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# An Evaluation Technique for an F/A-18 Aircraft Loads Model Using F/A-18 Systems Research Aircraft Flight Data

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# AN EVALUATION TECHNIQUE FOR AN F/A-18 AIRCRAFT LOADS MODEL USING F/A-18 SYSTEMS RESEARCH AIRCRAFT FLIGHT DATA

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**Abstract**

A limited evaluation of the F/A-18 baseline loads model was performed on the Systems Research Aircraft at NASA Dryden Flight Research Center (Edwards, California). Boeing developed the F/A-18 loads model using a linear aeroelastic analysis in conjunction with a flight simulator to determine loads at discrete locations on the aircraft. This experiment was designed so that analysis of doublets could be used to establish aircraft aerodynamic and loads response at 20 flight conditions. Instrumentation on the right outboard leading edge flap, left aileron, and left stabilator measured the hinge moment so that comparisons could be made between in-flight-measured hinge moments and loads model-predicted values at these locations. Comparisons showed that the difference between the loads model-predicted and in-flight-measured hinge moments was up to 130 percent of the flight limit load. A stepwise regression technique was used to determine new loads derivatives. These derivatives were placed in the loads model, which reduced the error to within 10 percent of the flight limit load. This paper discusses the flight test methodology, a process for determining loads coefficients, and the direct comparisons of predicted and measured hinge moments and loads coefficients.

**Nomenclature**

| | |
|---|---|
| AAW | active aeroelastic wing |
| *dad* | differential aileron deflection, radians |
| *dail* | symmetric aileron deflection, radians |
| *dfilef* | differential inboard leading edge flap deflection, radians |
| *dfolef* | differential outboard leading edge flap, radians |
| *dftail* | differential stabilator deflection, radians |
| *dilef* | symmetric inboard leading edge flap deflection, radians |
| *diftef* | differential trailing edge flap deflection, radians |

| | |
|---|---|
| *dolef* | symmetric outboard leading edge flap deflection, radians |
| *drud* | differential rudder deflection, radians |
| *dstab* | symmetric stabilator deflection, radians |
| *dtef* | symmetric trailing edge flap deflection, radians |
| $FLL_a$ | flight limit load, absolute value |
| $Hm_x$ | hinge moment derivative as a result of nondimensionalized parameter *x*, percent of flight limit load, absolute value/unit of *x* |
| *Hp* | pressure altitude, ft |
| *i* | incidence |
| LEF | leading edge flap |
| *Ny* | lateral acceleration, *g* |
| *Nz* | vertical acceleration, *g* |
| OBES | onboard excitation system |
| *P* | nondimensionalized roll rate |
| *Pdot* | nondimensionalized roll acceleration |
| psf | pounds per square foot |
| *Q* | nondimensionalized pitch rate |
| $q_{act}$ | actual dynamic pressure, psf |
| *Qdot* | nondimensionalized pitch acceleration |
| $q_{target}$ | target dynamic pressure, psf |
| *R* | nondimensionalized yaw rate |
| *Rdot* | nondimensionalized yaw acceleration |
| $ROLEFHM_{act}$ | actual right outboard leading edge flap hinge moment, percent of flight limit load, absolute value |
| *rudtoe* | symmetric rudder deflection, radians |
| SRA | Systems Research Aircraft |
| TEF | trailing edge flap |
| α | angle of attack, radians |
| β | angle of sideslip, radians |

## Introduction

NASA Dryden Flight Research Center (Edwards, California) performed a limited F/A-18 baseline loads model evaluation as part of the active aeroelastic wing (AAW) risk reduction experiment on the Systems Research Aircraft (SRA).[1] The ongoing AAW[2] program uses an F/A-18 with wings modified for reduced torsional stiffness so that tools may be developed that concurrently integrate control and structural design to save structural weight, reduce drag, improve cruise and roll performance, and increase fatigue life. The AAW risk reduction experiment grew out of the program development to test techniques to be used during the program for identifying individual control surface effectiveness and loads derivatives and for performing flight flutter testing. This experiment used the F/A-18 SRA aircraft because this highly instrumented research vehicle has an easily modified flight control system similar to the AAW aircraft. The two fundamental

differences between the SRA and AAW aircraft are as follows:

- The SRA wings have the same stiffness as a production F/A-18 has, while the AAW aircraft wings have reduced torsional stiffness.
- The SRA inboard and outboard leading edge flaps (LEF) operate together, while the AAW LEFs operate separately.

Boeing developed the F/A-18 loads model for use with the flight simulator to determine loads at discrete locations on the aircraft. The model consists of FORTRAN code that uses a loads database consisting of loads coefficients with aircraft flight parameters to determine loads at 36 discrete locations on the aircraft. The standard F/A-18 loads database, which for this paper will be called the *baseline database*, was then modified to reflect the increased flexibility of the AAW aircraft so that it could be used in developing the AAW control laws. The loads models for both the AAW aircraft and the baseline F/A-18 predicted higher-than-expected loads, especially for the outboard LEF, which has become the limiting factor in the AAW control law development. This conservatism results from the fact that both loads model databases were obtained using a finite element model and a doublet-lattice aerodynamic model. Although an attempt was made to modify the baseline database with loads obtained during the original flight test of the F/A-18, only limited changes could be made because of the nature of the flight test maneuvers performed.[3] Analysis has shown that high-fidelity loads and aerodynamics models are required to make the design tools that are being developed during the AAW program work. The purposes of this experiment were to determine the level and sources of conservatism inherent in the baseline database and to develop a method for modifying the loads model database based on in-flight measured loads.

The F/A-18 loads model allows 36 discrete loads to be calculated at 20 flight conditions. During this experiment, three control surfaces were instrumented for hinge moment: the right outboard LEF, the left aileron, and the left stabilator. Each of the control surfaces performed doublets so that aerodynamic and load responses to these deflections could be determined. This paper focuses on evaluating the right outboard LEF hinge moment from flight test in comparison with the loads model-predicted hinge moment. The flight test methodology is discussed; a process for determining loads coefficients is discussed; and direct comparisons of predicted and measured hinge moments and loads coefficients are presented.

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## Flight Test Methodology

The design of the AAW risk reduction experiment facilitates the determination of individual control surface effects on the overall aerodynamics of the F/A-18 aircraft. A series of doublet maneuvers were performed at 20 different flight conditions, during which the onboard excitation system (OBES)[4] commanded a series of independent control surface deflections. In addition to the aerodynamic parameters, three control surfaces—the right outboard LEF, the left

stabilator and the left aileron—were instrumented and calibrated to measure hinge moments. The hinge moments were monitored in real time in the control room during each flight. The following will discuss each component of the flight test methodology that was used in this experiment including flight conditions, OBES maneuvers, instrumentation, and control room monitoring.

This experiment consisted of performing doublet maneuvers at 20 different flight conditions or test points. The flight conditions included a Mach range of 0.85 to 1.3 and an altitude range of 5,000 to 25,000 ft as seen in figure 1. After obtaining a specified flight condition and trimming the aircraft for level flight, the pilot entered and engaged the correct OBES maneuver to be flown. Each OBES maneuver consisted of a series of longitudinal or lateral-directional doublets. The OBES commanded the type and size of doublet that was to be performed.

Figure 2 shows the order and direction of these doublets. Figure 2(a) shows a typical longitudinal maneuver consisting of a series of single-surface doublets for the left control surfaces; for simplicity, the right control surface deflections, which were equal in magnitude and direction, are not shown. Each longitudinal maneuver consists of a symmetric LEF doublet followed by a symmetric trailing edge flap (TEF) doublet, a symmetric aileron doublet, and a symmetric stabilator doublet. Between each doublet, was a 5-second (sec) pause. Figure 2(b) shows a typical lateral-directional maneuver; again, the right control surface deflections, which were equal in magnitude and opposite in direction, are not shown. Each lateral-directional maneuver consists of an anti-symmetric rudder doublet followed by an anti-symmetric LEF doublet, an anti-symmetric TEF doublet, an anti-symmetric aileron doublet, and an anti-symmetric stabilator doublet. Either small, medium, or large longitudinal and lateral-directional doublets were flown at each flight condition. Doublet size was based on expected aircraft aerodynamic and load response. Figure 1 shows how the doublet sizes varied throughout the flight envelope. The following table lists the type of doublet with its corresponding control surface deflections in degrees for each of the six maneuvers.

Doublet control surface deflections.

| Maneuver | Rudder | LEF | TEF | Aileron | Stabilator |
|---|---|---|---|---|---|
| Large lateral-directional | ±4 | ±3 | ±5 | ±6 | ±3 |
| Large longitudinal | N/A | +3 | +5 | ±6 | ±1 |
| Medium lateral-directional | ±4 | ±2 | ±4 | ±5 | ±3 |
| Medium longitudinal | N/A | +2 | +4 | ±5 | ±1 |
| Small lateral-directional | ±4 | ±1 | ±3 | ±4 | ±3 |
| Small longitudinal | N/A | +1 | +3 | ±4 | ±1 |

Test points were performed in order of increasing dynamic pressure so that the maneuvers could be evaluated for loads before proceeding to higher loading conditions. As previously mentioned, each doublet input was separated by a 5-sec pause to verify that each control surface returned to its trim deflection. This approach enabled safe conduct of the flight test while obtaining hinge moment data at every required test condition in both the longitudinal and lateral directions by varying one parameter at a time.

As stated previously, three control surfaces on the SRA aircraft were instrumented and calibrated for hinge moment: the right outboard LEF, the left aileron, and the left stabilator. Figure 3 illustrates the three locations on the aircraft that were instrumented for this experiment. Both the left aileron and left stabilator rod-ends were instrumented with sixteen strain gages configured into four, four-active-arm bending bridges. Figure 4 shows the placement of the bridges on the left stabilator rod-end. Figure 4(a) shows the locations of the primary and spare compression bridges, while figure 4(b) shows the locations of the primary and spare tension bridges. The left aileron rod-end strain gage placement was similar to that of the left stabilator rod-end. The strain gage outputs were calibrated with load by placing the stabilator and aileron rod-ends in a load test machine and applying known tensile and compressive loads.

The right outboard LEF was instrumented with twelve strain gages configured into three, four-active-arm bending bridges on the lugs of the transmission. Figure 5 shows the gage placement on the right outboard LEF transmission. After the transmission and flap were reinstalled on the aircraft, these strain gages were calibrated by applying known compressive loads to the right outboard LEF using a hydraulic jack, load cell, and load pad. Before each flight, a ground check was performed in which load was applied to verify that all of the instrumentation was functioning. Phasing maneuvers were also performed in-flight to ensure that the instrumentation was functioning correctly.

During flight testing, data from all three instrumented control surfaces were telemetered to the control room for real-time monitoring. Among the parameters observed during flight were the right and left outboard LEF positions, the left aileron and the left stabilator hinge moments, the right outboard LEF hinge moment, and outputs from all three strain gage bridges on the right outboard LEF. All listed parameters were output to and viewed on an eight-channel strip chart. In addition, all control surface deflections, vertical acceleration ($Nz$), angle of attack ($\alpha$), angle of sideslip ($\beta$), Mach number, altitude ($Hp$), pitch rate ($Q$), roll rate ($P$), and yaw rate ($R$) were monitored in real time in the control room. Monitoring the control surface deflection allowed the test engineer to call directly to the pilot to terminate the maneuver if a control surface actuator were to stall during high dynamic pressure test points. If a control surface actuator had stalled, the maneuver would have been unusable for analysis. In addition, a stalled control surface actuator could have caused a structural overload condition because of the nature of the control surface doublets. Monitoring also included observing real-time measured hinge moments and predicted hinge moments as percentages of the absolute value of the flight limit load (designated percentage of $FLL_a$). The predicted hinge moments were calculated in real time by the loads model using basic aircraft parameters and flight conditions

telemetered from the aircraft. In this way, measured and predicted hinge moments for all three instrumented control surfaces were compared during flight.

The control room display incorporated warnings to indicate the percentage of the absolute value of the flight limit load, that was reached during flight. Had the measured hinge moment reached 80 percent of $FLL_a$, the value displayed would have turned yellow, and if it had reached 100 percent of $FLL_a$, the value displayed would have turned red. In addition to these safety-of-flight warnings, there was a research requirement for a warning to flash if a measured hinge moment exceeded its predicted hinge moment by 10 percent of $FLL_a$ so that the test engineer could call to terminate the test point.

## Data Processing Methodology

Data processing for this experiment consisted of several stages: The first stage was the preliminary analysis in which direct comparisons of the measured and predicted hinge moments were made. After this stage was complete, time histories of each maneuver were processed through a stepwise regression technique[5] that had been implemented in MATLAB by Dr. E. A. Morelli at NASA Langley Research Center (Hampton, Virginia). This regression technique related each of the aircraft parameters to the measured hinge moment. The most highly correlated parameter was retained in the model, and the estimated load resulting from that parameter was removed from the overall hinge moment. The next most highly correlated parameter was then selected, and the estimated load resulting from that parameter was removed from the measured hinge moment. This process was repeated for each selected aircraft parameter. However, after each parameter was selected for retention in the regression model, the previously selected parameters were reevaluated to ensure that they were still significant in predicting the overall load. This analysis stage established loads coefficients, which will be called *regressed coefficients*. The regressed coefficients then were compared with the coefficients contained in the baseline database, which will be called *baseline coefficients*.

The final stage of the analysis consisted of replacing the baseline coefficients with the regressed coefficients. The flight data were then rerun through the loads model, and the post-regression hinge moment was calculated. The results of using this technique on the right outboard LEF hinge moment is discussed in the following section. The following paragraphs describe the first two stages of this procedure in greater detail.

### First Stage

As previously mentioned, the first stage of the analysis consisted of direct comparisons of the measured and predicted hinge moments. This task was performed by creating time history plots of the hinge moment data. The histories allowed the overall conservatism to be evaluated at each test point and insight to be gained as to the sources of the conservatism in the predicted hinge moment. After the overall conservatism was established, the sources of the differences in the predicted and measured hinge moments were established, which was accomplished using the stepwise regression technique.

**Second Stage**

The second stage of the analysis was to use the stepwise regression technique to determine the loads derivatives to be included in the baseline database. To explain the process used to determine the loads coefficients based on the flight data, it is important to first understand how the loads model predicts the load for a particular flight condition. The baseline database consists of loads derivatives that are used in the loads model to calculate load at a particular location on the aircraft. The loads model can calculate 36 discrete loads on the F/A-18 as seen in figure 6. These loads include control surface hinge moments; wing root and wing fold shear, bending, and torque; and the horizontal and vertical tail shear, bending, and torque for each side of the aircraft.

The loads model determines the range of Mach number and altitude in which the aircraft is flying. This range establishes which set of loads derivatives to use at that test point. These derivatives are then used to calculate the load at the target Mach number and altitude combination. The load is calculated by multiplying the derivatives by their respective flight parameter and adding them together to determine the overall load at that location.

During flight test, it is difficult to establish and maintain an exact flight condition. Therefore, it was necessary to calculate the actual load based on the load at the target Mach number and altitude. To calculate the actual load, the aerodynamic contributors to the overall load are multiplied by the ratio of the actual dynamic pressure ($q_{act}$) to the target dynamic pressure ($q_{target}$). The complete computation is shown in equation (1) for the determination of the right outboard LEF hinge moment ($ROLEFHM_{act}$).

$$
\begin{aligned}
ROLEFHM_{act} = \; & (q_{act}/q_{target})[Hm_i(i) \\
& + Hm_\alpha(\alpha) + Hm_Q(Q) \\
& + Hm_{dilef}(dilef) \\
& + Hm_{dolef}(dolef) \\
& + Hm_{dtef}(dtef) \\
& + Hm_{dail}(dail) \\
& + Hm_{rudtoe}(rudtoe) \\
& + Hm_{dstab}(dstab) \\
& - \{Hm_\beta(\beta) + Hm_P(P) \\
& + Hm_R(R) \qquad (1) \\
& + Hm_{dfilef}(dfilef) \\
& + Hm_{dfolef}(dfolef) \\
& + Hm_{diftef}(diftef) \\
& + Hm_{dad}(dad) \\
& + Hm_{drud}(drud) \\
& + Hm_{dftail}(dftail)\}] \\
& + [Hm_{Nz}(Nz) \\
& + Hm_{Qdot}(Qdot) \\
& - \{Hm_{Ny}(Ny) \\
& + Hm_{Pdot}(Pdot) \\
& + Hm_{Rdot}(Rdot)\}]
\end{aligned}
$$

Because of the nature of the database, it is required to subtract the lateral-directional terms from the longitudinal components for the right wing as shown in equation (1).

Prior to calculating the loads derivatives, it was necessary to modify the flight data so that the aircraft parameters match the loads model-expected input parameters. For example, the control surface symmetric and differential deflections between the right and left wings had to be calculated from the measured control surface deflections. In addition, all of the aircraft parameters were nondimensionalized, and the aerodynamic loads contributors were multiplied by the ratio of the actual dynamic pressure to the target dynamic pressure. These modified parameters were then loaded into the

stepwise regression program along with the measured hinge moment for each maneuver at each flight condition. Each longitudinal and lateral-directional maneuver was individually analyzed.

The first step in this regression technique calculated an intercorrelation matrix which established any parameter interdependencies. Highly correlated parameters were evaluated, and the dependent parameter was removed from the regression model. Because the doublet maneuvers consist of independent control surface deflections, the intercorrelations are relatively small. However, rudder deflections were eliminated from the longitudinal regression because there were no symmetric rudder doublets, thereby causing a gap in the database. Because the contribution of the symmetric rudder deflection to the overall outboard LEF hinge moment was small, however, the error introduced in this case was considered negligible.

After the initial selection of parameters was complete, the second step was to determine the correlation of the flight parameters with the measured hinge moment. The most highly correlated parameter is selected and, using least squares, the loads coefficient for that parameter is determined. After removing the load caused by that parameter from the model, the loads coefficient for the next most highly correlated parameter is determined, updating and reevaluating the significance of already calculated derivatives as required to obtain a best-fit solution.

The final selection of parameters required multiple runs of the regression technique to be performed, in which different parameters were retained in the model. The criteria for retaining parameters were as follows:
(1) Primary parameters had to contribute to the overall load and (2) secondary parameters had to contribute to the load without adversely affecting the primary parameter derivatives. The regression technique was applied to each of the longitudinal and lateral-directional maneuvers, and new loads derivatives were established.

## Flight Test Results

This section compares the measured right outboard LEF hinge moment with the loads model-predicted hinge moment and respective loads derivatives. All of the loads results in this section are given as a percentage of the absolute value of the flight limit load. The first stage of this analysis consisted of directly comparing the in-flight-measured and loads model-predicted hinge moments, which are called measured hinge moments and predicted hinge moments, respectively. Comparison of the measured and predicted hinge moments showed that the loads model was calculating, as expected, a conservative estimate of the actual hinge moments for both longitudinal and lateral-directional maneuvers in both the subsonic and supersonic segments of the flight regime.

For subsonic flight conditions, on average, the loads model predicted the right outboard LEF hinge moment 70 percent of $FLL_a$ higher than that measured during trimmed flight. As the doublets were performed, however, the difference between the predicted and measured loads increased. As seen in figure 7(a), which depicts a series of longitudinal doublets at Mach 0.95 and an altitude of 10,000 ft, the load difference increased to as much as 130 percent of $FLL_a$ during the LEF deflection. The influence of the various control surface deflections on the overall load can be seen easily in figure 7(b),

which shows the same maneuver with the trimmed loads for both the measured and predicted hinge moments removed. As the LEFs deflect, the difference between the changes in the load for the measured and predicted hinge moments was approximately 65 percent of $FLL_a$.

The next control surface deflections were the TEFs. This doublet produced a difference of only 10 percent of $FLL_a$, therefore showing that the loads derivatives associated with the TEF doublet are not as conservative as the LEF doublet. The aileron deflections produced a difference of 60 percent of $FLL_a$, and the stabilator doublets caused a difference of almost 70 percent of $FLL_a$. Figures 8(a) and 8(b) were produced using the same procedure to look at the lateral-directional doublets for the same flight condition. Figure 8(a) shows a similar difference in load when looking purely at the load resulting from trimmed flight.

Figure 8(b) then looks at the changes in the load resulting from lateral-directional control surface deflections when the trimmed load is removed. The change in load resulting from the rudder deflections differs by only about 5 percent of $FLL_a$. The LEF deflections, however, cause a difference of as much as 65 percent of $FLL_a$. The TEF deflection shows a difference once again of less than 5 percent of $FLL_a$, and the aileron caused a difference of approximately 10 percent of $FLL_a$. The stabilator deflection, however, caused a hinge moment difference of approximately the same magnitude, but in the opposite direction from the measured hinge moment.

With these observations, it was necessary to perform the second stage of the analysis. The second stage used the stepwise regression technique to determine the actual contributions of each input parameter so that both the flight data regressed and baseline loads derivatives could be compared. As mentioned in the previous section, the parameters to be maintained within the regression model had to be determined. First, to determine which parameters to retain within the regression model, the intercorrelation of the flight parameters was evaluated. Because of the independent nature of the control surface deflections, the intercorrelations were relatively low. Second, the significant parameters had to be determined. For the longitudinal maneuvers, only symmetric parameters were retained at this stage, excluding the symmetric rudder deflection because no symmetric rudder doublets were performed. For the lateral-directional maneuvers, only the anti-symmetric terms were retained in the regression model.

Final selection required that the stepwise regression technique be used to evaluate the addition of each of these terms in their respective regression models. Figure 9 displays the results of this evaluation for the Mach 0.95 and an altitude of 10,000 ft for longitudinal doublets. This evaluation was made in six steps. The first step was to include only the LEF symmetric deflection. Second, all of the control surfaces were included and the resulting regressed hinge moment was compared with the regressed hinge moment from the case in which only the LEF deflection was included and the measured hinge moment (fig. 9(a)). The load was more accurately estimated when all control surfaces, except for the rudder, were included than when only the LEF was used in the regression model. The third step was to include angle of attack and the fourth to include pitch rate in the regression model. The inclusion of each of these parameters

contributed to the regressed hinge moment without adversely affecting the derivatives being calculated (fig. 9(b)). Figure 9(c) shows the final two steps which include the vertical acceleration and then the pitch acceleration. As each parameter was included, the resulting regressed hinge moment was able to more accurately estimate the actual measured hinge moment without adversely affecting the primary control surface parameters. Therefore, all of these parameters were retained within the regressor model. For the longitudinal case, the final equation was as follows:

$$
\begin{aligned}
ROLEFHM_{act} = \; & (q_{act}/q_{target})[Hm_i(i) \\
& + Hm_{\alpha}(\alpha) + Hm_Q(Q) \\
& + Hm_{dilef}(dilef) \\
& + Hm_{dolef}(dolef) \\
& + Hm_{dtef}(dtef) \\
& + Hm_{dail}(dail) \\
& + Hm_{dstab}(dstab)] \\
& + [Hm_{Nz}(Nz) \\
& + Hm_{Odot}(Qdot)]
\end{aligned}
\tag{2}
$$

The same procedure was applied for the lateral-directional maneuvers, and the following equation was established for analysis of the lateral-directional doublets:

$$
\begin{aligned}
ROLEFHM_{act} = \; & (q_{act}/q_{target})[Hm_i(i) \\
& - \{Hm_{\beta}(\beta) + Hm_P(P) \\
& + Hm_R(R) \\
& + Hm_{dfilef}(dfilef) \\
& + Hm_{dfolef}(dfolef) \\
& + Hm_{diftef}(diftef) \\
& + Hm_{dad}(dad) \\
& + Hm_{drud}(drud) \\
& + Hm_{dftail}(dftail)\}] \\
& - [Hm_{Nv}(Ny) \\
& + Hm_{Pdot}(Pdot) \\
& + Hm_{Rdot}(Rdot)]
\end{aligned}
\tag{3}
$$

After the required parameters were established, the loads derivatives were obtained for this flight condition.

Figure 10(a) shows the baseline database and the regressed coefficients for the trimmed flight condition, which corresponds with $Hm_i$, at Mach 0.95. The exact value of the coefficient to be used was determined by looking at the trends and consistency of the data. Figure 10(b) shows the inboard LEF regressed and baseline database coefficients at Mach 0.95. Previously, direct comparison had estimated that the hinge moment on the right outboard LEF was overpredicted by as much as 130 percent of $FLL_a$ during the LEF deflections. Figure 10(b) demonstrates that one source of this conservatism is the load associated with the deflection of the inboard LEF by showing the difference in the regressed and the baseline database derivatives resulting from inboard LEF deflection.

After derivatives were obtained from both the longitudinal and lateral-directional doublets, the outboard LEF derivatives were replaced within the loads model and the flight maneuvers were rerun through the model. Figure 11(a) shows the regressed hinge moment compared with the measured and predicted hinge moments for the longitudinal maneuver, and figure 11(b) contains the regressed hinge moment along with the in-flight measured and predicted hinge moments for the lateral-directional maneuver. The stepwise regression technique could calculate a hinge moment that was within 10 percent of $FLL_a$ of the measured hinge moment, in contrast to the 70 to 130 percent of $FLL_a$ difference from the baseline database derivatives.

The flight regime also included numerous supersonic test points. This section uses data collected at Mach 1.1 and an altitude of 10,000 ft to demonstrate the use of these

techniques when evaluating flight data. This condition was chosen because the loads model predicted the highest hinge moments at that test condition. Figure 12(a) shows the overall predicted and measured hinge moments for a longitudinal maneuver at this condition. For this condition, the difference in the measured and predicted hinge moments due to trimmed flight is approximately 30 percent of $FLL_a$.

Figure 12(b) demonstrates the differences in the load resulting from the control surface deflections after removing the load caused by trimmed flight. When the LEF is deflected, the difference in the measured and predicted loads is approximately 55 percent of $FLL_a$, while the TEF and aileron deflections cause a difference within 10 percent of $FLL_a$, and the stabilator doublet cause a difference of approximately 50 percent of $FLL_a$.

The hinge moments resulting from the lateral-directional doublets at this condition are in figure 13(a), with their respective deltas shown in figure 13(b). The trimmed load, as estimated in figure 13(a), agrees with that seen during the longitudinal maneuver. The delta loads, as shown in figure 13(b), establish that the differences between the predicted and measured hinge moments are approximately 10 percent of $FLL_a$ during the rudder deflection, 70 percent of $FLL_a$ during the LEF deflections, 5 percent of $FLL_a$ during the TEF deflections, and 10 percent of $FLL_a$ during the aileron deflections. However, the difference during the stabilator deflections is essentially zero.

The stepwise regression was then used to establish regressed loads derivatives. Figure 14(a) compares the right outboard LEF hinge moment calculated using the regressed derivatives with the measured and original predicted hinge moments for the longitudinal maneuver. The regressed derivatives cause the measured and regressed hinge moments to agree to within 2 percent of $FLL_a$ in contrast to the 30 to 80 percent of $FLL_a$ shown previously with the original predicted hinge moment. Figure 14(b) displays a reduction in the difference between the predicted and measured hinge moment, from up to 70 percent to less than 2 percent of $FLL_a$ when the regressed derivatives are used to calculate hinge moment, and the measured, regressed, and predicted hinge moment time histories are plotted for the lateral-directional maneuver.

## Conclusions

The active aeroelastic wing risk reduction experiment on the F/A-18 SRA aircraft successfully established the conservatism inherent in the baseline F/A-18 loads model using the outboard leading edge flap (LEF) hinge moment as an example. The loads model was shown to be overall more conservative within the subsonic regime than it was in the supersonic regime. The comparisons in this experiment also showed that the main sources of the conservative prediction were included in the trimmed flight load and during the LEF deflections for the right outboard LEF. In the subsonic regime, the longitudinal maneuvers overpredicted the hinge moment by 70 to 130 percent of flight limit load ($FLL_a$), with the lateral-directional maneuvers being less conservative. In the supersonic regime the loads model overpredicted the right outboard LEF hinge moment by 30 to 100 percent of $FLL_a$. The lateral-directional maneuvers were more conservative than the longitudinal except during the LEF deflections. The stepwise regression technique was able to produce new loads derivatives that could predict the hinge moment within 10 percent

of $FLL_a$ subsonically and 2 percent of $FLL_a$ supersonically.

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4. Regenie, Victoria A., Michael Earls, Jeanette Le, and Michael Thomson, *Experience with ADA on the F-18 High Alpha Research Vehicle Flight Test Program*, NASA TM-104259, Oct. 1992.

5. Draper, N. R. and H. Smith, *Applied Regression Analysis*, John Wiley & Sons, Inc., 1966.

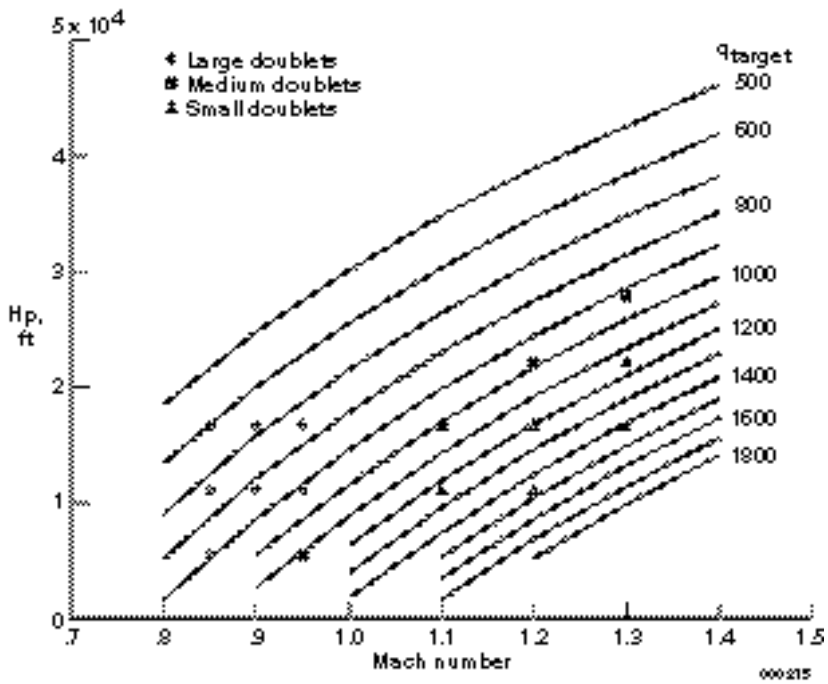
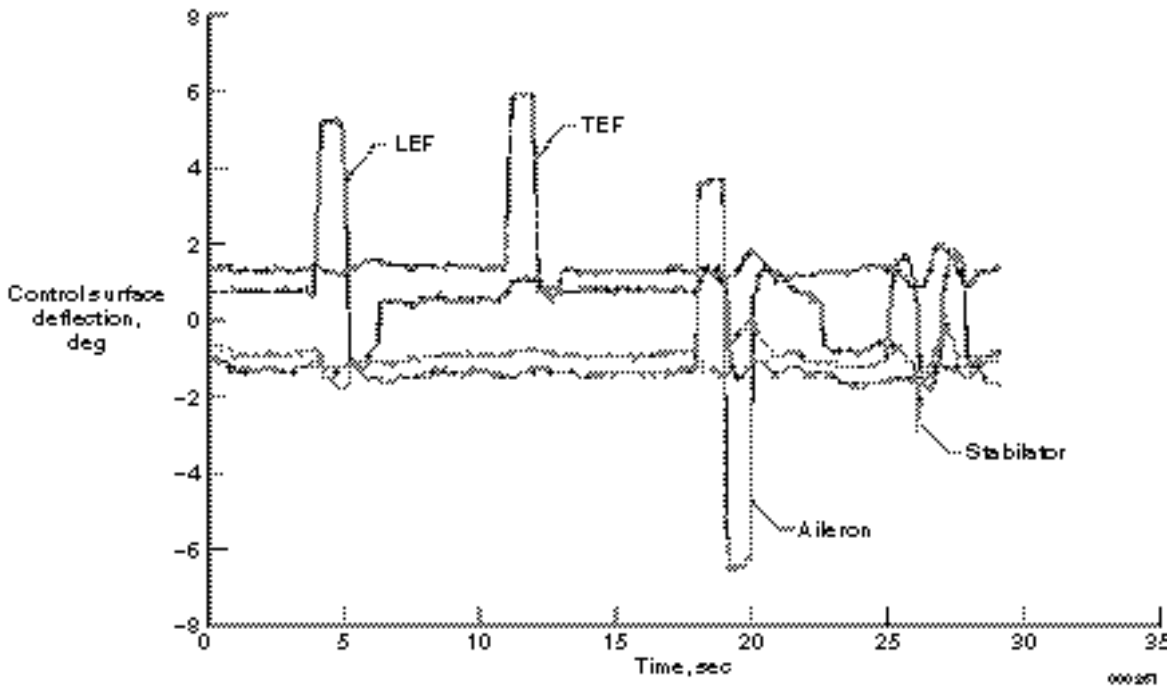
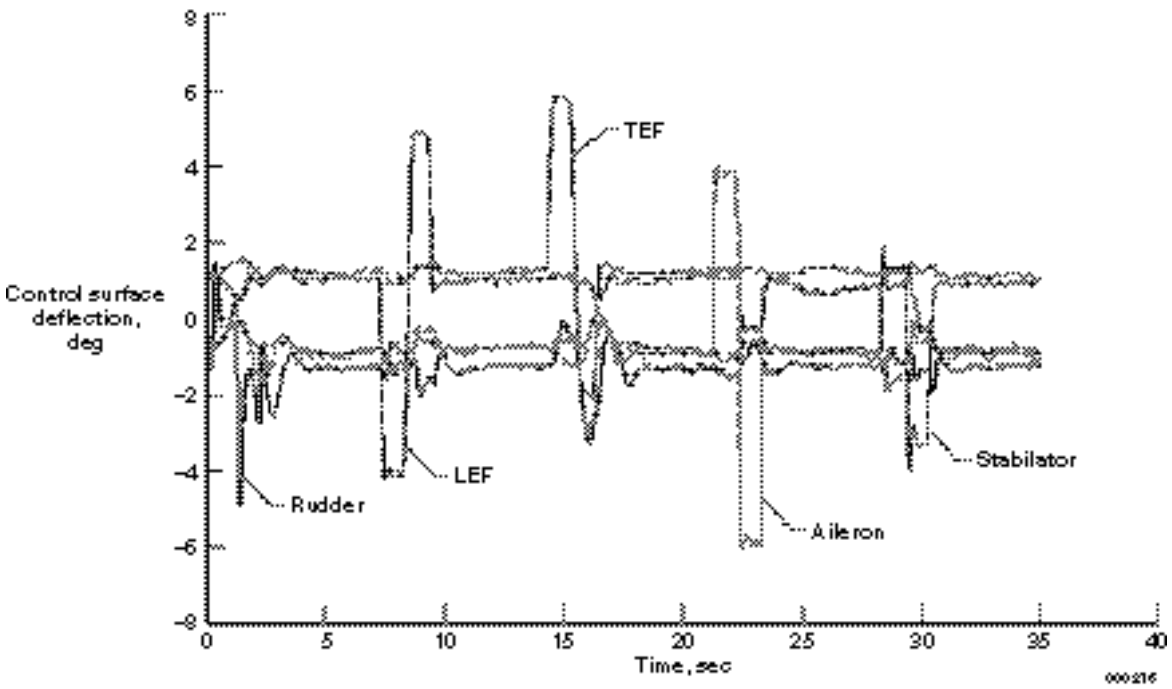




Figure 1. Flight envelope with doublet sizes.




(a) Large longitudinal doublets.




(b) Large lateral-directional doublets.

Figure 2. Control surface deflections over time.

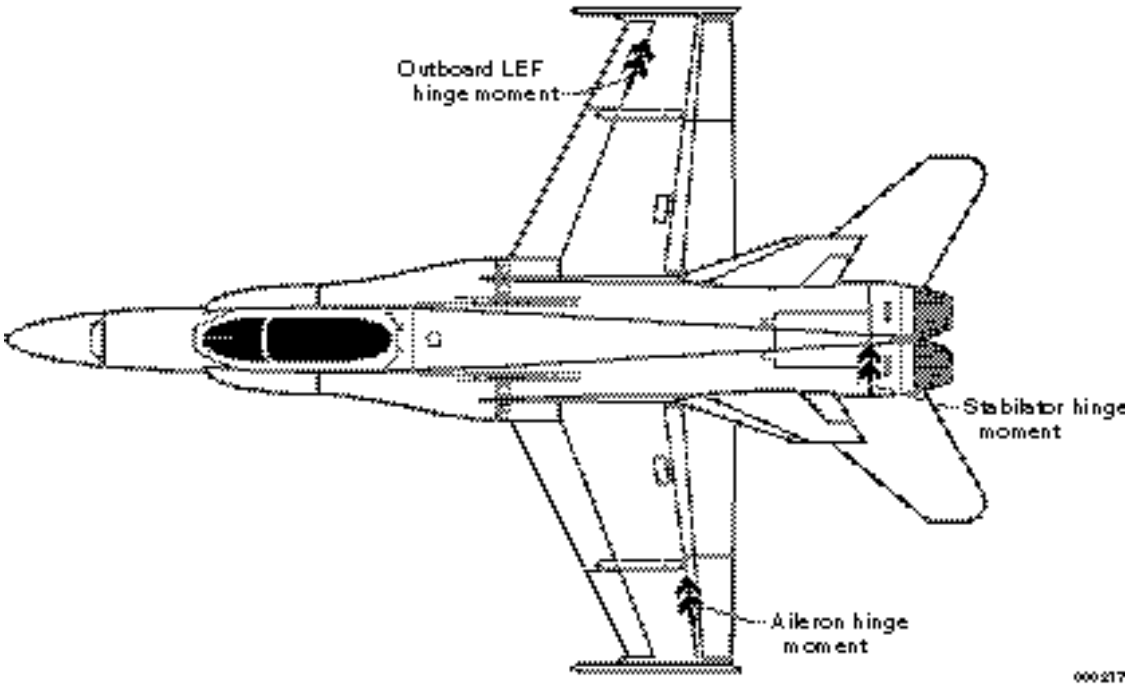
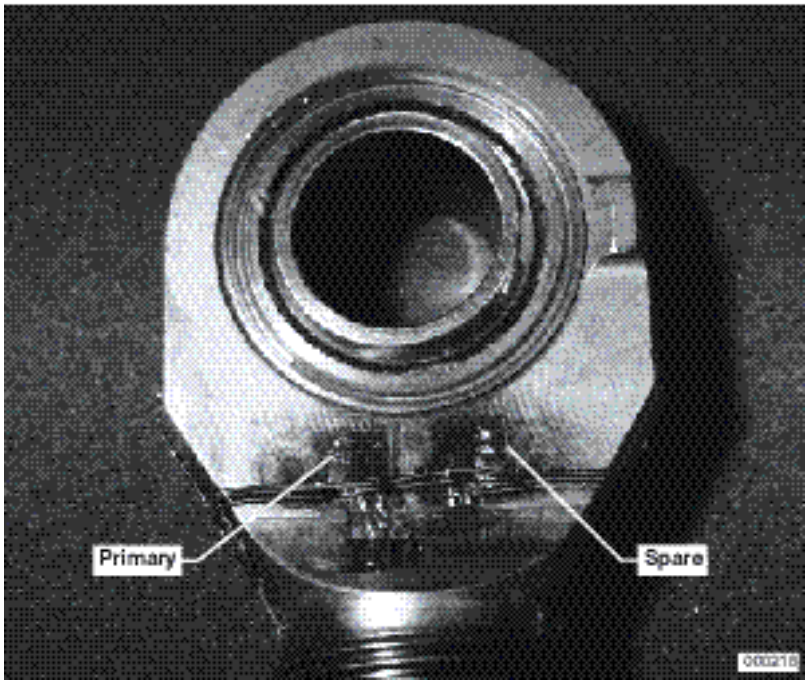
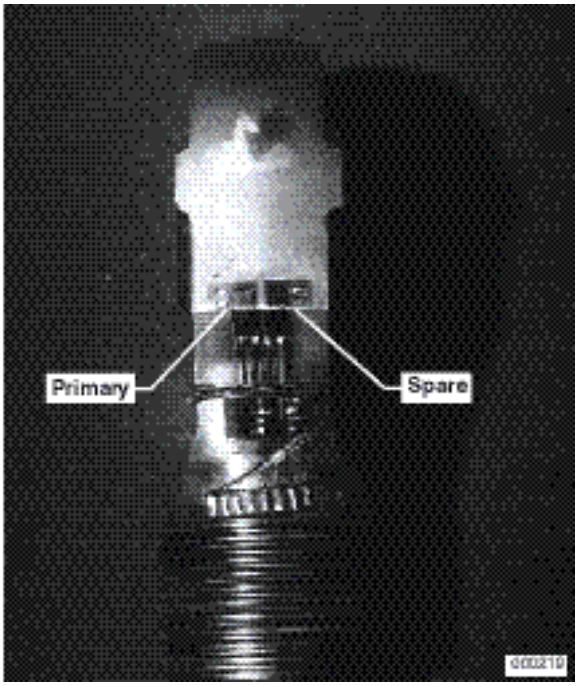



Figure 3. Measured control surface locations (positive directions shown).




(a) Compression bridges

Figure 4. Left stabilator rod-end with strain gage bridges installed.




(b) Tension bridges

Figure 4. Concluded.

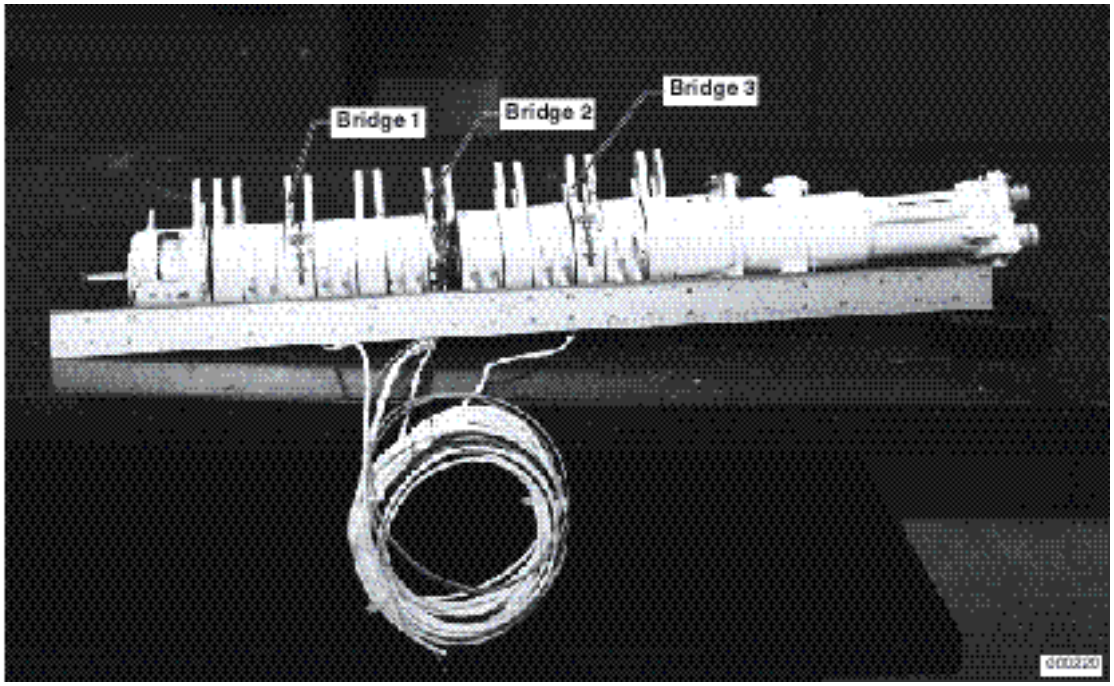



Figure 5. Right outboard leading edge flap transmission  with strain gage bridges installed.

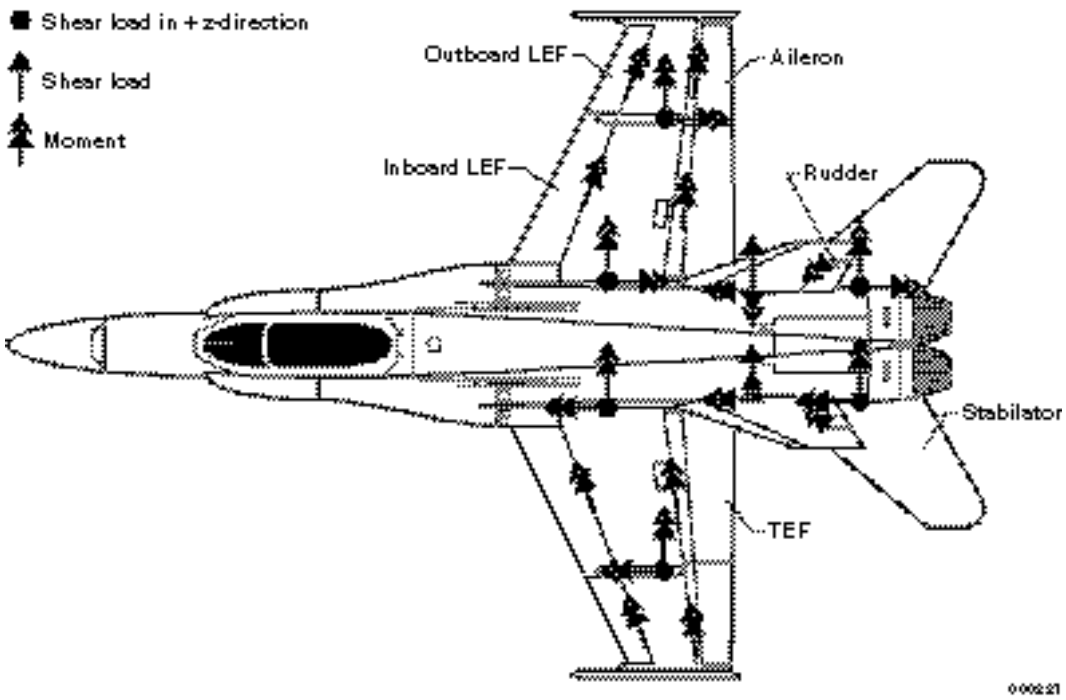
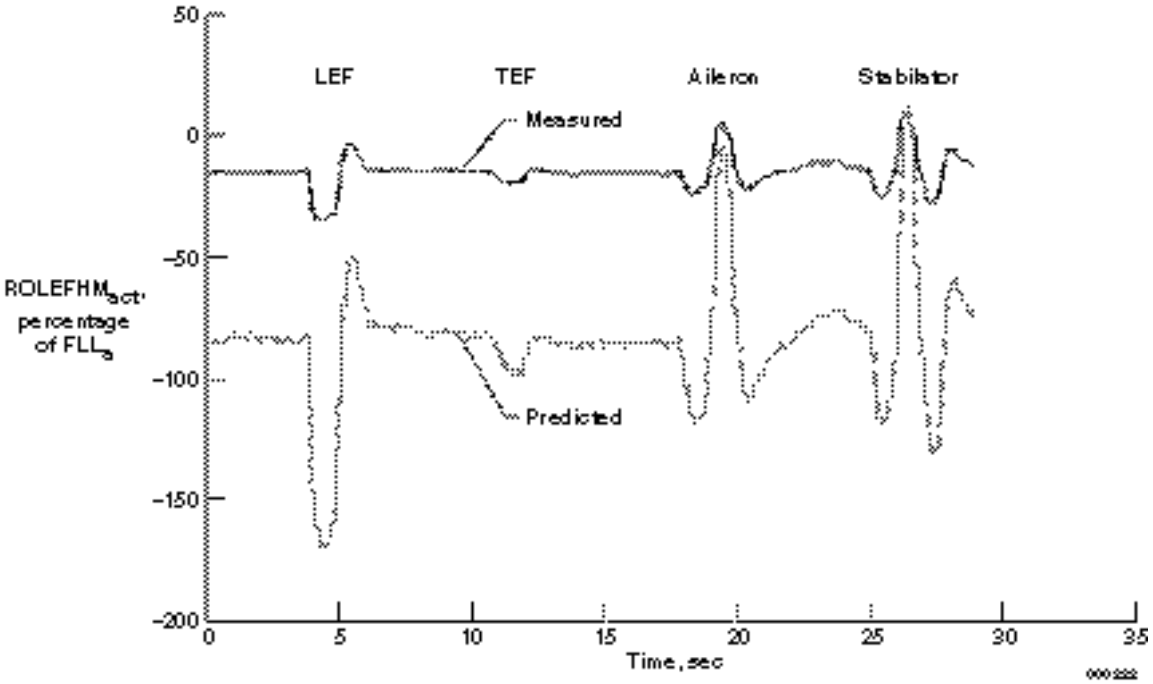
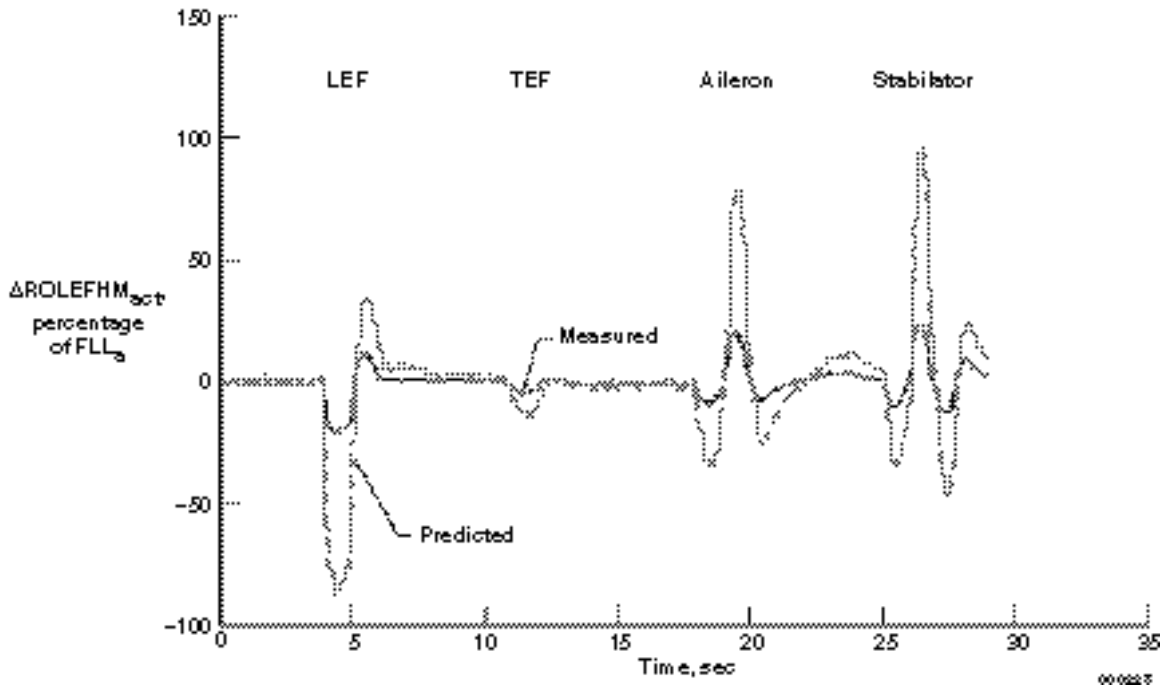



Figure 6. Loads model-calculated loads locations (positive direction shown).



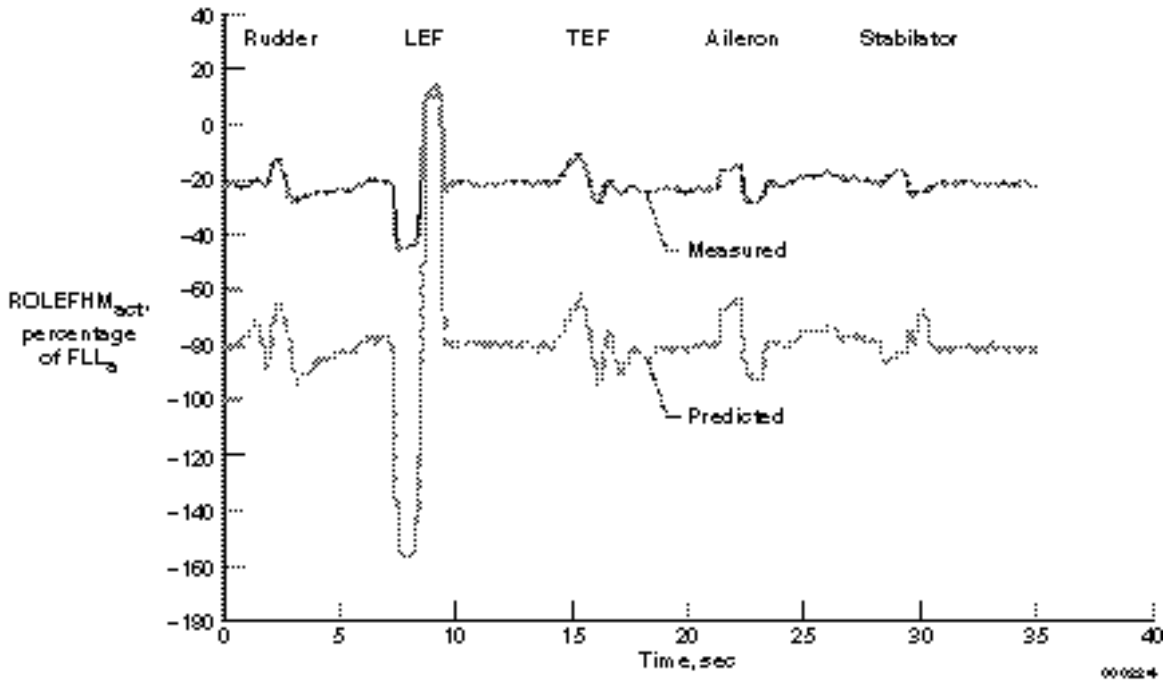

(a) Overall hinge moment.

Figure 7. Hinge moments at Mach 0.95 and at an altitude of 10,000 ft.



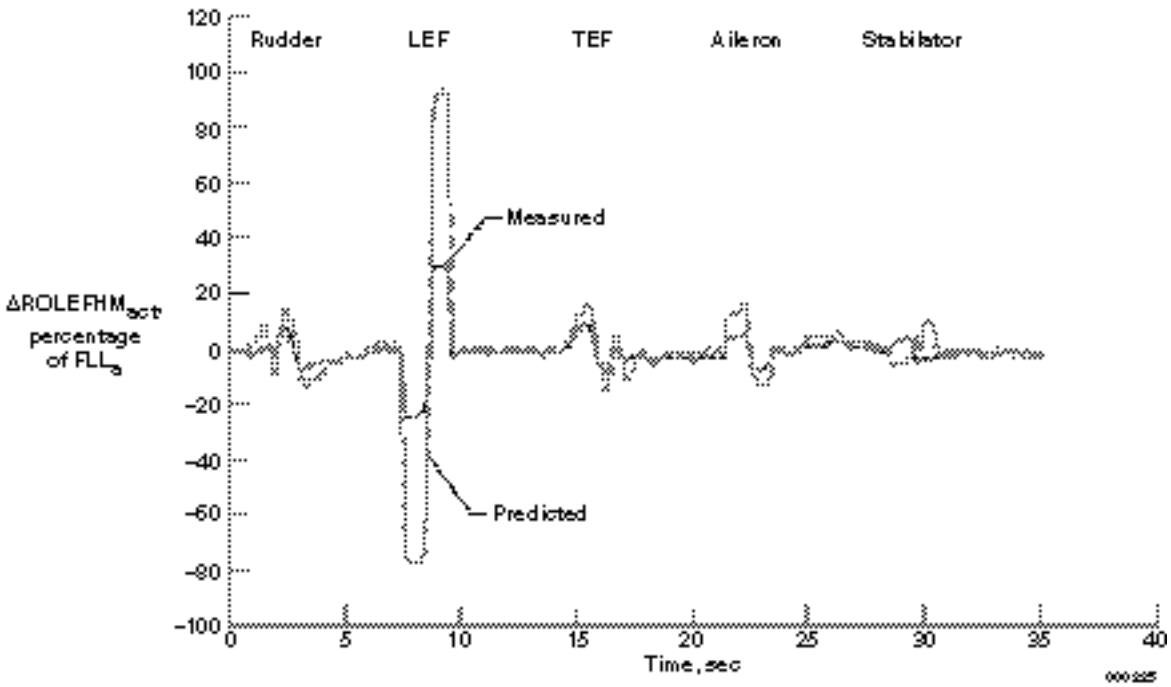

(b) With trimmed load removed.

Figure 7. Concluded.



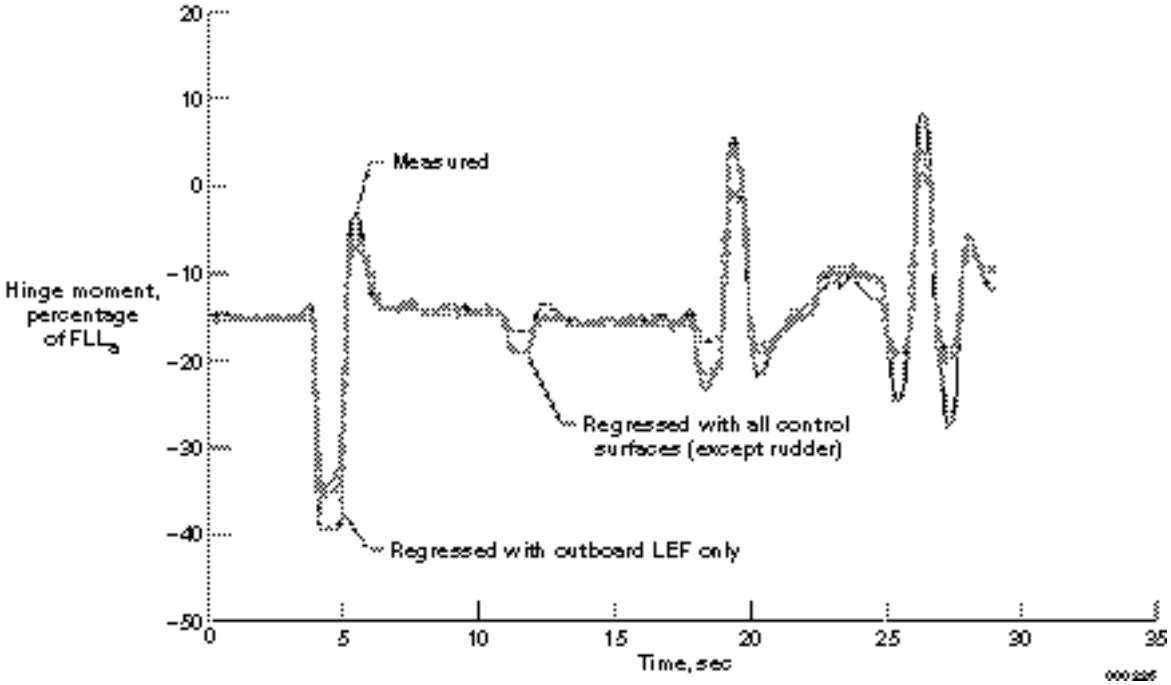

(a) Overall hinge moment.

Figure 8. Hinge moments resulting from large lateral-directional doublets at Mach 0.95 and an altitude of 10,000 ft.



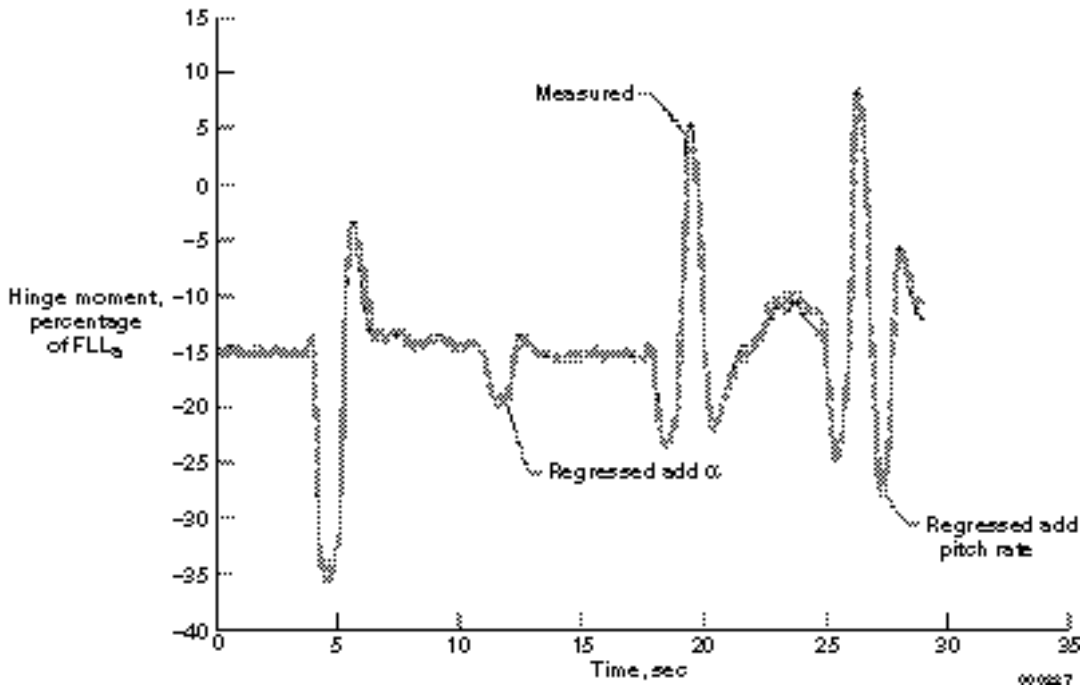

(b) With trimmed load removed.

Figure 8. Concluded.

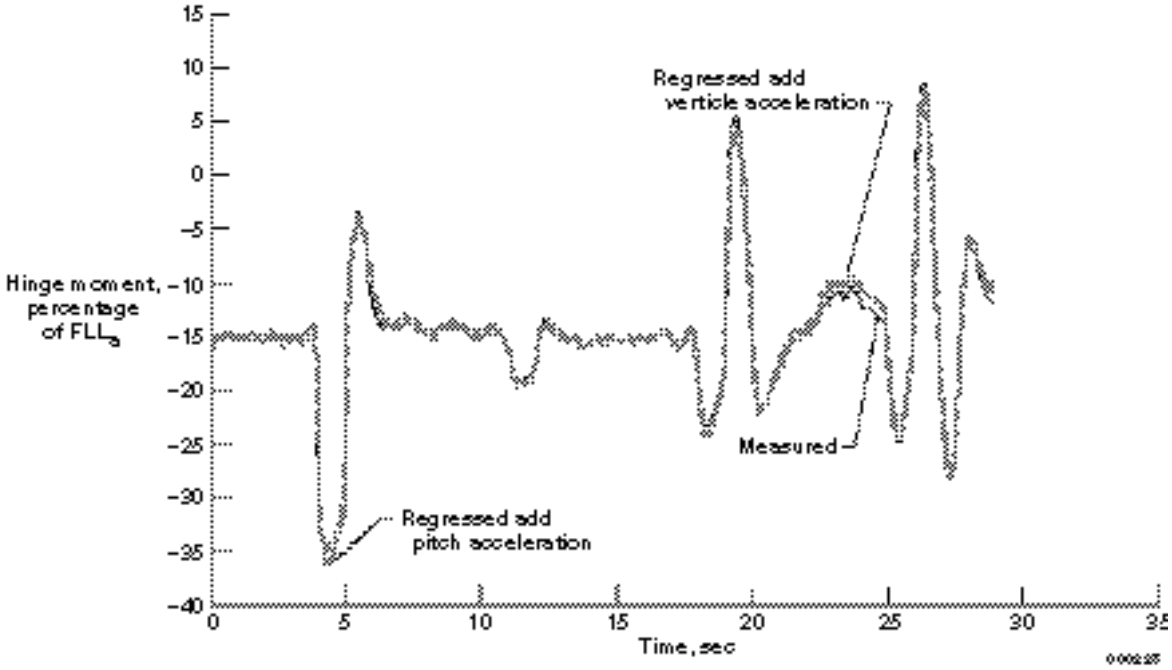



(a) Hinge moments regressed with outboard leading edge flap and all control surfaces.

Figure 9. Measured and regressed hinge moments as a function of time at Mach 0.95 and at an altitude of 10,000 ft.

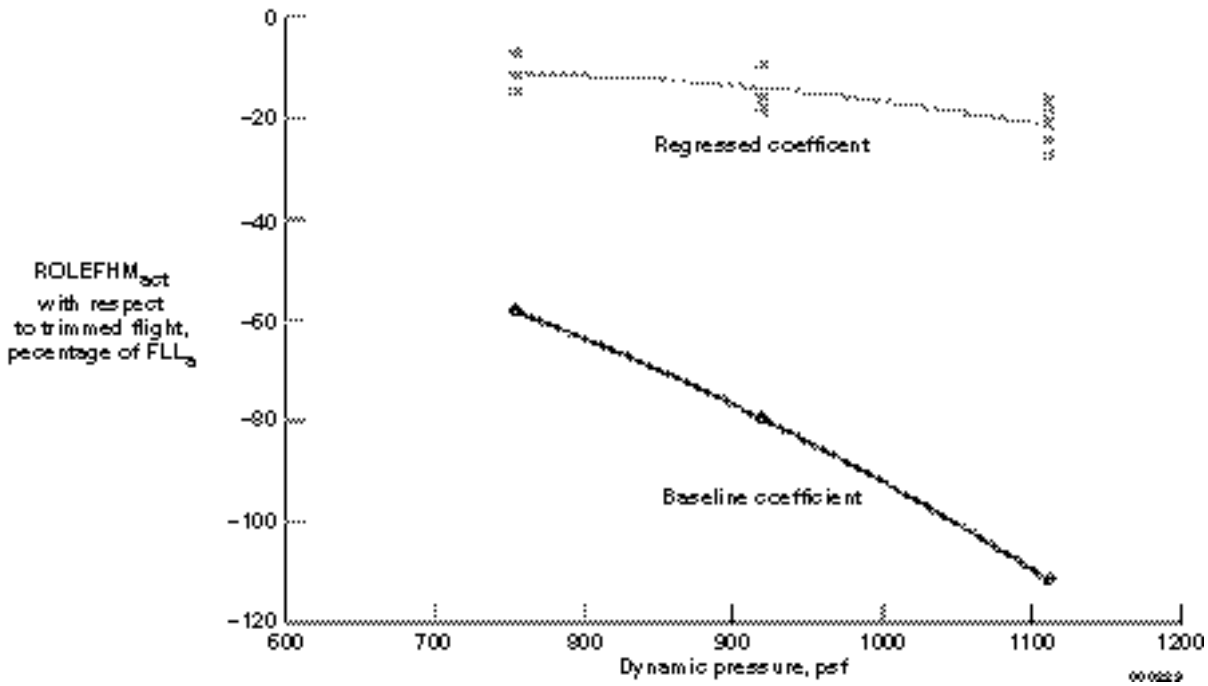



(b) Regressed hinge moments with angle of attack and pitch rate added.

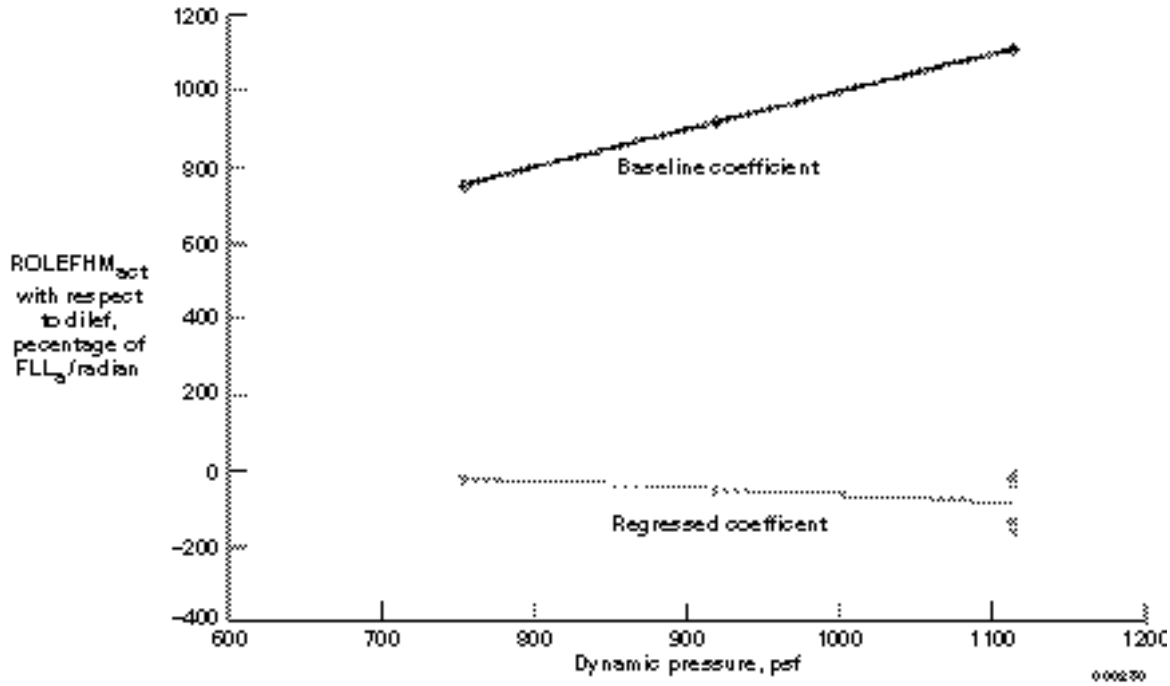



(c) Regressed hinge moments with vertical and pitch accelerations added.

Figure 9. Concluded.

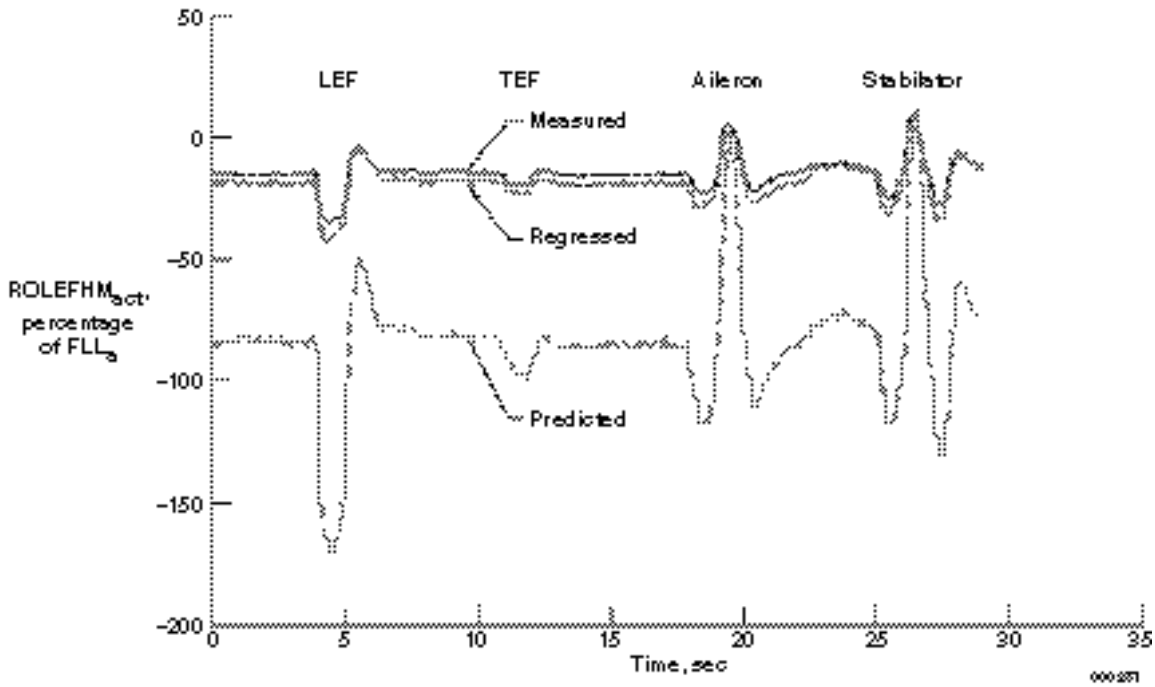



(a) Trimmed flight loads derivatives.

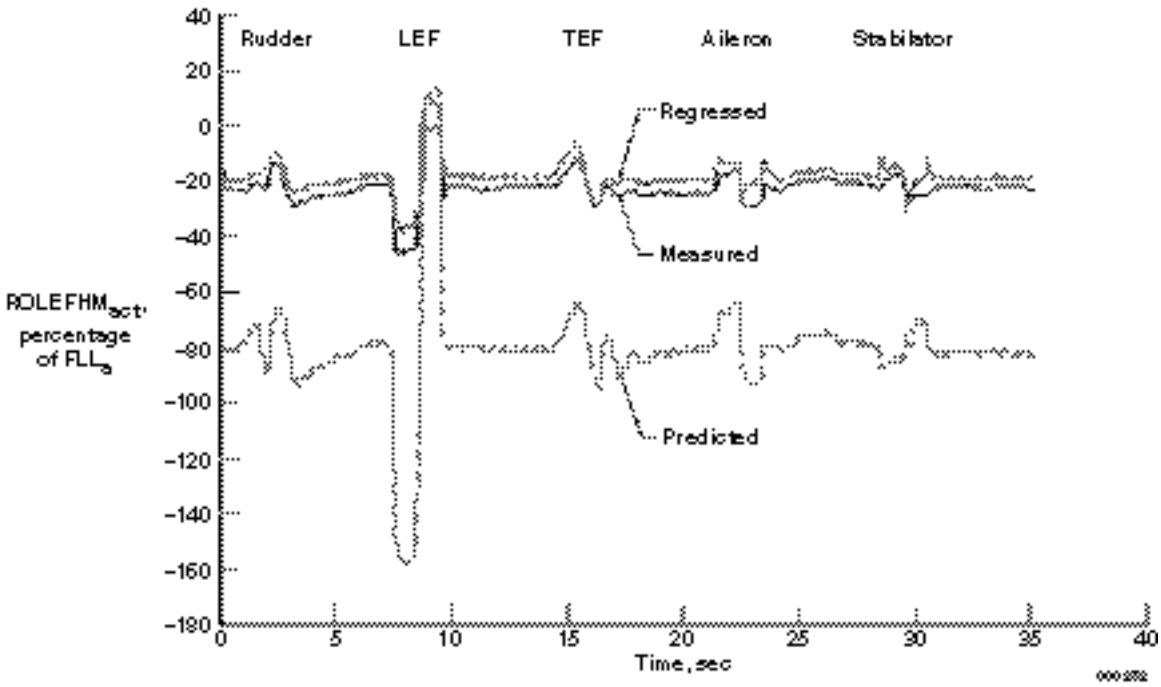



(b) Loads derivatives caused by symmetric inboard leading edge flap deflection.

Figure 10. Loads derivatives as a function of dynamic pressure at Mach 0.95.

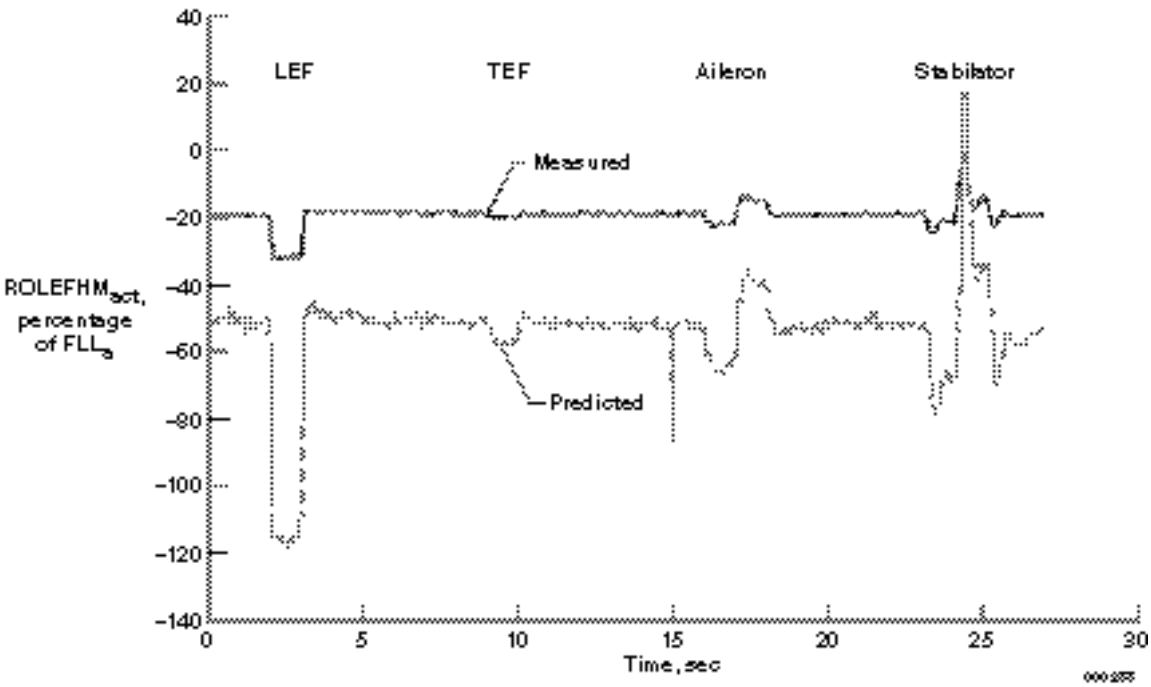



(a) As a result of large longitudinal doublets.

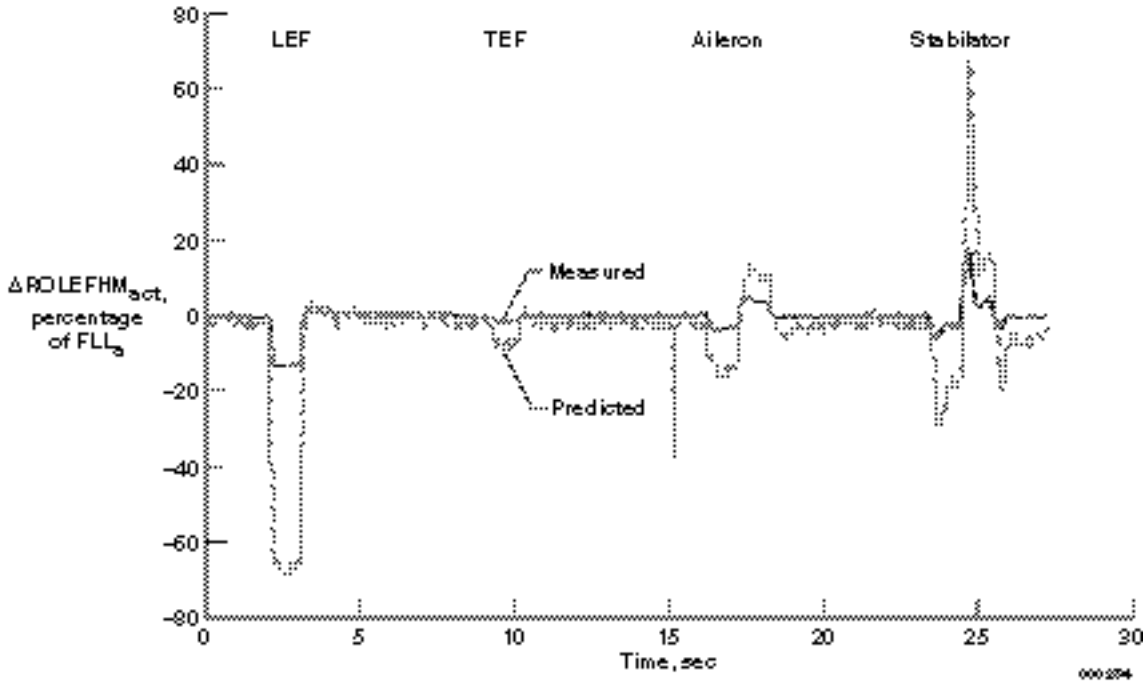



(b) As a result of large lateral-directional doublets.

Figure 11. Hinge moment as a function of time at Mach 0.95 and at an altitude of 10,000 ft.

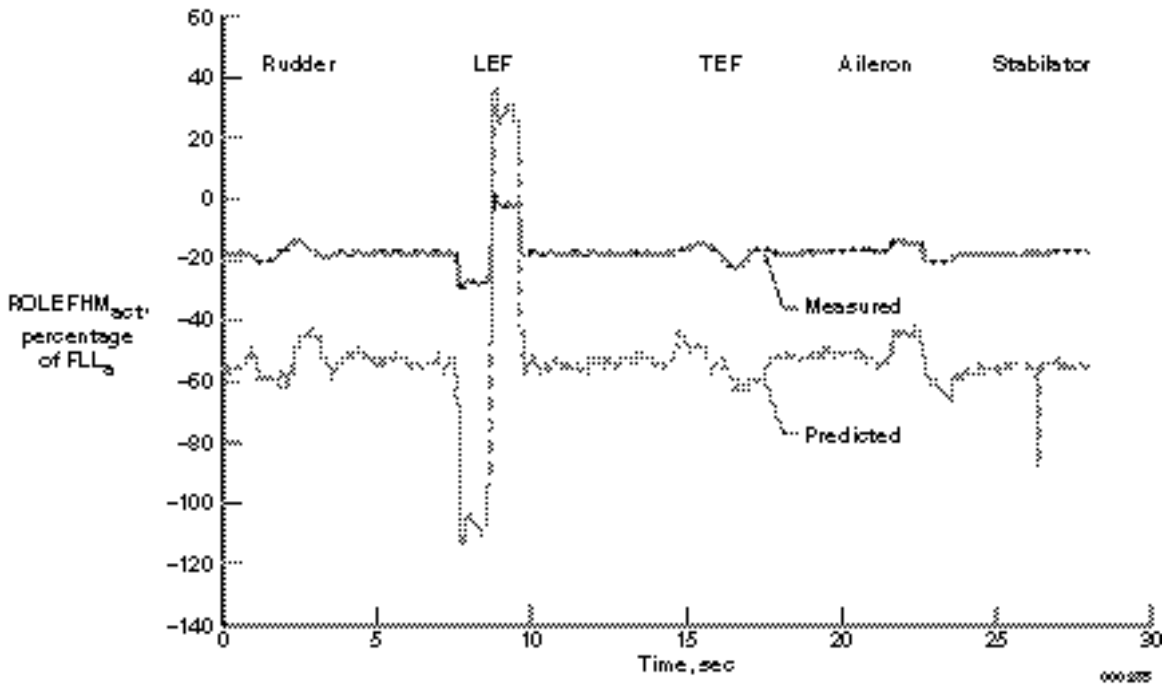



(a) Overall hinge moment.

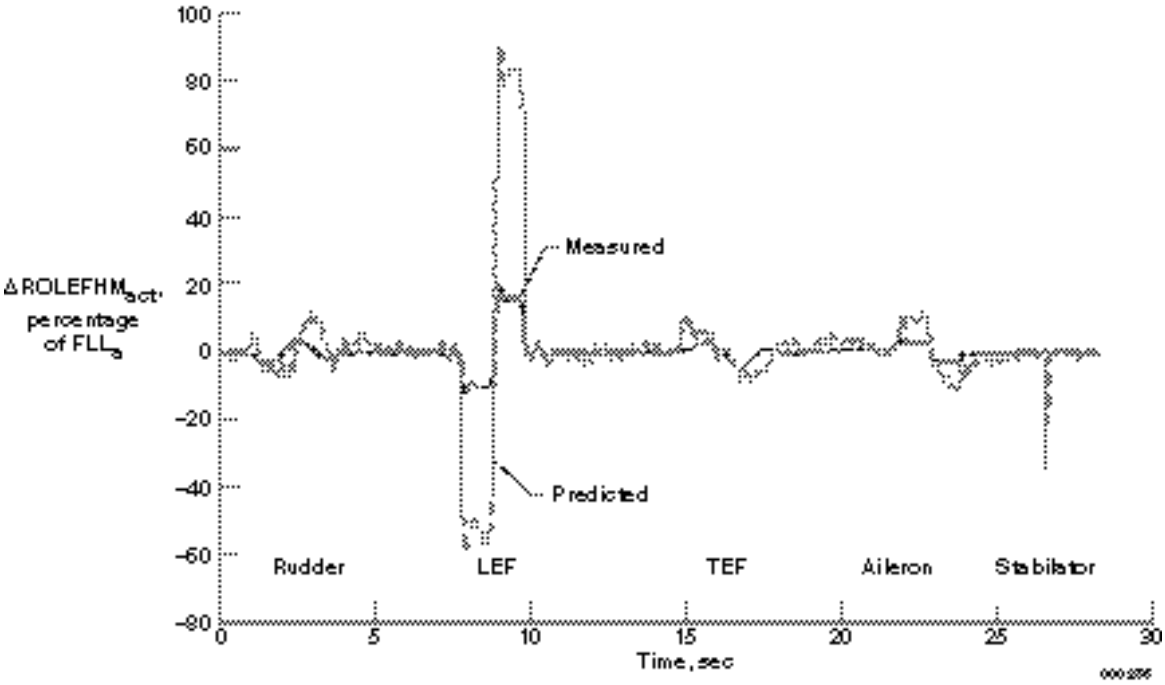



(b) With trimmed load removed.

Figure 12. Hinge moment as a result of small longitudinal doublets at Mach 1.1 and at an altitude of 10,000 ft.

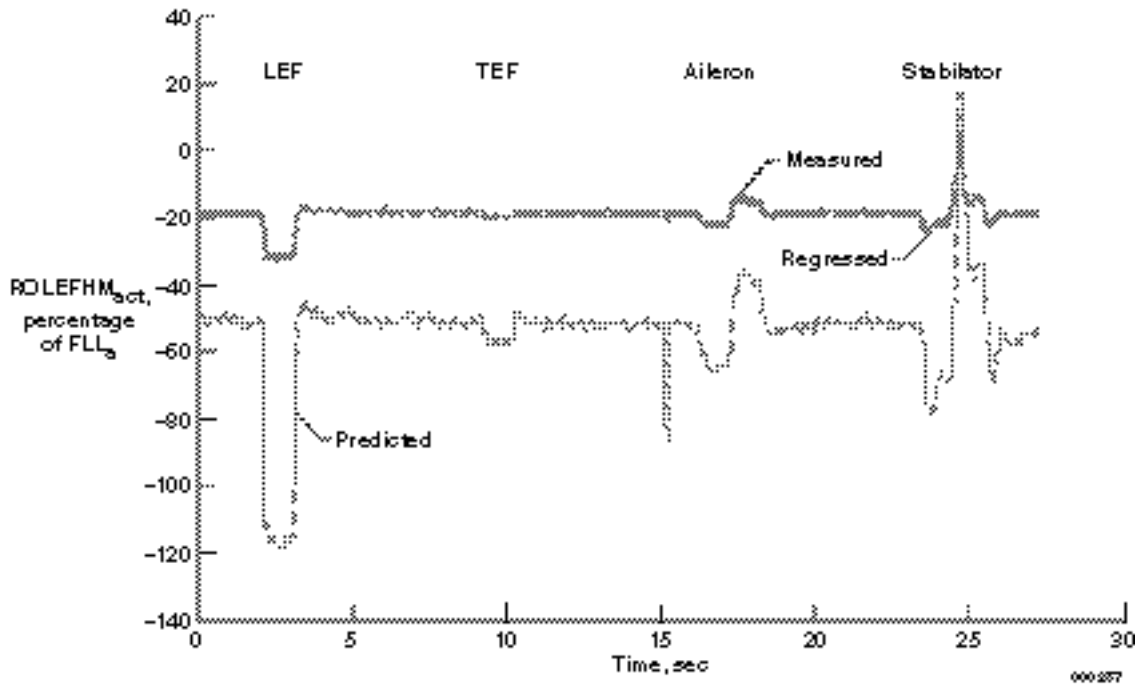



(a) Overall hinge moment.

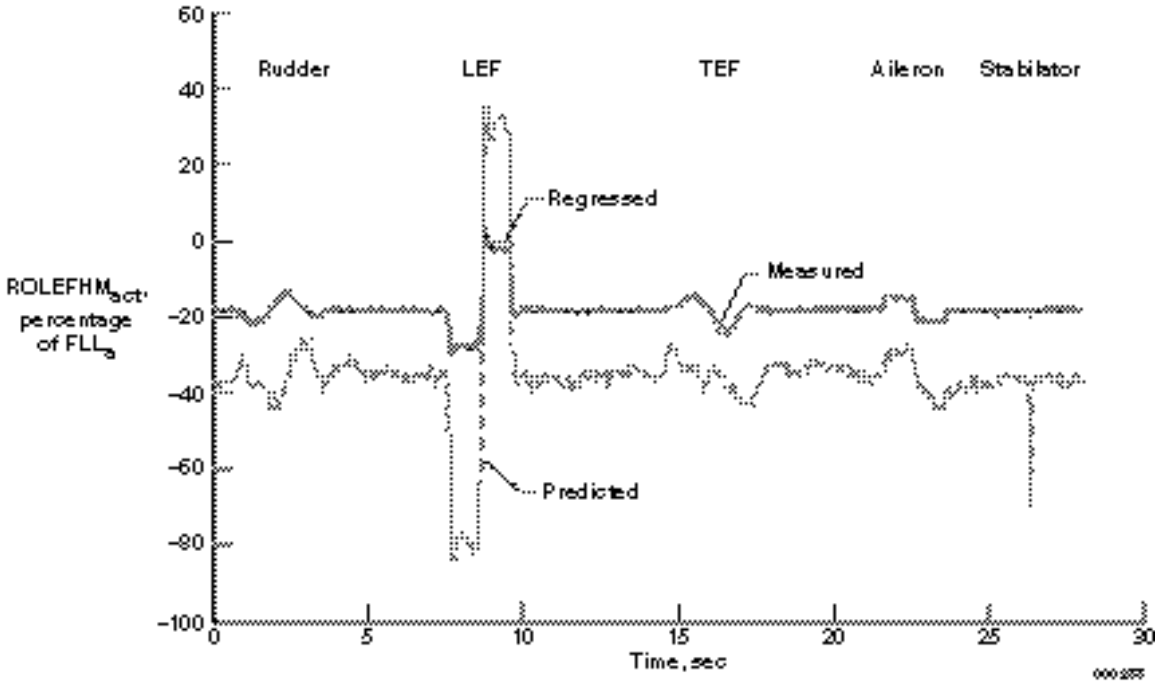



(b) With trimmed load removed.

Figure 13. Hinge moment as a result of small lateral-directional doublets at Mach 1.1 and at an altitude of 10,000 ft.




(a) As a result of small longitudinal doublets.




(b) As a result of small lateral-directional doublets.

Figure 14. Hinge moment as a function of time at Mach 1.1 and at an altitude of 10,000 ft.

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**13. ABSTRACT (Maximum 200 words)**

A limited evaluation of the F/A-18 baseline loads model was performed on the Systems Research Aircraft at NASA Dryden Flight Research Center (Edwards, California). Boeing developed the F/A-18 loads model using a linear aeroelastic analysis in conjunction with a flight simulator to determine loads at discrete locations on the aircraft. This experiment was designed so that analysis of doublets could be used to establish aircraft aerodynamic and loads response at 20 flight conditions. Instrumentation on the right outboard leading edge flap, left aileron, and left stabilator measured the hinge moment so that comparisons could be made between in-flight-measured hinge moments and loads model-predicted values at these locations. Comparisons showed that the difference between the loads model-predicted and in-flight-measured hinge moments was up to 130 percent of the flight limit load. A stepwise regression technique was used to determine new loads derivatives. These derivatives were placed in the loads model, which reduced the error to within 10 percent of the flight limit load. This paper discusses the flight test methodology, a process for determining loads coefficients, and the direct comparisons of predicted and measured hinge moments and loads coefficients.

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