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Flight Loads Test of the Indigenous Defensive Fighter

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Flight loads test is a primary structural verification test in fighter aircraft development. The indigenous defensive fighter flight loads test is the first complete flight loads test executed in Taiwan, Republic of China. The basic configuration part of the flight test, including flight loads survey and structural demonstration, was accomplished in 42 flights with external store configurations to follow. Results give both similarity and deviation compared to predictions, and numerous valuable experiences were accumulated from ground calibration test and flight test. One significant improvement in flight test, the automatic roll capability, was introduced to greatly improve maneuver quality during testing and resulted in safe and efficient flight test.

Introduction

THE indigenous defensive fighter (IDF) program was started in the mid-1980s by Aero Industry Development Center (AIDC) in Taiwan, Republic of China. The purpose of the program is to develop and manufacture a lightweight, high-maneuverability fighter aircraft to obtain defensive air superiority over the Taiwan Strait.

The basic configuration flight loads test of the IDF was executed from February 1990 to April 1991 at CCK AFB, Taiwan, R.O.C. The external store configuration flight loads test is planned to be conducted in the near future. The purpose of the flight loads test was to obtain data for determination of the structural adequacy of the IDF aircraft for the conditions determined critical through analysis and review of test data. The test employed buildup to, and demonstration of, the design limit conditions for the parameters determined to be critical. Test results will also be used to improve analysis methods or for advanced versions of the production airplane if needed (Fig. 1).

In this article, a brief description of the test article is given first, including a detailed discussion of the multifunctional test aid. Next is the introduction of loads and aircraft response measuring instrumentation; also mentioned are the test data recording equipment and the real time monitor facility. For the ground calibration test, the calibration methods, hardware setup, and the calibration results are described. The flight loads test objectives, test maneuvers, and test sequence are also depicted. Finally, the flight loads test results are presented with different component's load trends.

Test Article Description

The IDF is a lightweight, twin-engine, high-maneuverability fighter aircraft with midmounted, moderately swept wing. Highly swept strake and well-designed fuselage geometry blend the wing and fuselage into a lifting body. The leading-edge flaps deflect according to a preset angle of attack (AOA)-related schedule for optimal lift-to-drag ratio.

The IDF is controlled by a digital fly-by-wire flight control system that consists of three independent sets of sensors, three channels of digital flight control computer, one channel of analog backup flight control computer, and electrically signaled actuators. The pilot's control inputs are transferred into digital signals inside the flight control computer together with other sensors' response. After processing by the operational flight program in the computer, the outputs are sent to different actuators to maneuver the aircraft. The continuous control and feedback cycle described above makes advanced test aids possible during the flight test program.

For the IDF flight test program, a unique multifunctional test aid was developed. The flight control test/flutter panel (FCT/FP) is designed to excite control surface for the flutter flight test, generate control doublets for the flight control test, and provide various limiters and control inputs for the flight loads test.

All the required functions and limiters were designed and put into the flight control computer according to test requirements. The FCT/FP worked as a pilot terminal to select and enable the function or limiter needed. Any of the 99 selections can be selected by use of a pair of push wheels. After the enable switch is turned on, an armed light indicates the function or the limiter is set. Several ways are available to disable the FCT/FP setting if desired. The most used and convenient way is to hit the paddle switch on the control stick.

The *g*-command limiter provides variable load factor limiting that is essential for the test program. Lateral/directional maneuvers are very difficult to perform while maintaining the

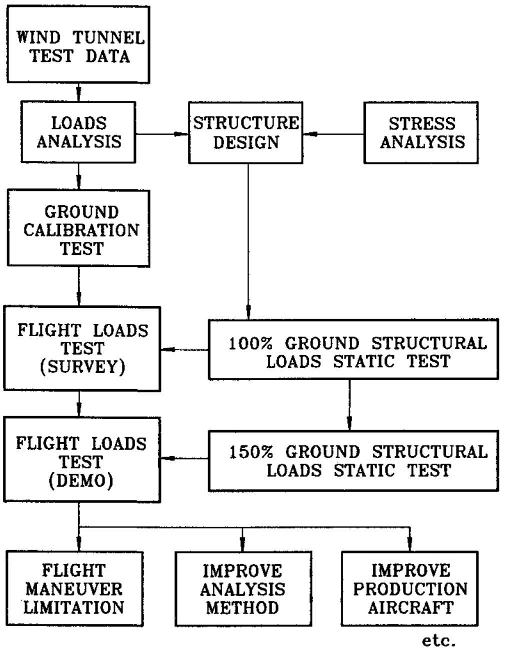

Fig. 1 Static loads analysis and loads test flow chart.

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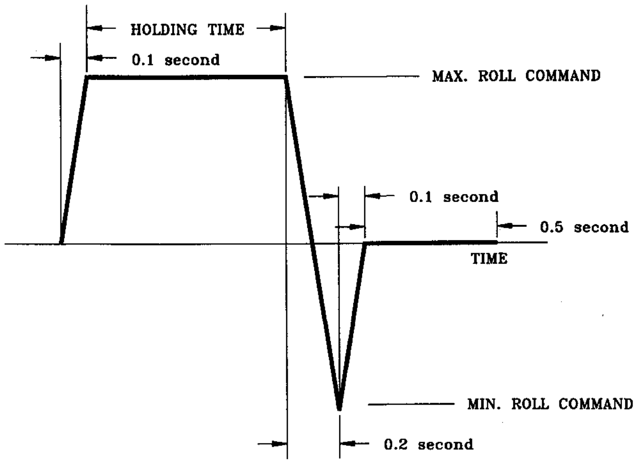

Fig. 2 Roll command time history in automatic roll function.

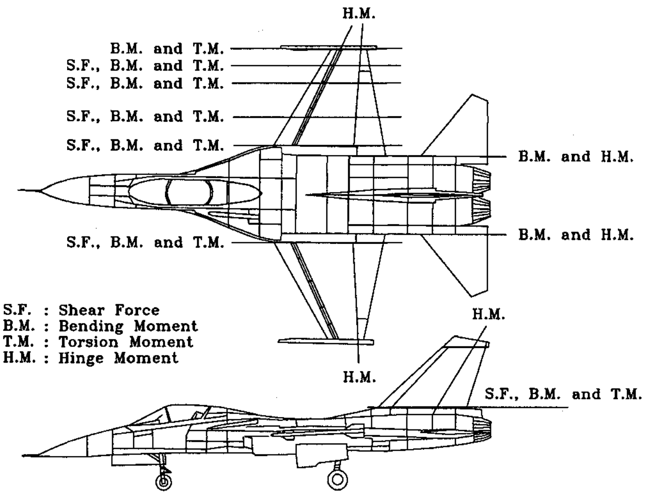

Fig. 3 IDF flight loads measurement.

required constant *g*-command, and would require many repeats without the limiter. Symmetric maneuvers performed with the limiter avoids inadvertent *g* overshoots.

The rudder pedal command limiter (right side only) makes exact partial abrupt pedal input possible for directional maneuvers, while allowing full left pedal command.

The automatic roll command function not only incorporates *g*-command and roll-rate-command limitings, but also generates roll commands that exactly duplicates structural design criteria maneuver requirements.[1] Since the value of *g*-command limit could be previously determined, standard entry conditions of level or elevated-*g* roll at different speeds and altitudes are easily reached by the pilot with a full aft stick and proper bank angle. The most powerful part of the function is the preset roll command (Fig. 2), where the holding time duplicates analysis requirements in flight test and the difficult-for-human design criteria roll command input is executed exactly the same for every roll maneuver. Once at the correct entry conditions, the rolls are initiated by use of the trim button.

The roll-rate-command limits provides a buildup approach from lower roll rate to critical high roll rate maneuvers. With all the aids that the automatic roll command function supplied, the pilot's work load during roll maneuvers, especially elevated *g* rolls, is greatly reduced by elimination of repeat rolls, which also contributes to greater test productivity.

Instrumentation and Data Recording

The purpose of the test was to obtain quality data. In the IDF flight loads test, both the loads and aircraft response data were measured and analyzed. Shear force, bending moment,

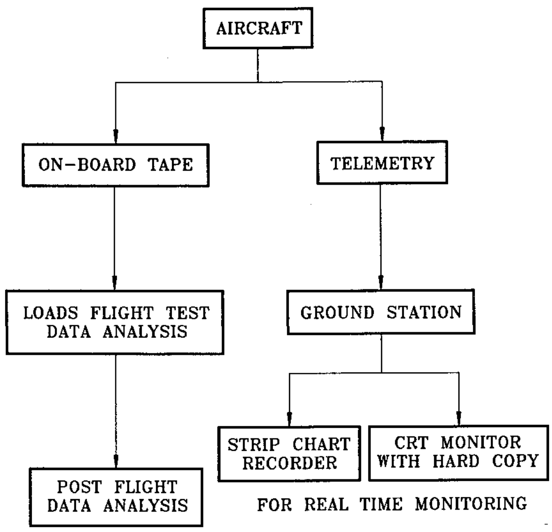

Fig. 4 Flight loads test methodology.

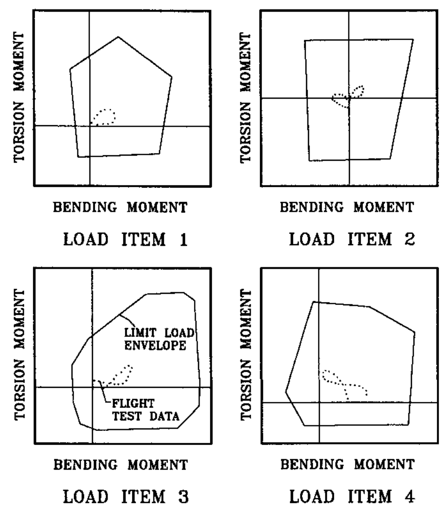

Fig. 5 Graphic CRT real time display.

and torsion moment were measured at five distributed right wing stations (from root to tip), left wing root section, and vertical tail (VT) root section. All the control surfaces, including left and right trailing-edge flaps (TEF), rudder and both horizontal tails (HT), had hinge moment measurement, plus right leading-edge flap (LEF) hinge moment and root bending moment for both horizontal tails.[2] A total of 161 load strain gauge bridges were installed to satisfy the requirements stated above (Fig. 3). Another 72 channels were used for wing and fuselage stress data.

The aircraft response parameters were also measured during the test. All those parameters that would interact with the loads magnitude and distribution, e.g., airspeed, Mach number, altitude, angle of attack, control surface deflections, and pilot stick forces, were scanned and recorded together with the loads data.

Single strain gauge bridges were used to measure simple structure loads like control surface hinge moments. For the complicated structure, parallel circuits were made to combine several strain gauge bridge outputs to describe the loads.

Since test data were required for both real time monitoring and postflight analysis, the onboard data system had the ability to record and transmit test data at the same time. The onboard data system consisted of a pulse code modulation (PCM) data system incorporating power supply and signal-conditioning equipment, a pilot operated magnetic tape recorder, and a telemetry (TM) system.

Continuous ground monitoring of the TM signal and test control via voice communication in flight test control room was possible. Real time display of the TM signal was accomplished on strip chart recorders and cathode-ray tube (CRT) monitors. All the data displayed were the output from the ground station computer that gave direct, combined, or calculated data from both response and load sensors (Fig. 4). Two types of CRT displays were used for different real time data. The status CRT that displayed alpha-numeric data with one refreshment/s provided flight condition, fuel, and flight control information and responses of the aircraft. The graphic CRT gave real time plots of combined wing, VT and HT bending-torsion loads compared with limit load envelopes. Rapid hard copy of the graphic CRT was available (Fig. 5). With all the essential data being displayed and monitored, safer and better tests were accomplished.

Ground Calibration Test

To interpret strain gauge output from flight loads test, the gages need to be calibrated on the ground. The method was very straightforward: load the aircraft, read the outputs, and relate outputs to loads. However, the design and operation of the ground calibration test (GCT) were more complicated and experienced some difficulties.[3]

The fully combined circuits were utilized to combine certain strain gauges' outputs for representing specific loads.[3] Choices of the strain gauges to be combined were determined through a regression analysis method.

The hardware setup of the GCT (Fig. 6) included the main fixture to hold the aircraft in place, the Edison Unit to supply hydraulic power and regulation for the load-applying actuators, the actuators and whipple trees to apply correct loads in both magnitude and distribution, and the data monitoring and recording system. Other safety equipment like deflection safety switches and potentiometers were used for emergency shutdown of the hydraulic power and for deflection indication that supplied extra safety control of the test.

Design criteria maneuver loads are varied and so were the calibration load distributions on the aircraft. Thus, various loading conditions were chosen to make the calibration complete. For example, using the 80% structural limit load envelope (see Fig. 5) as reference, loading conditions were chosen from all four quadrants. The analytical loading distributions were utilized to design calibration loading conditions. Both the distribution and magnitude of the loads were carefully considered to generate different, relatively high, but safe loading conditions that gave realistic load-response relationships.[1,4]

Conventional load applying methods were used in wing load calibration, which loaded relatively large areas (compared to Ref. 3) for different conditions.[5] Previous experience with similar wing/LEF designs has shown an influence of LEF position on strain gauge sensitivity. A fixed 5-deg (leading-edge down) deflection of both LEFs was a reasonable compromise from various deflections for different loading conditions. The reason was that most of the critical maneuver loading conditions are with 0–10-deg LEF deflections. It also saved valuable test time and manpower. Compression pads were used to load the LEFs, while load actuators were connected to the TEFs' hinge points on the wing box. Inboard and outboard parts of the wing box were loaded separately through inboard weapon hardpoints and with tension/compression pads. To simulate wingtip loads, a one-piece dummy missile-launcher was loaded.

The LEF hinge moment calibration test was executed with the flap mounted on the wing.[5] Since LEF is driven by 4 rotary actuators on the 4 hinges, and the total hinge moment is the sum of them, each hinge was calibrated with the others disconnected to get individual calibration slope. A special tool was designed to hold the LEF in place and lock the hinge being calibrated.

The VT calibration loading method was unconventional compared to the wing since the entire VT was loaded for all calibration conditions, varying the c.p. to simulate all types of design load conditions.[5] Individual load actuators had different outputs for each loading condition. This method resulted in higher loads and accuracy together with efficiency since no setup changes were required after the initial setup.

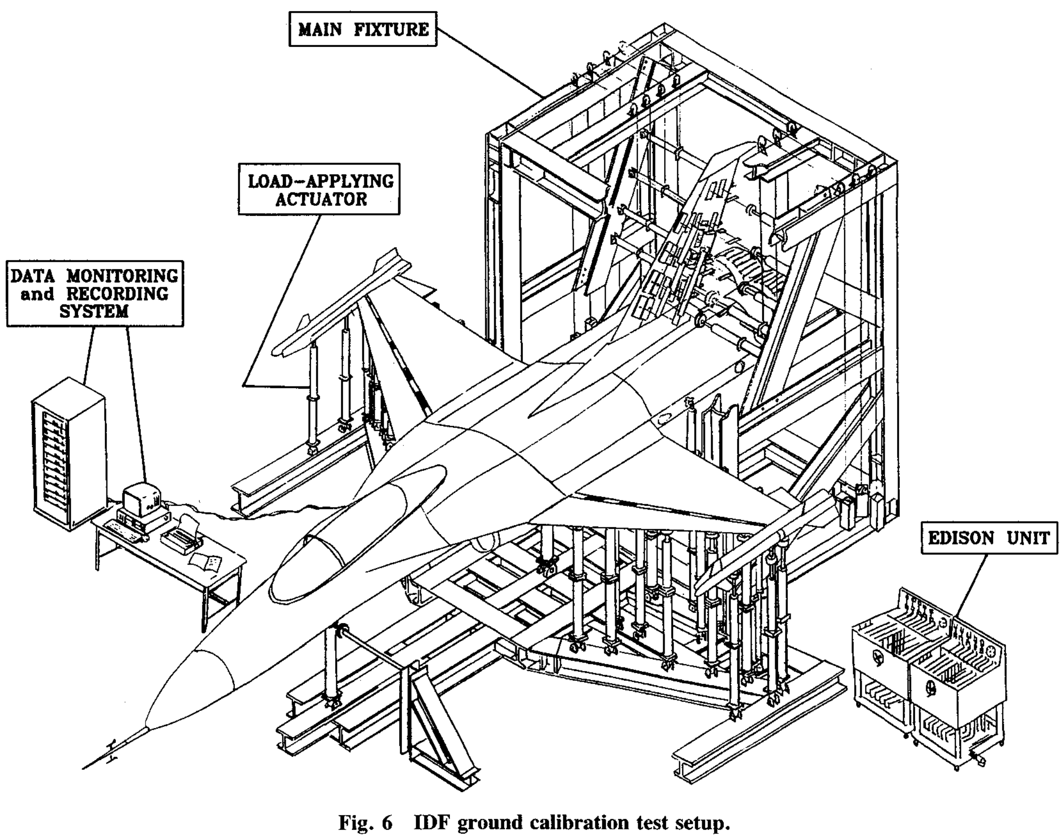

Fig. 6 IDF ground calibration test setup.

Tension pads with whipple trees applied loads on VT leading-edge and main box portions. Rudder hinge points were also loaded with actuators. Total time for VT calibration was 4 days, including setup, 11 load conditions, regression analysis, circuit fabrication and installation, and two check load conditions.

On the HTs, only the root bending moments were calibrated.[6] The HT is normally inserted into the aft fuselage through a single shaft, and therefore it was possible for the tails to be calibrated apart from the aircraft. The HT bending moment calibration test was executed on a fixture with real fuselage bearings and dummy control actuator to simulate the real condition. Compression pads and load actuators were arranged to generate bending moment with different torsion moments.

The last part of the GCT was control surfaces' hinge moment calibration.[7] With all the control surfaces being driven by single actuators and supported with simple hinges, only the control actuators axial force needed to be calibrated for hinge moment calculation. Actuators were put into a universal test machine with both ends connected and aligned to take axial forces. Tension and compression forces were both applied under fully extended (for tension only) and retracted (for compression only) configurations to protect the actuator and exclude the pressure influences from the hydraulic fluid. Calibrations of all control surfaces' actuators were executed right after the components were delivered to save time.

Micro Measurement System 4000 worked as the real time data monitor and raw data recorder. Self-developed BASIC and C-coded programs were used to transform and process the raw data on personal computers for simple curve-fitting analysis. Complicated regression analyses, for wing and VT only, were executed in Control Data Corporation main frame computer.

Load vs strain gauge response slopes were the results, but varied in types and usage afterwards.[8] For the LEF and all control surfaces' hinge moments plus HT bending moments, single bridge calibration slopes were passed on directly to flight test data processing system. For the wing and VT, different combined circuits were designed and manufactured to meet regression analysis results. Several principles were used to select the optimal strain gauge combinations for specific load measurements. High accuracy and good sensitivity were the basic principles for the combination. When several load measurements' equations require one specific strain gauge in them, the priority of these load measurements decides which load measurement can include the strain gauge. For example, since wing bending moment is more important in load analysis than pitching moment and shear, bending moment equation has higher priority. After connecting the required strain gauges to the circuits, final check calibration load conditions were applied to verify regression analysis and circuits' performance. Final results were quite good, with acceptable measurements being developed for all required data items.

Flight Test

The IDF flight loads test plan was published in September 1988, which included test objectives, success criteria, aircraft configuration, test maneuvers and sequence, instrumentation requirements, data display requirements for both real-time and postflight data processing.[9]

Among the test objectives, the following ones were considered most important and interesting to loads analysis group:

1) Comparing flight measured load distributions with predicted values can either give proof to present analysis methods or supply data base for revising these methods. To fulfill this objective, design criteria maneuver loads were compared from analysis and flight test. Level flight 360-deg roll, e.g., was chosen for critical TEF hinge moment.

2) Determination of flight maneuver limits is one of the main concerns of the customer.

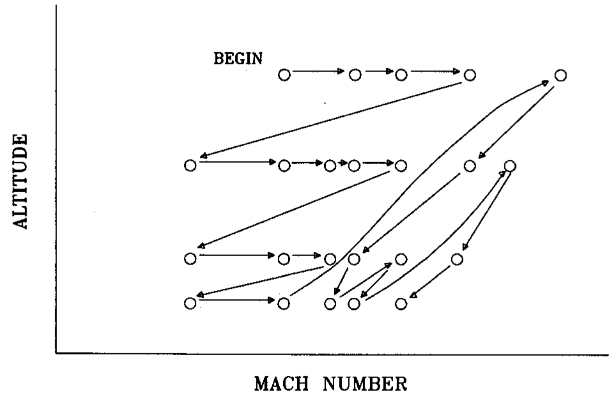

Fig. 7 Flight loads test sequence.

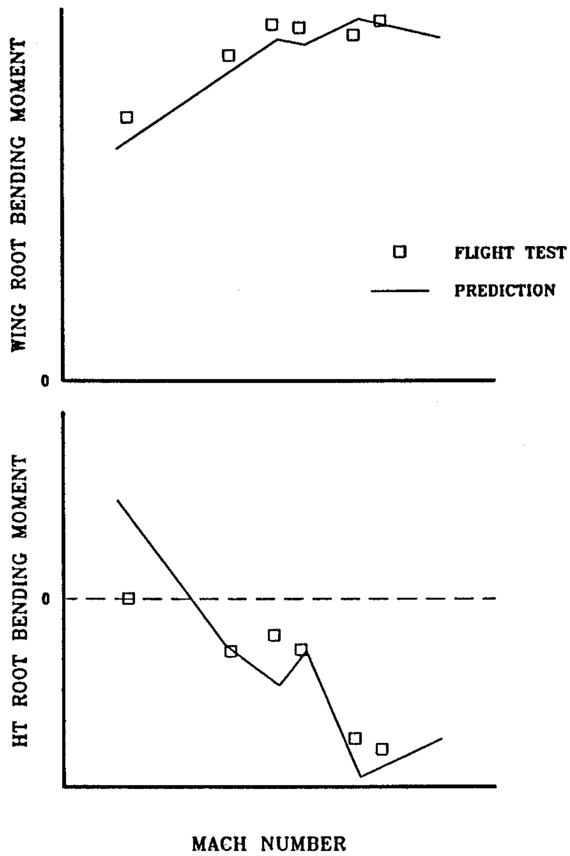

Fig. 8 Wing and HT root bending moment in symmetric maneuvers.

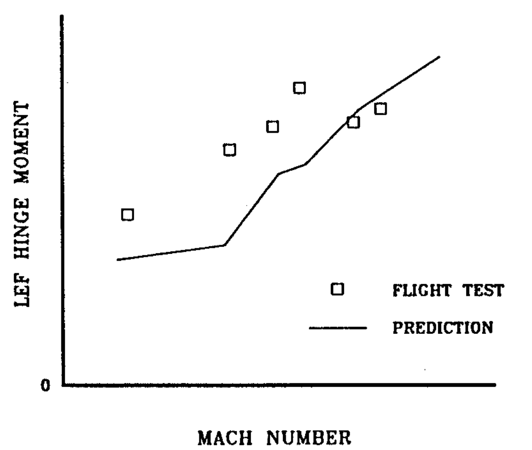

Fig. 9 LEF hinge moment in symmetric maneuvers.

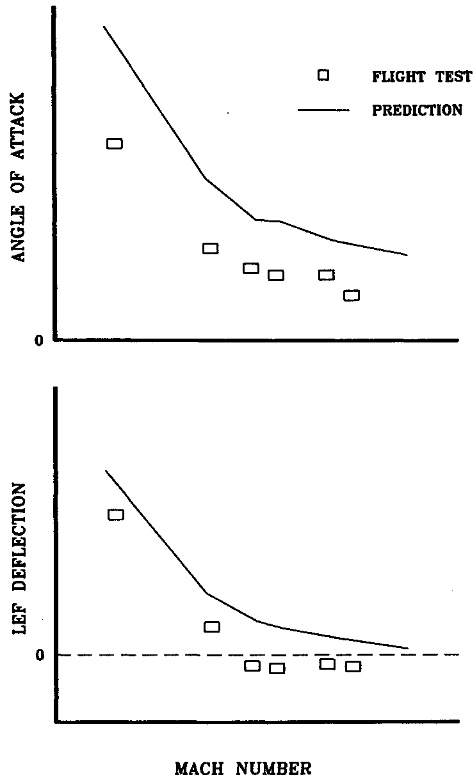

Fig. 10 AOA and LEF deflection in symmetric maneuvers.

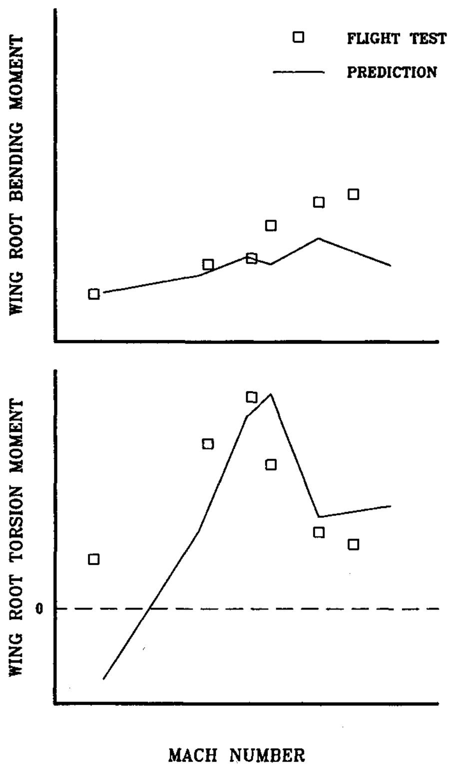

Fig. 11 Wing root bending moment and torsion moment in elevated-*g* roll maneuvers.

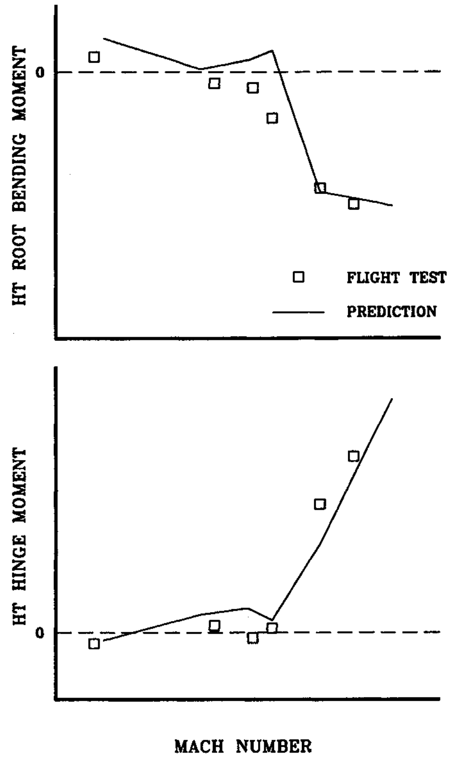

Fig. 12 HT root bending moment and hinge moment in elevated-*g* roll maneuvers.

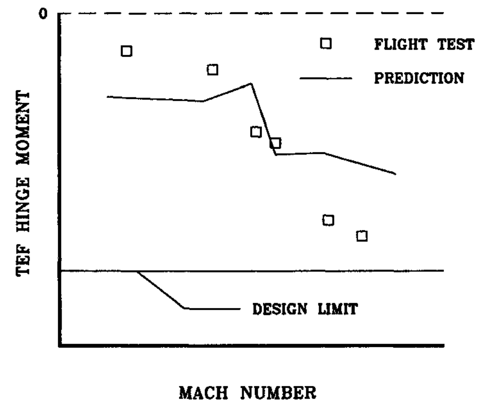

Fig. 13 TEF hinge moment in elevated-*g* roll maneuvers.

3) Revised loads for the production airplane from improved analysis results is the most realistic objective and gives direct benefits to the program.

The test was conducted in two phases, 80% loads survey and 100% structural demonstration. The major restriction for the first phase was not exceeding 80% design loads, and survey test results were then used to predict 100% structural loads and conditions. With this predicted 100% structural loads, stress group executed the ultimate strength static loads ground tests (150%) to expand the structural flight limit to 100%. Demonstration maneuvers were then flown to 100% limits.

Test maneuvers are listed as follows, along with how the FCT/FP provided assistance: 1) balanced symmetric maneuvers (positive and negative): *g*-command limiter; 2) abrupt pullup/pushover: *g*-command limiter; 3) slow down turn: *g*-command limiter; 4) automatic $-1\,g$ 180-deg roll: *g*-command limiter, roll-rate-command limiter, and programmed roll command input; 5) automatic 1 *g* and elevated *g* 360-deg rolls: *g*-command limiter, roll-rate-command limiter, and programmed roll command input; 6) slow sideslip: *g*-command limiter and rudder-pedal-command limiter; 7) low- and high-speed rudder kicks: *g*-command limiter and rudder-pedal-command limiter; 8) rudder reversal: *g*-command limiter and rudder-pedal-command limiter.

The flight areas to execute the maneuvers listed above were at four different altitudes and seven different speeds, ranging from subsonic through transonic to supersonic (Fig. 7). The sequence of flight tests was designed to utilize already obtained test data for prediction of the following test conditions.

The flight test started on February 12, 1990, and lasted 14 months until April 18, 1991. A total of 149 test points were

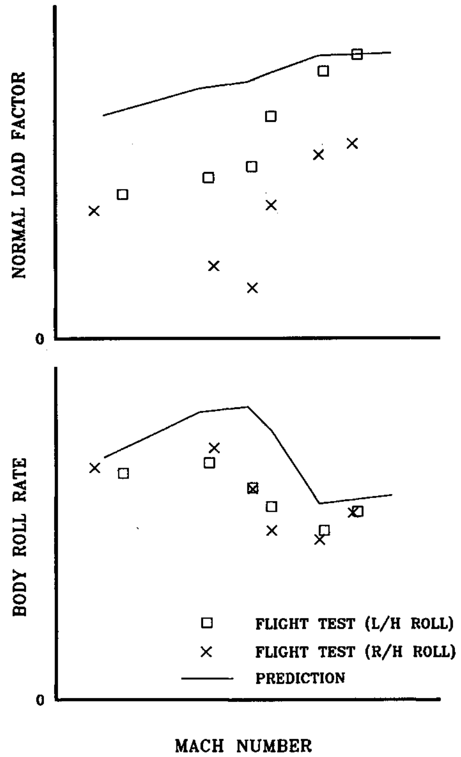

Fig. 14 Normal load factor and body roll rate in elevated-*g* roll maneuvers (L/H and R/H roll included).

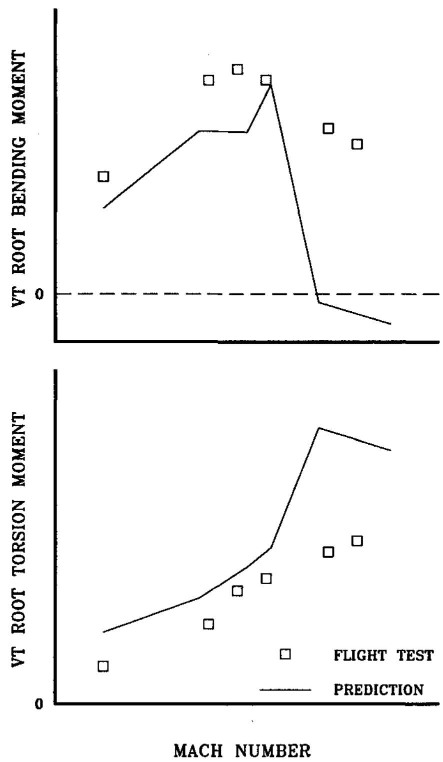

Fig. 15 VT root bending moment and torsion moment in steady sideslip maneuvers.

completed in 42 flights (40 flights were planned in advance). The first automatic roll condition utilizing the FCT/FP was executed on May 10, 1990. The great improvement in flight test safety, maneuver quality, and productivity was a proud achievement of AIDC.

The results of this safe, efficient, and minimum repeats flight test were made possible through total cooperation of test pilots, professional groups, and manufacturing and data processing engineers. Selected results of the IDF flight loads test are shown in the next section.

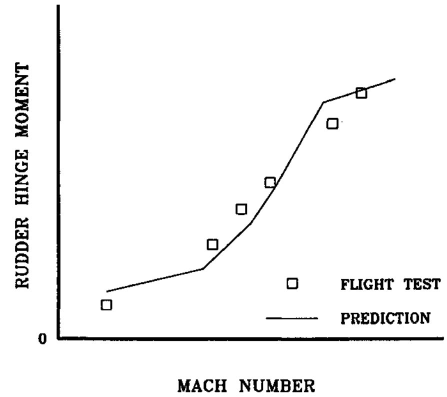

Fig. 16 Rudder hinge moment in steady sideslip maneuvers.

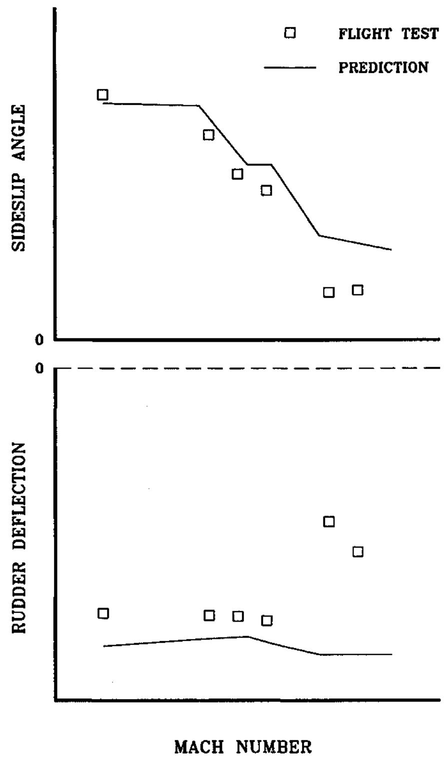

Fig. 17 Sideslip angle and rudder deflection in steady sideslip maneuvers.

Results

Selected flight test data are shown for symmetric, roll, and directional maneuvers in Figs. 8–10, Figs. 11–14, and Figs. 15–17, respectively. Generally speaking, the flight test data agree well with predictions, but some deviations existed.[10]

For example, wing and HT root bending moments agreed with predictions very well in symmetric maneuvers (Fig. 8). However, for LEF hinge moment (Fig. 9), although the maximum load is lower than prediction, subsonic loads are higher, which could result in durability concerns since most usage is at subsonic conditions. The lower than predicted angle of attack and induced lower LEF deflection are the reasons for the deviation stated above (Fig. 10).

Another good example is shown in elevated *g* 360-deg roll maneuvers. The wing and HT root loads compare well with predictions (Figs. 11 and 12). The TEF hinge moment shows some differences but is still well inside the design limit (Fig. 13). Obvious deviations are the aircraft response data (Fig. 14). The normal load factor and the roll rate differ from predictions, and in addition, the normal load factors during left and right rolls are different from each other.

The comparison results of the directional maneuvers are significant only for the VT and the rudder. The bending and torsion moments of the VT compare well with the analysis in the low-to-medium speed range, but deviate in the high-speed zone (Fig. 15). However, the rudder hinge moment matches the prediction in every speed range (Fig. 16). As for the aircraft responses, the test data and the prediction also differ in high-speed range (Fig. 17).

The IDF flight loads test is the first Military Specification-type flight loads test conducted by AIDC. The program enjoyed much success and encountered fewer difficulties than expected. Perhaps the biggest difficulty was to persuade the engineers and pilots to have confidence in using the FCT/FP to execute the flight test. The data obtained from this test will serve as the basis for updated loads analysis for current and future IDF versions.

We gained a great deal of experience from this test and expect future test programs will be even more successful.

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