variable camber wing system is possible. Upper and lower contour matched very well with theory. The surface systems produced aerodynamically acceptable shapes in all "off-design" travel positions. Figure 17 shows the component in several positions. Measurements of deflection rates, response characteristics, power requirements, and internal structural loads indicated the system is capable of performing a smooth contour, variable camber wing function.

Conclusions

Mission adaptive wing technology offers great performance improvement potential for future aircraft. Cruise-type aircraft (transports and bombers) can greatly benefit from the cruise optimization capabilities afforded by variable camber. Many aircraft heretofore requiring separate dedicated high lift and roll control systems can reduce weight and system power requirements with nondedicated (multifunction) variable camber control surfaces. The maneuver load control feature of a mission adaptive wing can increase a fighter's maximum load factor or a bomber's wing span without an increase in fixed structural weight. These and many other advantages make mission adaptive wing technology a technology for the future.