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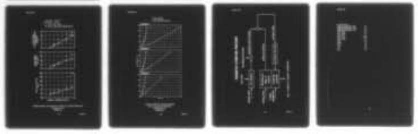

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Technical Memorandum

ON IMPROVING THE FLIGHT FIDELITY OF OPERATIONAL FLIGHT/WEAPON SYSTEM TRAINERS

by

CDR M. D. Hewett
Mr. R. T. Galloway, Jr.

Strike Aircraft Test Directorate

7 October 1975

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A team approach utilizing the complementary talents and expertise of Naval test pilots, flight test engineers, computer specialists, and simulator specialists from various Naval field activities has been effective in improving the flight fidelity of existing Operational Flight Trainers and Weapon System Trainers and in guiding contractors in providing the best fidelity possible in new flight simulators. The paper discusses this team approach and presents the results obtained in several programs.

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PREFACE

This Technical Memorandum contains a paper which will be submitted to the joint Flight Mechanics Panel/Guidance and Control Panel Symposium on "Flight Simulation/Guidance Systems Simulation." The conference is to be held in The Hague, Netherlands, on 20 - 24 October 1975. An abstract of the paper was submitted and accepted by the Technical Program Committee on 21 February 1975. The paper will be presented by CDR M. D. Hewett (primary author) in Session IV at 1400 on Tuesday, 21 October 1975.

APPROVED FOR RELEASE
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ON IMPROVING THE FLIGHT FIDELITY OF OPERATIONAL FLIGHT/WEAPON SYSTEM TRAINERS

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SUMMARY

A team approach utilizing the complementary talents and expertise of Naval test pilots, flight test engineers, computer specialists, and simulator specialists from various Naval field activities has been effective in improving the flight fidelity of existing Operational Flight Trainers and Weapon System Trainers and in guiding contractors in providing the best fidelity possible in new flight simulators. The paper discusses this team approach and presents the results obtained in several programs.

The team uses conventional flight test techniques to quantify the parameters necessary to describe the flying qualities and performance of the simulator and the airplane. From this comparative data the flight fidelity deficiencies of the simulator are quantitatively identified. The software of the simulator (and in rare instances the hardware) is then modified by an iterative process until the flying qualities of the simulator match those of the airplane. The paper discusses this process of matching flying qualities by conventional flight test techniques in detail.

In addition, recent advances in the field of parameter identification are discussed as applied to the extraction of stability derivatives from flight test data. An advanced state-of-the-art maximum likelihood estimation algorithm is now operational at the Naval Air Test Center. This algorithm can and is being used in several active programs to provide an accurate flying qualities and performance data base for a given airplane.

SYMBOLS

C_D	drag coefficient
C_L	lift coefficient
C_M	pitching moment coefficient
C_N	yawing moment coefficient
C_l	rolling moment coefficient
$C_{M(x)}$	pitching moment derivative
$C_{N(x)}$	yawing moment derivative
$C_{l(x)}$	rolling moment derivative
$C_{Y(x)}$	side force derivative
p	roll rate
q	pitch rate
r	yaw rate
δ_a	lateral control deflection
δ_e	longitudinal control deflection
δ_r	directional control deflection
n_z	normal acceleration
S	wing area
u	true airspeed
W	gross weight
k	a constant
α	angle of attack
β	sideslip
δ	control deflection
ζ	damping ratio
ρ	air density
ω	frequency

<u>Subscripts</u>

n	natural
d	damped

INTRODUCTION

The U. S. Navy uses Operational Flight Trainers (OFT) and Weapon System Trainers (WST) to train pilots in today's complicated and expensive aircraft weapon systems. Over the years these devices have acquired a dismal reputation for faithful simulation of a given airplane's flying qualities. As a result the training value of these simulators has been less than optimal. In many cases this lack of faithful flying qualities simulation has reduced the role of these expensive devices to that of procedures trainers for instrument flight and emergency conditions vice that for which they were designed: complete operational flight and weapon system training.

This degraded training value could be tolerated by the Navy as long as enough airplanes, fuel, and money were available to train and maintain proficiency with actual flight time. However, the energy crisis, increased aircraft operating costs, and austere budgeting have made actual flight time an expensive commodity. Because of these factors increased emphasis has been placed on the use of simulators for training and proficiency. In fact, the Chief of Naval Operations has issued instructions (reference (1)) that Naval Aviators participating in the Proficiency Flying Program may substitute 10% (10 hours) of their total annual minimum flight time requirement with 12 hours or more of simulator time on a certified OFT or WST. The instruction further states that "as additional simulators become available and more is learned on the 'transfer of learning' gained through the use of simulation, the program will be expanded." With this ever increasing emphasis on the use of simulators for training and proficiency and the growing need to actually substitute simulator time for flight time, we have found it absolutely necessary to bring our full technical resources to bear on the problem of providing the best flight simulation possible within given cost constraints.

Another factor which has highlighted the need for faithful flying qualities simulation in Operational Flight and Weapons System Trainers is the addition of visual display systems. Carrier and field landings, aerobatics, weapons delivery, and a multitude of other mission related tasks can now be simulated with visual systems. The addition of such systems, however, tends to magnify the flying qualities and performance discrepancies of the basic simulator. Recently, a visual display system was added to one cockpit of a 2F90 Device at the Naval Air Station, Kingsville, Texas. It was quickly found that simulated carrier and field landings and bombing runs with the visual display had relatively little training value for student pilots because the simulation of the real TA-4J airplane flying qualities was so poor.

Generally, Operational Flight and Weapons System Trainers are capable of providing excellent flying qualities and performance simulation of the real airplane. Although hardware limitations are always a factor, it is poor software programming that is responsible for most of the degradation in flying qualities simulation of the typical trainer. Aircraft manufacturers generally rely on the wind tunnel data as a data base. Flight test data are not available because the first training device is usually delivered to the Fleet at about the same time that the first airplane comes off the production line. Since wind tunnel data represent at best only an estimate of airplane flight characteristics, the use of these data as a data base for a simulator results in poor flying qualities simulation. In addition, there has been no organized effort within the Navy or by any manufacturer to reprogram a simulator once flight test data are available. The 2F90 Device is typical. Although this device has been around for years and TA-4J airplanes have acquired thousands of flight hours, the device until very recently still used wind tunnel data as a data base.

Furthermore, simulator manufacturers have been ineffective in transforming fleet user flying qualities complaints into viable fixes for fidelity improvements. Fleet pilots, used exclusively in the past for fleet acceptance of a new simulator, are capable of recognizing a flying qualities discrepancy, but they are simply not trained to describe an aerodynamic phenomenon in engineering terms. The communications gap between the fleet pilot and the simulator specialist is difficult to overcome.

Recently, the Naval Air Test Center (NATC) has become involved in an effort to improve the flight fidelity of existing Operational Flight and Weapons System Trainers and in evaluating and improving the flight fidelity of new trainers. Results indicate that NATC has been effective in bridging the communications gap between the fleet pilots (user) and the simulator specialist. Conventional flight test techniques are used in the simulator and in the airplane to identify and quantify the flying qualities deficiencies of the simulator. The test techniques used are standard flying qualities and performance tests (references (2) and (3)) designed to isolate the effects of specific stability derivatives and performance parameters which provide the data base for the simulator. The data base is then modified as required and the tests repeated in the simulator and the airplane until a match is obtained.

A team approach to the problem has made this process possible. The necessary team members are fleet experienced pilots intimately familiar with the airplane being simulated, test pilots trained in flying qualities and performance testing, flight test engineers experienced in both flight test techniques and simulators, and simulator and computer experts with an intimate knowledge of simulators in general and the simulator under test in specific. Such teams composed of personnel from the Naval Air Test Center, the Naval Training Equipment Center, the Naval Education and Training Program Development Center and the Naval Air Training Command have been successful in significantly improving the flight fidelity of the 2F90 Device which simulates the TA-4J airplane and the new 2F101 Device which simulates the T-2 airplane both used by the Naval Air Training Command.

Recent advances in the field of parameter identification as applied to flight test have significantly improved the process of extracting stability derivatives from flight time history responses to certain control inputs. The identification algorithm used at the Naval Air Test Center is based on a maximum likelihood estimation scheme which includes a rank deficient solution, and the capacity to handle both instrumentation and process noise. The algorithm has direct application to simulation flight fidelity because a far more accurate and complete data base can be provided from flight test data than was ever possible in the past. The process is expected to have a significant impact on simulator software programming.

This paper describes the ongoing programs at the Naval Air Test Center to improve the flight fidelity of operational flight trainers using both conventional flight tests and advanced systems identification techniques. Conventional test techniques will be described as to the exact flight tests used, their order of application and the iterative process of optimizing the software package of a given simulator for good flight fidelity. The parameter identification program will be discussed and results obtained from flight tests will be presented. The application and extrapolation of parameter identification techniques to improve simulator flight fidelity will be outlined.

CONVENTIONAL TEST METHODS

General

The conventional flight test techniques used to identify and quantify the flight fidelity discrepancies of a given OFT or WST are described in this section. These conventional test methods are the standard performance, stability, and control flight tests methods used to test new aircraft for flying qualities and performance specification compliance. They are described in detail in references (2) and (3). It is possible with these methods to isolate the effects of a number of the stability derivatives and coefficients required to complete the mathematical model used in the simulator software to model the motion of the simulated airplane. The effects of many other important coefficients and derivatives on the response of the simulation to control inputs cannot be isolated by a specific test. In most of these cases, however, an iterative technique can be devised consisting of a series of tests performed in a specific order to determine the individual contribution of each parameter to the response of the simulator. In this technique the concept is not to calculate specific values of each derivative or parameter but rather to use an identical series of tests in the simulator and airplane to match the output or response of the simulator to control inputs by adjusting these parameters. This technique is iterative in all cases except those in which certain tests can be used to isolate specific parameters. The iterative technique amounts to an output error method in terms of mathematical optimization theory. Of course, as in any optimization technique an initial guess of all parameters must be made at each flight condition to start the iterative procedure. We simply use those values present in the simulation at the beginning of the flight fidelity improvement program.

There are two basic categories of tests to be performed in both simulator and airplane. First, performance tests are conducted to quantify aircraft and simulator thrust and drag characteristics. The idea in performance testing is to determine the various coefficients in the lift and drag equations of motion. That is, we must determine lift and drag coefficients as functions of Mach number and angle of attack, contributions to drag and lift of all functional devices such as landing gear, speed brakes, flaps, etc., engine thrust characteristics, and so on. The second basic category is stability and control testing. The purpose of stability and control testing is to determine the various coefficients and parameters in the three moment equations of motion; roll, pitch and yaw.

Performance Tests

The performance tests used to quantify thrust and drag characteristics are shown in table I, items 3, 4 and 6. The proper order of tests is also indicated. The test methods used in performance work are described in detail in reference (2).

Steady state trim points are obtained throughout the flight envelope for speed/power relationships. At each stabilized trim point we record airspeed, altitude, engine parameters, angle of attack, power lever angle, aircraft attitude and gross weight. Since installed engine thrust is generally known as a function of airspeed and altitude, these steady state trim points can be used to establish or to verify drag polar information (basic drag and lift coefficients (C_L and C_D) as a function of Mach number and angle of attack) in the simulator software. Repeating the trim points in all aerodynamic configurations such as landing gear down, flaps down, speed brakes deployed, etc., it is possible to determine the contributions to lift and drag of each device.

Timed level accelerations, level decelerations, and timed climbs and descents can then be used to further refine and verify thrust, lift, and drag relationships.

Another important area in performance not listed in table I is engine acceleration and deceleration characteristics. Timed engine response is obtained and matched by altering the engine model if necessary.

Of course, all of these performance tests are performed throughout the flight envelope in both simulator and airplane in all configurations. The process of incorporating software fixes as a result of these tests in the lift and drag equations of motion is iterative since certain terms interact. For example, a change to the basic lift coefficient affects the drag coefficient through the drag polar.

An interesting performance fidelity problem arose in the 2F90 program which illustrates the degree of sophistication required of the mathematical model to accurately simulate aircraft performance characteristics and the difficulties encountered in translating a fidelity discrepancy to a software program fix. Pilots complained that simulator response to throttle changes in the power approach configuration, in particular, was not realistic. The simulated airplane tended to float as power was reduced and was not as responsive as the airplane to power addition. Engine and thrust acceleration and deceleration data failed to show a discrepancy between simulator and airplane. Steady state thrust and drag relationships obtained from trim points in the power approach configuration had already been corrected and matched well. The problem was with aircraft transient response to throttle changes. After much investigation, it was discovered that ram drag was not incorporated as a separate term in the drag equation. Ram drag has a substantial effect on aircraft transient response to power changes due to the increase in ram drag during engine decelerations from intake air spillage and vice versa. The incorporation of this term tailored by qualitative pilot opinion solved the aircraft response problem in the power approach configuration.

Stability and Control Tests

For flying qualities or stability and control work, the testing is divided into two categories: longitudinal flying qualities and lateral-directional flying qualities. This is, of course, a natural break since the linearized pitching moment equation is decoupled from the yawing and rolling moment equations. Stability and control test methods are discussed in reference (3).

First, longitudinal flying qualities test methods will be considered. The tests used to isolate longitudinal flying qualities fidelity deficiencies are given in table I along with the previously discussed performance tests. The first step is to perform static tests on the mechanical characteristics of the longitudinal control system. This is the starting point for flying qualities testing. Breakout forces, deadbands, static force versus deflection, full throw forces and deflections, control centering characteristics, friction levels, freeplay, viscous effects, trim rates, and so forth, are measured and matched between simulator and airplane.

In the 2F90 and 2F101 fidelity improvement programs a hardware change was made in the area of mechanical characteristics of the longitudinal and lateral-directional control systems. Diodes were added in the analog force circuitry to simulate breakout forces. In the 2F90 Deivce, germanium diodes with cut-in voltages of approximately 0.1 volts were suitable for longitudinal and lateral control system breakout simulation whereas silicon diodes with a cut-in voltage of 0.7 volts were more suitable for directional control system breakout. In figure 1 the effect of the addition of breakout diodes is shown in the longitudinal control system of the 2F90 Device.

On the 2F90 and 2F101 fidelity improvement programs hand held instrumentation and pilot recorded data was used for flying qualities testing and found to be adequate. Force gages, a three second stop watch, tape measures and the like typified the instrumentation used. On a new airplane and simulator an instrumented airplane is available for flying qualities and performance work and would be used to gather flight data for the simulator.

Having matched the static control system mechanical characteristics, we now turn to "in flight" tests. The pitching moment contribution of various aerodynamic devices such as flaps, landing gear, speed brakes, etc. can be determined by performing longitudinal open loop trim changes. After stabilizing the airplane or simulator at a given trim point in the flight envelope, a time history of the open loop pitch angle change from trim is recorded with actuation or deactuation of the various devices. A match is obtained between simulator and airplane by adjusting the pitching moment coefficient of the device in question until acceptable time history matches are obtained.

The next test is designed to isolate the effects of the important stability derivative $C_{M\alpha}$, the rate of change of pitching moment with angle of attack. From theoretical analysis (reference (3)) it can be shown that

$$C_{M\alpha} \simeq -k\omega_n^{2} \qquad (1)$$

where ω_n is the longitudinal short period natural frequency. This is a very approximate relation but is sufficient as a starting point. Short period natural frequency can be estimated at a given flight condition by observing the open loop pitch response to a pitch doublet designed to excite the short period mode of motion or by a frequency response test such as observing the pitch response of the airplane to sinusoidal control pumps of varying frequency. The derivative $C_{M\alpha}$ is considered correct in the simulator software if airplane and simulator short period responses match when using the same type input in each vehicle.

The next test yields indications of the longitudinal static stability of the airplane and simulator, and is used to determine longitudinal control position and force from trim versus airspeed about a trim point. The test method is described in reference (3). Figure 2 shows an example from the 2F90 program. The trim points are as shown. The circles represent airplane data. The shaded triangles represent the 2F90 OFT before modification. The open triangles represent the 2F90 after modification. From theoretical analysis it can be shown (reference (3)) that the stability derivatives that have the most effect on these control force and deflection gradients are $C_{M\alpha}$ and $C_{M\delta_e}$, the rate of change of pitching moment with elevator deflection. Since $C_{M\alpha}$ has been determined from short period results, the static longitudinal stability test results can be matched between simulator and airplane by varying $C_{M\delta_e}$. By also recording angle of attack data during the static longitudinal stability tests it is possible to obtain a first cut at $C_{L\alpha}$, lift curve slope. Figure 2 shows this angle of attack - airspeed gradient from a test point in the 2F90 program.

The next test listed in table I involves maneuvering longitudinal stability. The test method is described in detail in reference (3). The objective is to obtain the following gradients from a number of trim points throughout the flight envelope:

1) longitudinal control forces vs normal acceleration,

2) longitudinal control displacement vs normal acceleration,

3) angle of attack vs normal acceleration.

These gradients are all obtained at constant airspeed. Figure 3 is an example from the 2F90 program. From theoretical analysis (reference (3)) it can be shown that the rate of change of longitudinal control force and displacement with normal acceleration are a function primarily of the stability derivatives $C_{M\alpha}$, $C_{M\delta_e}$, and C_{M_q}, the rate of change of pitching moment with pitch rate, and bobweight effects. Since $C_{M\alpha}$ and $C_{M\delta_e}$ have been adjusted at a given trim point by previous tests, the primary derivative to be adjusted to match maneuvering stability results is C_{M_q}. The lift curve slope, $C_{L\alpha}$, can be further refined by matching the data collected in figure 3.

In order to obtain a good match of longitudinal flying qualities between simulator and airplane the entire sequence of tests listed in table I must be iterated a number of times and of course all tests must be performed throughout the flight envelope of the airplane.

The next test is a determination and match of aircraft stall and post stall characteristics. In tactical fighter and attack aircraft an accurate simulation of this area of flight is extremely desirable. Since this area cannot be modeled by linear equations of motion to any satisfactory degree and since nonlinear programming is costly in terms of both computation time and memory requirements, the degree of simulation required in this area is a critical decision early in the design stages of the simulator. We have found that with a minimum of effort and expense it is possible to provide acceptable stall characteristics with a moderate number of logic routines and adjustments to aerodynamic coefficients in the linearized equations of motion at high angles of attack. For example, in the 2F90 program a logic routine was added to simulate wing rock and consisted of a sinusoidal roll function with amplitude increasing with increasing angle of attack commencing at 19 units. In addition, $C_{M_{BASIC}}$ was increased at stall angles of attack effectively decreasing elevator control which provided an oscillating motion in pitch above stall that was very representative of the airplane.

Other miscellaneous longitudinal flying qualities tests include investigations of phugoid frequency and damping, takeoff and landing characteristics (ground effects), transonic effects, and so on.

Lateral-directional flying qualities tests methods will now be considered. The tests used to isolate lateral-directional flying qualities fidelity deficiencies are given in table II. The first step is to perform static tests on the mechanical characteristics of the lateral (aileron) and directional (rudder) control system. As with the longitudinal controls, breakout forces, deadbands, static forces versus deflection, full throw forces and deflections, control centering characteristics, friction levels, freeplay, viscous effects, trim rates, etc. are measured and matched between simulator and airplane.

Next, lateral control effectiveness is evaluated with lateral control rolls performed throughout the flight envelope. The most effective test technique found was to observe the roll and yaw response of the airplane and simulator to a lateral control step input performed by the pilot. In tactical aircraft with high roll rates it is desirable to restrict the step size to reduce roll rates to within accurately measurable limits. On the 2F90 program a stick restriction jig was used to limit lateral stick displacement to one inch (2.54 cm.) while performing these tests. Bank angle time histories were then generated by recording times to given changes in bank angle. Representative results from the 2F90 program are given in figure 4. The important stability derivatives $C_{\ell_{\delta_a}}$, aileron power, and C_{ℓ_p}, roll damping, have the most pronounced effects on the results of these tests and can be used to match simulator and airplane roll rates. Before modification the 2F90 device exhibited extremely slow roll response for all one inch stick deflection tests as shown in figure 4. For example, in the simulator time to roll 180° at 250 kt in configuration CR was 14.8 sec vice 2.4 sec for the airplane. However, roll response to full stick inputs closely matched published flight test data. The slow roll response of the simulator was attributed to a software routine that modified the true commanded aileron deflection by the relation:

$$\delta_{a_f} = \frac{(\delta_a)^2}{40} \qquad (2)$$

where δ_a is true aileron deflection and δ_{a_f} is the modified aileron deflection applied to the roll moment equation. The value 40 represents full aileron deflection (total differential between left and right surfaces) in degrees. This relation had been installed by the simulator manufacturer in response to fleet user complaints that Device 2F90 was too sensitive laterally. Prior to NATC involvement, another effort had been made to make Device 2F90 lateral response more realistic when using the visual display. The δ_{a_f} relation was removed and a small dead zone around neutral stick deflection was installed in the software routine that calculated true aileron deflection as a function of lateral stick deflection. This modification caused severe lateral PIO problems in the simulator that were uncharacteristic of the airplane especially during high gain, closed loop tasks such as maintaining lineup during field and carrier approaches when using the visual display.

In order to match simulator response to the airplane the δ_{a_f} relation and the deadzone were discarded. Adjustments were made to the values of aileron effectiveness, $C_{\ell_{\delta_a}}$, and roll damping, C_{ℓ_p}, until a proper match was obtained by quantitative and qualitative analysis. Qualitative analysis through such tasks as turn reversals, instrument patterns, and approaches (using the visual display) was used to guide the adjustment process.

The next tests to be performed are the dynamic lateral-directional stability tests; specifically the determination of the Dutch roll mode frequency and damping. From these tests the derivatives C_{N_β}, the rate of change of yawing moment with sideslip, and C_{N_r}, the yaw damping derivative can be determined (reference (3)).

Steady heading sideslip tests (reference (3)) can then be used to determine $C_{N_{\delta_r}}$, rudder power, C_{ℓ_β}, dihedral effect, and C_{Y_β}, the side force derivative.

Testing Peripheral Equipment for Flight Fidelity

After all major flying qualities and performance discrepancies are eliminated in the fixed base simulation, the motion base is added and evaluated. Items to be evaluated include acceleration cues in all degrees of freedom simulated, aerodynamic stall buffet and transonic buffet simulation.

Again the experience gained on the 2F90 program is instructive. The buffet provided to simulate aerodynamic stall through the motion system was unsatisfactory in three respects. First, the buffet was initiated at 20 units AOA regardless of the type stall encountered. In essence, accelerated stall buffet, which is a function of Mach number and angle of attack was not simulated. This was considered a major discrepancy since buffet onset is used by the pilot in most aerobatic and mission related visual maneuvers to gain optimum performance from the airplane. Second, the amplitude of the buffet at onset was high, simulating the heavy buffet associated with deep stall. In the airplane, buffet at onset is light in maneuvering flight and increases in amplitude with increasing angle of attack. Third, the frequency of the buffet was low (10 Hertz) and constant; again typical of deep stall buffet. The light buffet encountered in the airplane in maneuvering flight is of much higher frequency. In summary, 1g stall buffet was well simulated whereas accelerated stall buffet was not simulated. Data on buffet onset, amplitude and frequency were obtained from the airplane. Using these data as a basis, a function was added to the software to provide buffet onset as a function of angle of attack and Mach number. A second function was added to the software to provide a different variable buffet amplitude routine as a function of angle of attack after onset for the accelerated stall case. The final problem was buffet frequency.

Frequency limitations of the hydraulic motion system precluded increasing the frequency of the buffet to simulate the high frequency light buffet encountered in accelerated stalls. Thus no change was made to buffet frequency.

The next stage in the flight fidelity improvement program is to add the visual display to the basic simulator in the fixed base mode of operation if provided. In the 2F90 device the addition of the visual display system allows pilot training to be conducted in VFR flight. Closed loop VFR flying tasks made possible by the addition of the visual display include field landings and takeoffs, carrier landings and takeoffs, scored bombing, formation flight, aerobatics, and familiarization flying. The Computer Generated Image (CGI) display was not evaluated per se. The purpose of the flight fidelity improvement effort was to improve the flight dynamics of the simulator so that the simulator with the visual display added could be used for VFR training. The visual display on the 2F90 device was evaluated qualitatively by a test pilot using closed loop mission tasks to compare airplane and simulator performance and flying qualities. Many refinements to the various stability derivatives and parameters in the mathematical model were made as a result of these tests. In particular the ram drag trim addition referred to previously in the performance section of this paper originated during closed loop evaluations of the visual display in the landing mission.

Fidelity Improvement Program

A flight fidelity improvement program is best conducted in stages as indicated in table III. First, one must collect baseline data in the airplane. It is important to use more than one airplane to gather this data. Differences between airplanes are sometimes significant. The tests are repeated in the simulator. Data reduction and the formulation of a plan of action for fidelity improvement follows. One then starts the iterative reprogramming process.

An important aspect of the flight fidelity improvement programs we have conducted was the continuous refamiliarization required by the pilots in the airplane. It is estimated that eight hours of simulator time is sufficient to destroy a pilot's familiarity with the airplane to the point that he can no longer make valid qualitative judgements on flying qualities during closed loop tests. Table IV presents a summary of the actual flight time flown by test pilots in support of the various fidelity improvement programs embarked upon by NATC.

ADVANCED TEST METHODS

The application of conventional test methods to simulator fidelity improvement have been considered above. Let us now address advanced methods. Specifically, the application of digital parameter identification methods to obtain the coefficients and stability derivatives from flight test data will be discussed. As was mentioned before, this is not an easy task. All the services, the National Aeronautics and Space Administration, and industry have done a great deal of research in this area. The effort at the Naval Air Test Center is combined with Systems Control, Incorporated (SCI) at Palo Alto, California, and the Office of Naval Research. SCI has delivered a very powerful advanced algorithm recently which is being used in a number of programs at this time. The algorithm employs a maximum likelihood estimation scheme to extract stability derivatives from flight test data in the presence of measurement noise as well as process noise. The theory and program are presented in detail in references (4) and (5) along with flight test results obtained to date.

Basically the program can be described by figure 5. An appropriately instrumented airplane is given a control input. The airplane responds. That response is contaminated by instrument noise and process noise. A mathematical model of the aircraft, using the equations of motion and an initial guess for the aircraft coefficients, is given the same input. The model response is compared to the contaminated aircraft response and a response error is generated. A criterion function is formed (response error squared is a good one) and this criterion function is minimized by an optimization algorithm; in this case a maximum likelihood estimator. The lower loop in the figure is iterated until a "best" estimate of aircraft parameters is obtained. The algorithm also generates the statistics of both the measurement and process noise. The advantage of this program for simulator applications is that we are able to obtain the aircraft coefficients throughout the flight envelope very accurately and extremely fast. Basic SCIDNT options are presented in reference (4) and are shown in table V.

This program is now operational at NATC and has significantly increased our capability to analyze flight data to obtain stability derivatives for use in a mathematical model in a simulator. The algorithm has been used successfully on several flight test programs but has not as yet been used specifically on a simulator flight fidelity improvement program.

CONCLUSIONS

In this paper the application of conventional fight test techniques to the improvement of the flight fidelity of operational flight and weapon system trainers has been discussed. Examples from flight fidelity improvement programs conducted on a number of devices has been presented. In these programs it was discovered that the primary culprit in flight fidelity was inadequate and incorrect computer software programming caused by the inadequacy of the data base used to formulate the software package. The application of the conventional test methods discussed herein features the use of actual flight data to tailor simulator responses by incorporation software fixes in the device. Fidelity improvement programs using these techniques have been successful.

The application of advanced test methods has also been discussed. Recent advances in the practical applications of control and estimation theory have made it possible to extract stability derivatives and other parameters from flight test data to a degree and with accuracy not possible in the past.

It is generally agreed that the training obtainable from a simulator depends to a great extent on the state of mind of the trainee; specifically, his opinions of the fidelity of the simulation. Obviously, we cannot give him everything. Simulators cost a lot of money. What we can do is give him the best simulation possible within the limits of the hardware we can afford to buy. Software optimization takes time, team work, and commitment. The results are well worth the effort.

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4. Burton, R. A., Advancement in Parameter Identification and Aircraft Flight Testing, Paper 15, AGARD Conference Proceedings No. 172 on Methods for Aircraft State and Parameter Identification, May 1975.

5. Stepner, D. E. and Mehra, R. K., NASA Contractor Report CR-2200, Maximum Likelihood Identification and Optimal Input Design for Identifying Aircraft Stability and Control Derivatives, March 1973.

TABLE I
PRIMARY TEST SEQUENCE FOR LONGITUDINAL PARAMETERS

TEST	TEST PARAMETER	SIMULATOR PARAMETER
1. Longitudinal Control System Mechanical Characteristics	a. Breakout Force b. Friction c. Centering d. Stick Deflection Limits	Control system electrical and mechanical elements
	Stick Displacement: vs Stick Force vs Surface Deflection	Software routines
2. Weight and Balance	a. Gross Weight b. Moments of Inertia c. Variation of CG with store loading, configuration and fuel usage	Software routines
3. Steady State Trim Points (Gear and Flaps Up)	Airspeed, Gross Weight, α	C_L vs α
	Longitudinal Trim	$C_{m_{TRIM}}$ (lower α range)
	Engine RPM, Fuel Flow, EGT, Power Lever Position	Steady state engine characteristics, Thrust-Drag balance
4. Lever Accelerations and Decelerations	Time from V_{MIN} to V_{MAX} a. Cruise configuration b. a. with speedbrakes open c. Landing configuration	a. Basic airframe drag b. Speedbrake drag c. Landing gear and flap drag
5. Longitudinal Trim	$\Delta\Theta$ due to: a. Flap operation b. Landing gear operation c. Power changes d. Speedbrake operation	Pitching moment contribution of each device
6. Steady State Trim Points (Power Approach Configuration at On-speed Angle of Attack)	Airspeed, Gross Weight	Δ_{C_L} due to flaps
	Longitudinal Trim	$C_{m_{TRIM}}$ (higher α range)

TABLE I (continued)

7. Short Period Excitation (Sinusoidal Stick Pumping)	Undamped short period natural frequency	C_{m_α}
8. Static Longitudinal Stability	Stick position gradient	C_{m_α}, $C_{m_{\delta e}}$
	Stick force gradient	Stick position gradient
	Angle of Attack gradient	C_{L_α}
9. Maneuvering Longitudinal Stability	Stick position gradient	C_{m_α}, $C_{m_{\delta_e}}$, C_{m_Θ}
	Stick force gradient	Stick position gradient, Bobweight
	Angle of Attack gradient	C_{L_α}
10. Stalls (unaccelerated)	Minimum airspeed	$C_{L_{MAX}}$
	Stall characteristics	Pitching moment parameters at high Angles of Attack

TABLE II
PRIMARY TEST SEQUENCE FOR LATERAL-DIRECTIONAL PARAMETERS

TEST	TEST PARAMETER	SIMULATOR PARAMETER
1. Lateral and Directional Control System	Same as longitudinal	Same as longitudinal
2. Lateral Control Effectiveness	a. Initial roll response to partial deflection inputs b. Full deflection rolls	a. $C_{\ell_{\delta a}}$ and C_{ℓ_p} (1) b. $C_{n_{\delta a}}$ and C_{n_p} (2) (Adverse yaw)
3. Dutch Roll	a. Undamped natural frequency b. Damping ratio	a. C_{n_β} b. C_{n_r}
4. Steady Heading Sideslip	a. $\Delta\beta/\Delta\delta_r$ b. $\Delta\phi/\Delta_\beta$ c. $\Delta\delta a/\Delta_\phi$	a. C_{n_β}, $C_{n_{\delta r}}$ b. C_{y_β} c. $C_{\ell_{\delta a}}$, C_{ℓ_β}

Notes: (1) $C_{\ell_{\delta a}}$ and C_{ℓ_p} must be considered simultaneously to adjust initial roll response.
(2) $C_{n_{\delta a}}$ and C_{n_p} must be considered simultaneously to adjust adverse yaw characteristics.

TABLE III
STAGES IN SIMULATOR CORRECTION PROCESS

ITEM	TASK
1.	Collect Baseline Data
2.	Repeat Tests in Simulator
3.	Reduce Data and Formulate Plan
4.	Reprogram Simulator
5.	Add Peripheral Equipment
6.	Evaluate Total System

TABLE IV
AIRCRAFT FLIGHT TIME REQUIRED

OFT/WST	FLIGHT HOURS	NUMBER OF AIRCRAFT UTILIZED
2F101 (T-2C)	63.3	7
2F90 (TA-4J)	26.3	11
2F103 (A-7E NCLT)	15.1	7
2F108 (A-4M)	30.0	2
2F107 (KC-130)	8.0	2

TABLE V
SCIDNT CAPABILITIES AND OPTIONS

NUMBER	DESCRIPTION
1.	Any parameter may be fixed or contrained to be within certain bounds.
2.	A Priori weighting may be placed on parameter estimates.
3.	Standard deviations of parameter estimation errors are computed.
4.	Biases and random noise errors in instruments are computed.
5.	Process noise may be included and its magnitude and break frequency identified.
6.	Process noise effects may be included but not identified.
7.	Measurements from failed instruments may be deleted.
8.	States may be deleted which do not significantly enter the aircraft modes of the particular data record considered.
9.	Rank deficient solution may be used to compute the inverse of the information matrix.

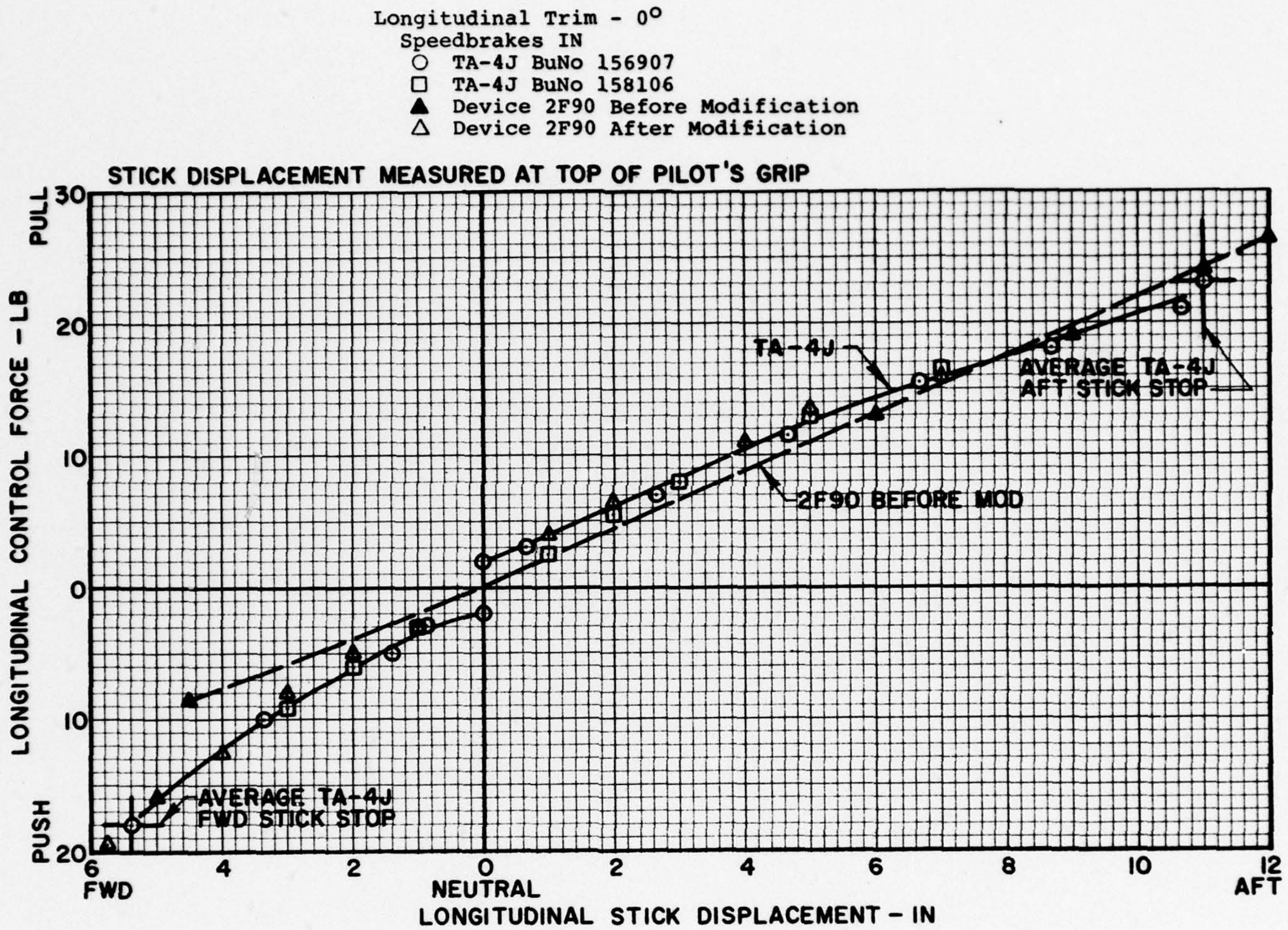
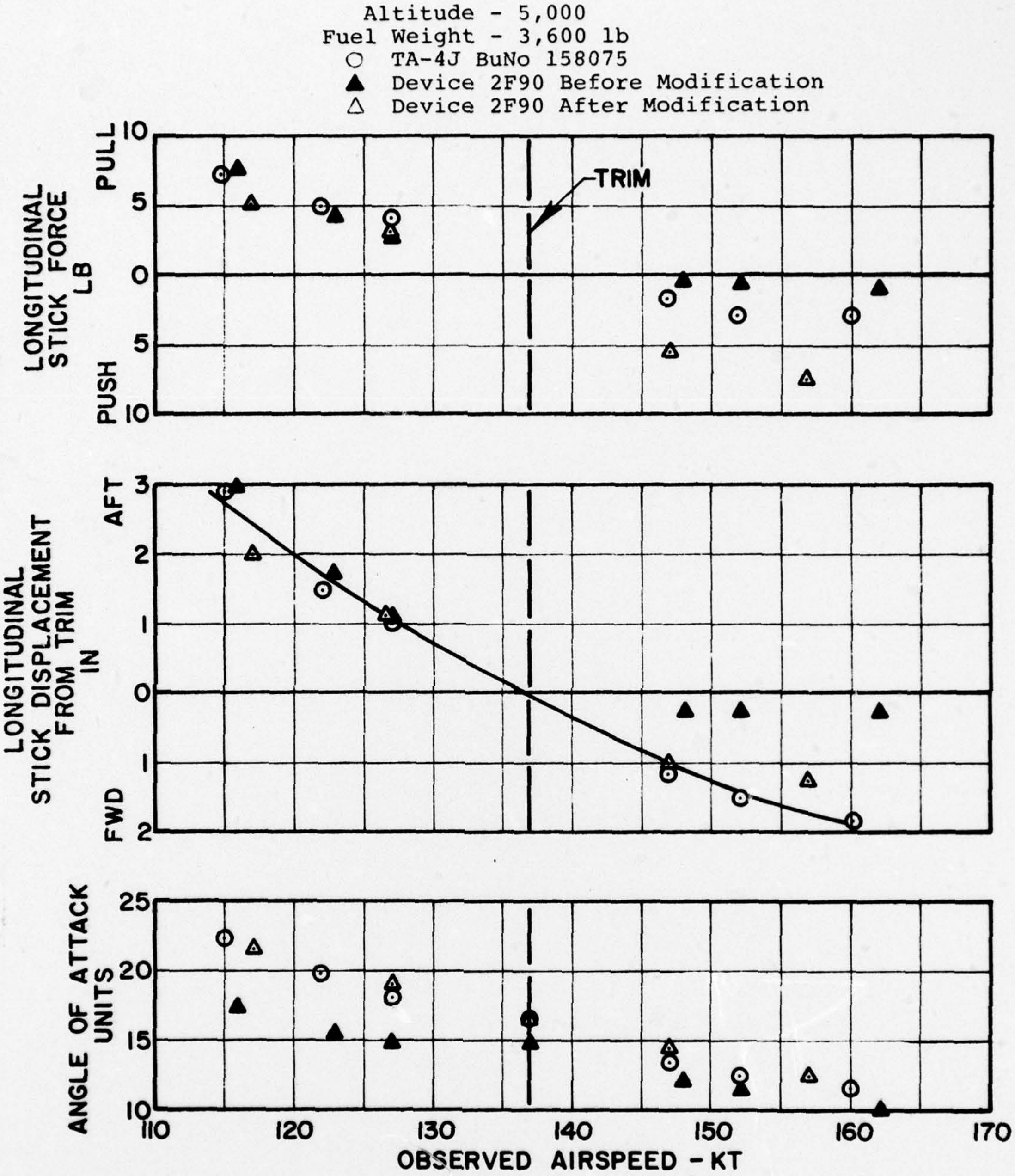


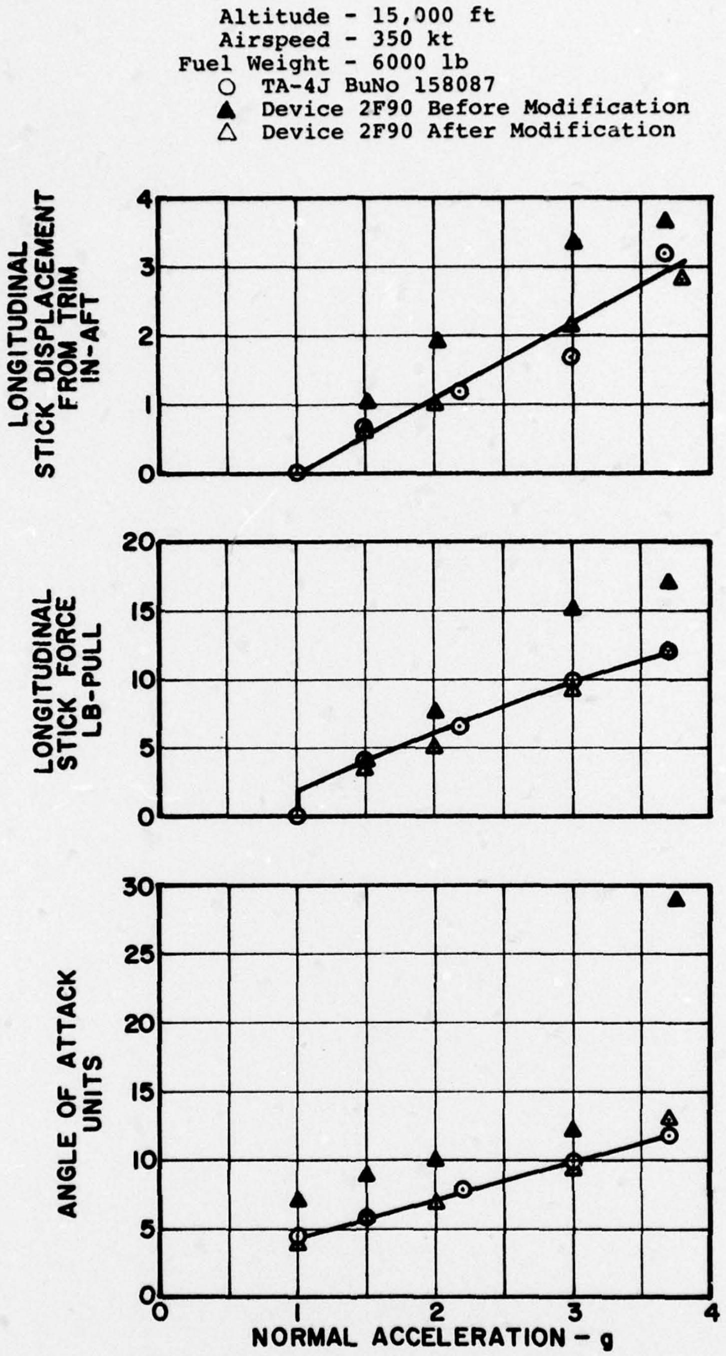
Figure 1

LONGTUDINAL CONTROL CYCLE
Longitudinal Trim: 0°
Speedbrakes IN



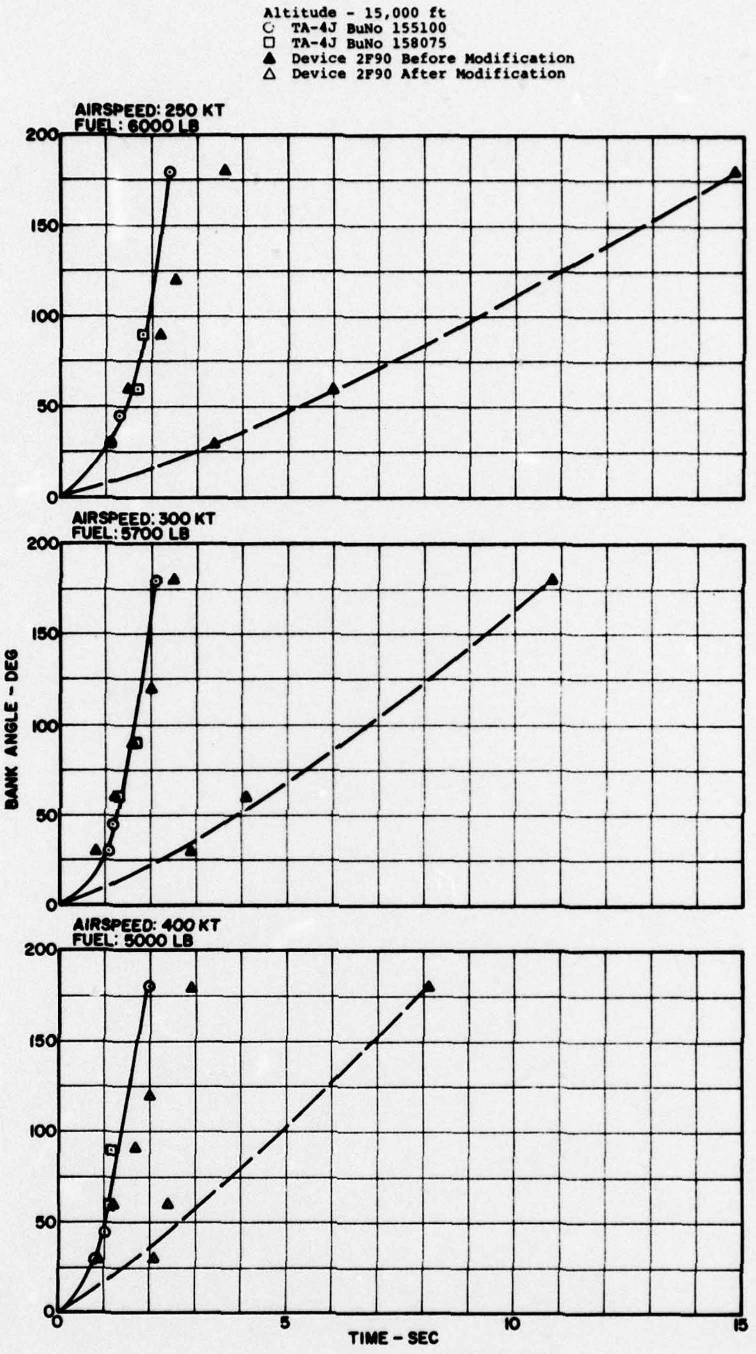
STATIC LONGITUDINAL STABILITY CHARACTERISTICS
Configuration PA
5,000 Feet

Figure 2



MANEUVERING LONGITUDINAL STABILITY CHARACTERISTICS
Configuration CR
15,000 Feet

Figure 3



LATERAL CONTROL EFFECTIVENESS
One Inch Lateral Stick Deflection
Configuration CR
15,000 Feet

Figure 4

PARAMETER ESTIMATION PROCEDURE

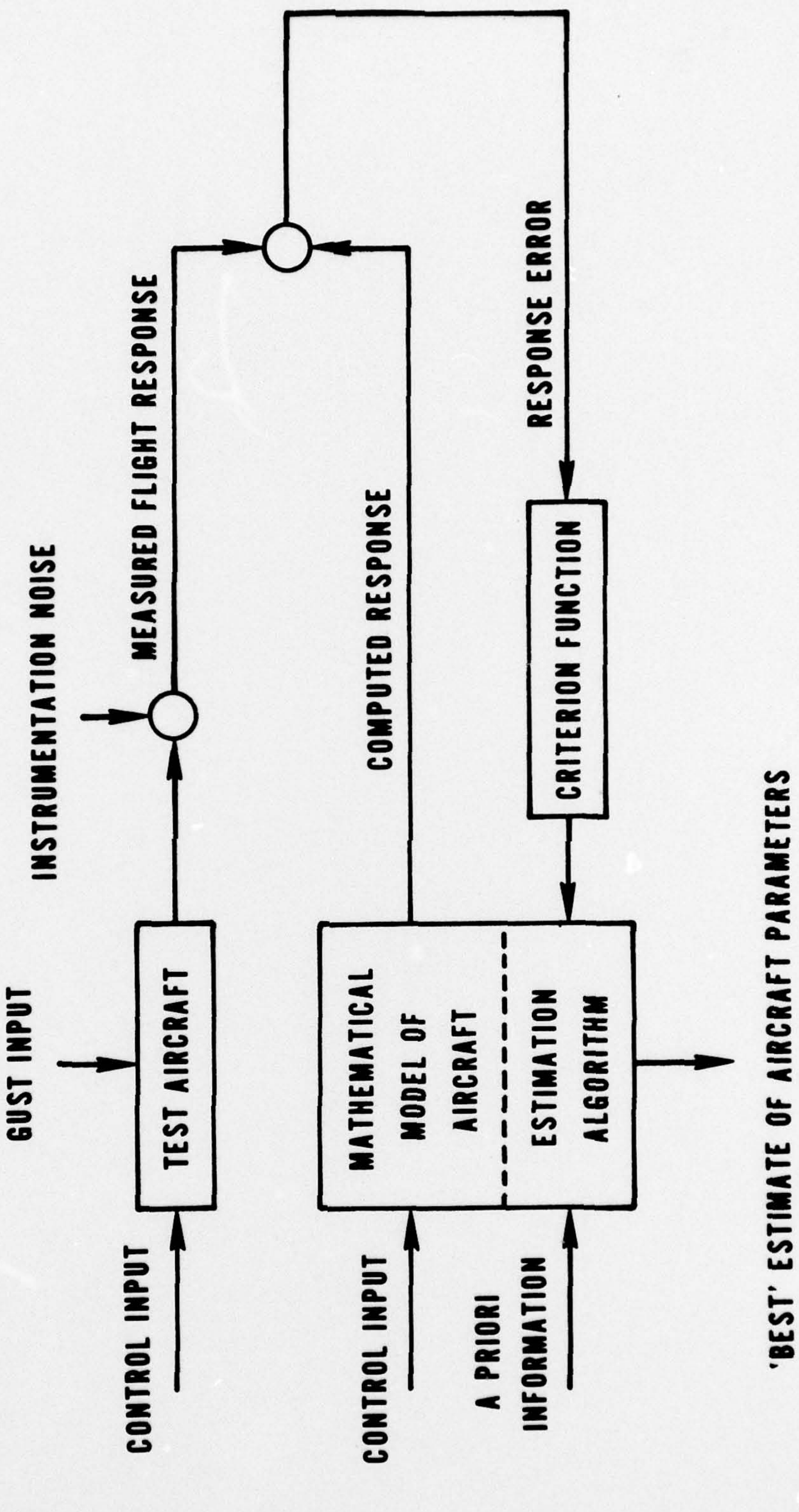


Figure 5

Distribution:

COMNAVAIRTESTCEN CT02	(1)
COMNAVAIRTESTCEN CT03	(1)
COMNAVAIRTESTCEN CT08	(1)
SATD SA01	(1)
SATD SA02	(1)
SATD SA04	(1)
SATD SA41	(200)
SATD SA60	(1)
SETD	(1)
RWTD	(1)
ATTD	(1)
CSD	(1)
TSD	(1)
TPS	(1)