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

CDR M. D. HEWETT and MR. R. T. GALLOWAY
Naval Air Test Center
Patuxent River, Maryland

and CDR J. C. MURRAY
Naval Air Training Command
Corpus Christi, Texas

INTRODUCTION

The Navy uses simulators known as Operational Flight Trainers (OFT) and Weapons System Trainers (WST) to train new pilots, retrain pilots, and maintain pilot proficiency in today's complicated and expensive aircraft weapons systems. Over the years these devices have acquired a dismal reputation in the fleet for faithful simulation of the subject 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 devices to that of expensive procedures trainers for instrument flight and emergency conditions vice that for which they were designed: i.e. operational flight and weapons system training.

The degraded training value of these simulators 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 a scarce commodity. Because of these factors, increased emphasis has been placed on the use of simulators for training and proficiency. In fact, OPNAV Instruction 3710.7G states that Naval Aviators participating in the Proficiency Flying Program may substitute 10% (10 hours) of the total annual minimum flight time requirement with 12 hours or more of simulator time logged. The Instruction further states that "as additional simulators become available and more is learned on the "transfer of learning" gained through the use of simulators, the program will be expanded." It is absolutely necessary, therefore, that the full technical resources of the Navy be brought to bear on the problem of providing the best possible flight simulation at a given cost. We feel that major progress has been demonstrated and that additional flight time substitution can now be made.

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 display 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 NAS 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 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 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 generally 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 was available. The 2F90 Device is typical. Although this device has been around for years and TA-4Js have acquired thousands and thousands of flight hours, the device still uses 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 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 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. If the flying qualities do not match, the process is repeated until they do.

A team approach to the problem has made this process possible. The necessary team members are fleet experienced pilots intimately familiar with the subtle feel characteristics of the airplane being simulated, test pilots trained in flying qualities and performance testing and intimately familiar with the aircraft being simulated, 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. In addition, it is necessary to have an overall project manager who can commit and schedule aircraft, simulators, personnel and funds where required to support the project in a timely manner. Without such coordination the purpose of the project may be lost. Such teams composed of personnel from the Naval Air Test Center, the Naval Training Equipment Center, the Naval Education Program Development Center and the Naval Air Training Command have been successful in significantly improving the flight fidelity of the 2F90 Device and the new 2F101 Device used by the Naval Air Training Command.

In addition, 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. A new digital computer program is in use at the Naval Air Test Center which combines a maximum likelihood estimator with an extended Kalman filter to identify lateral directional and longitudinal derivatives at a given flight condition in the presence of both measurement and process noise. The process is expected to have a significant impact on simulator software programming.

CONVENTIONAL TEST METHODS

The flight test techniques used to gather data for simulator flying qualities corrections are conventional performance stability and control tests used everyday at the Naval Air Test Center. Performance tests include steady state trim points for speed/power relationships; level flight accelerations and decelerations for drag data, speed brake effectiveness, and acceleration and deceleration; engine spool up and spool down times for power response; climbs and descents; and others. Stability and control tests include steady state trim points for power required, trim position, and angle of attack; static longitudinal stability tests for speed/ static stability, i.e. stick force and deflection per speed away from trim; maneuvering longitudinal stability tests for stick force and stick deflection per "g"; dynamic longitudinal stability tests for short period damping and frequency, and phugiod stability, damping, and frequency; steady heading sideslips for rudder and aileron forces per sideslip angle, rudder and aileron deflections per sideslip angle, and bank angle required to maintain heading per sideslip angle; lateral directional stability tests for dutch roll damping and frequency; roll performance tests for roll mode time constant; spiral stability tests for spiral mode time constant; stalls for stall and departure characteristics; trim changes with flap, landing gear, and speed brake actuations; and others. These tests are performed throughout the flight envelope in the simulator and in the real airplane.

The process of correcting the flying qualities of a trainer is best conducted in stages. First, baseline flight test data must be collected on the real airplane. In many cases these data or portions thereof may already exist from other flight test programs. It is advisable to gather baseline data on more than one airplane, as many airplane characteristics vary significantly between ships of the same model. The goal is to make what the pilot sees in the simulator cockpit match what he sees in the average airplane cockpit. The requirement to test more than one airplane complicates the problem of test instrumentation. On most programs there will neither be time nor funds to extensively instrument multiple airplanes and the trainer. Fortunately, data gathered by old fashioned handheld force gages, stop watches, tape measures, and production flight instruments have been found to be sufficiently accurate for most flight fidelity testing. These methods have the advantages of being cheap and offering great flexibility.

The second stage of the test program consists of repeating all flight tests in the simulator. For a compatible data base, simulator tests should be conducted using the same instrumentation as was used for the flight tests. No modifications are made to the simulator until all the data is collected in order to fully document simulator deficiencies. It is desirable to conduct this testing with all peripheral equipment such as motion base and external visual systems off.

The third stage consists of reducing the data and formulating a plan attack for correcting the simulator. The importance of this stage cannot be overemphasized.

The fourth stage involves applying corrections to the simulator's software and hardware. Since conventional flight tests measure only a manifestation of a stability derivative or a combination of stability derivatives and since the correction of one discrepancy will in all likelihood affect other areas, it is necessary to correct simulator discrepancies in a specific order. This minimizes the effects of software and hardware changes on previous results. Of course, some iteration is always required. Although the specific order of work cannot be generalized between simulators, it is possible to offer some guidelines for at least the software correction sequence. The primary longitudinal test and correction sequence is listed in Table 1. The idea is to isolate the effect of each major longitudinal parameter in the software so that it can be evaluated and adjusted as independently as possible. Still, two or three iterations through the adjustment process are generally required. Lateral control effectiveness and lateral directional stability problems are approached in the same manner. The primary test and correction sequence for lateral directional parameters is presented in Table 2. Once all corrections have been made, it is necessary to reperform all tests on the trainer to provide documentation of the total effects of the correction process.

During stage four it is advisable to provide the test pilots with the opportunity to fly the real airplane frequently. It has been found that with extensive concentrated simulator flying, a test pilot quickly becomes simulator oriented and his qualitative opinion of the flying qualities of the real airplane loses validity rapidly. In addition, fleet pilots who fly only the subject aircraft should be allowed to fly the simulator frequently. They will frequently detect small subtleties in flight control or motion

Table 1
PRIMARY TEST SEQUENCE FOR
LONGITUDINAL PARAMETERS

TEST	TEST PARAMETER	SIMULATOR PARAMETER
Longitudinal Control System Mechanical Characteristics	a. Breakout force b. Friction c. Centering d. Stick deflection limits	Control system electrical and mechanical characteristics
	Stick displacement: vs. stick force vs. surface defl.	Software routines
Weight and Balance	a. Gross weight b. Moments of inertia c. Variation of CG with store loading, configuration, and fuel usage	Software routines
Steady State Trim Points (CR congif.)	a. Airspeed b. Gross weight c. Angle of attack	C_L vs. AOA
	d. Longitudinal trim	$C_{m_{TRIM}}$ (lower α range)
	e. Engine RPM, fuel flow, EGT, Power lever angle	Engine model, Thrust-drag balance
Level accelerations and decelerations	Time V_{MIN} - V_{MAX} in a. CR configuration b. Speedbrakes open c. PA configuration	a. Basic airframe drag b. Speedbrake drag c. Landing gear and flap drag
Longitudinal Trim Changes (Open Loop)	$\Delta\theta$ due to: a. Flap operation b. Landing gear open c. Power changes d. Speedbrake open	Pitching moment contribution of each device
Steady State Trim Points (PA)	a. Airspeed b. Gross weight c. Angle of attack	ΔC_L due to flaps
	d. Longitudinal trim	$C_{m_{TRIM}}$ (high α range)

Table 1 cont'd

TEST	TEST PARAMETER	SIMULATOR PARAMETER
Short Period Excitation (pitch doublet and sinusoidal stick pumps)	a. Undamped natural frequency b. Damping ratio	C_{m_α}
Static Longitudinal Stability	a. Stick position gradient b. Stick force gradient c. Angle of attack gradient	a. C_{m_α}, $C_{m_{\delta_e}}$ b. Stick position gradient c. C_{L_α}
Maneuvering Longitudinal Stability	a. Stick position gradient b. Stick force gradient c. Angle of attack gradient	a. C_{m_α}, $C_{m_{\delta_e}}$, $C_{m_{\dot\theta}}$ b. Stick position gradient, bobweight c. C_{L_α}
Stalls (unaccelerated)	a. Minimum airspeed b. Stall characteristics	a. $C_{L_{MAX}}$ b. Pitching moment parameters at high α

Table 2
PRIMARY TEST SEQUENCE FOR
LATERAL-DIRECTIONAL PARAMETERS

TEST	TEST PARAMETER	SIMULATOR PARAMETER
Lateral and Directional Control System Mechanical Characteristics	Same as Longitudinal	Same as Longitudinal
Partial and Full Deflection Aileron Rolls	a. Time to roll to given Ø - partial δ_a	a. $C_{l_{\delta_a}}$, and C_{l_p} (1)
	b. Ø & β response to full δ_a rolls	b. $C_{n_{\delta_a}}$, and C_{n_p} (2)
Dutch Roll Excitation (Rudder doublets)	a. Undamped natural frequency	a. C_{n_β}
	b. Damping ratio	b. C_{n_r}
Steady Heading Sideslip	a. $\Delta\beta / \Delta\delta_r$ b. $\Delta Ø / \Delta\beta$ c. $\Delta\delta a / \Delta Ø$	a. C_{n_β}, C_{n_r} b. C_{y_β} c. $C_{l_{\delta_a}}$, C_{l_β}

Notes: (1) $C_{l_{\delta_a}}$ 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.

base feel that may not be detected by a test pilot.

The next stage consists of evaluating the effects of adding each piece of peripheral equipment such as the motion base and/or external visual displays individually. Necessary adjustments are made to the simulator as the effects of each piece of equipment on flying qualities are evaluated. Extreme care must be exercised in this stage to determine whether or not an apparent discrepancy is appearing because of a shortcoming of the added equipment or because the added equipment is uncovering a previously disguised discrepancy in the flying qualities of the basic simulator.

Finally, a total system evaluation is performed to insure that the simulator is optimized to provide the best simulation that the hardware is capable of providing. With effort, teamwork, and patience, the degree of flight fidelity attainable is remarkable even in such obsolete devices as the 2F90.

RESULTS

T-2C OFT

Last year Naval Air Test Center personnel were invited to participate in the evaluation of the new 2F101 Device which simulates the T-2C airplane. Our role became one of assisting the contractor at his facility in tailoring the flying qualities simulation of the device. The effort was extremely profitable to the Navy and to the manufacturer. The result was delivery to the Naval Air Training Command a device that at least from a flying qualities and performance standpoint closely resembled the real airplane.

The application of conventional flight test techniques to the simulator evaluation was responsible for identifying many flying qualities discrepancies in this device and realizing many fidelity improvements. An example is in order. Prior to NATC involvement, fleet pilots evaluating the device complained that, in general, stick forces seemed too high. The manufacturer maintained that the stick force gradients matched all available data and they could provide no further solution. NATC personnel conducted static and maneuvering longitudinal stability tests in both the airplane and the simulator. Test results confirmed that indeed stick force gradients in the simulator were correct, however, stick displacement gradients in the simulator were about half those in the real airplane. As a result, the stick felt more like a force controller to the fleet pilot. The solution to this problem was to reduce elevator effectiveness, $C_{m_{\delta_e}}$, thereby reducing the stick position gradient until the stick position gradient in the simulator matched that of the real airplane as shown by static longitudinal stability tests. Of course, stick force gradients were now too high but they were easily reduced by modifying the elevator hinge moment terms. Attention was then given to matching the maneuvering longitudinal stability data. Stick displacement per "g" was matched by adjusting pitch damping, $C_{m_{\dot{\theta}}}$, and stick force per "g" was then matched by adjusting the bobweight contribution. The final result was that longitudinal stick forces felt much more realistic to all of the evaluating pilots. In this case, the application of conventional flight test techniques led to an orderly solution to the problem.

TA-4J OFT

The 2F90 Device, which simulates the TA-4J airplane, has been in the inventory for several years, but its simulation of the real airplanes's flying qualities has always been poor. A recently added visual display system was found to have little training value because of this. In order to recoup the Navy's investment in the visual display system and all basic cockpits, a team composed of test pilots, flight test engineers, and computer and simulator specialists was requested to conduct a flight fidelity improvement program. This program was undertaken without the manufacturer's assistance. Although the program has not been completed to date, results to this point have been very encouraging. All pilots who have evaluated the modified simulator program have agreed that its flying qualities simulation has been markedly improved.

A few examples of flight fidelity improvements realized are in order. During initial investigations of the 2F90, it was noticed that the response to lateral control was very sluggish, and yet full deflection steady state roll rates were as fast or faster than those attainable in the real airplane. Also, when flying carrier or field approaches using the visual display system, the pilot invariably got into a lateral PIO that was totally uncharacteristic of the TA-4J. In obtaining baseline flight test data for lateral response, it was decided to limit lateral stick deflections to one inch through the use of an adjustable jig. The one inch limit was imposed so that roll response data could be obtained for normal use inputs and so that time to roll to a given bank angle could be timed accurately with a three second sweep stopwatch. Data was obtained on times to roll 30°, 60°, 90°, and 180° at various airspeeds. A comparison of simulator and flight test data showed that the simulator took as much as five times longer to roll to a given bank angle as the airplane at the same flight condition. A detailed study of the software revealed that a pseudo-aileron function had been added early in the life of the simulator. The function took the true commanded aileron deflection, squared it, divided it by the full throw deflection and then applied this new deflection to the rolling moment equation. In short, the 8° of aileron commanded by a one inch stick deflection was reduced to 1.6° Full throw deflection was not affected. This pseudo-aileron function was the simulator specialist's answer to fleet user complaints that the 2F90 was too sensitive laterally. After removing this function, it was found that indeed the simulator was very sensitive in roll. Even after roll control power, $C_{l_{\delta_a}}$, and roll damping, C_{l_p}, were adjusted so that the roll data between the simulator and the airplane matched, and simulator lateral breakout and full deflection forces were verified with airplane data, the simulator still seemed too sensitive in roll. From flight data, however, the key to the problem was discovered. Although both the airplane and the simulator have less than 1/2 lb. of breakout laterally, the airplane stick force exhibits a rapid non-linear build-up during the first 1/2 inch of stick deflection whereas in the simulator, force vs. deflection is linear. This phenomenon acts to desensitize lateral control for small pilot inputs. Mechanizing this non-linear relationship proved to be very difficult in the simulator software. The desired result was finally obtained by adding a pair of germanium diodes grounded by a leakage resistor in the analog circuitry to provide the desired non-linearity. As a result, the lateral control sensitivity problem was solved, and several pilots have agreed that laterally the 2F90 is now much more representative of the TA-4J. In both cases it was found that improvement of the simulator flight fidelity was followed by an immediate increase in simulator acceptance in the user.

ADVANCED TEST METHODS

A great deal of work has been done by many investigators in identifying stability derivatives from flight test data. The Naval Air Test Center has also been active in this area. Under funding from the Office of Naval Research, NATC has combined efforts with Systems Control Inc., Palo Alto, California, to develop an advanced parameter identification program utilizing modern optimal control methods to accomplish this task. As a result, a digital computer algorithm utilizing a maximum likelihood estimator combined with an extended Kalman filter to identify the standard longitudinal and lateral-directional stability derivatives from flight test data in the presence of measurement and process noise, is now operational on NATC's Sigma-9 computer. The algorithm will output estimates for the derivatives, matched time histories, and a covariance of error matrix giving the user an idea of the credibility that the algorithm attaches to each estimate. Initial results with F-14A data have been very encouraging. One primary application of this technology will be to provide a reliable data base for simulator software programming for any new airplane and/or simulator. It is estimated that this technology will be operational for this application by the spring of next year.

CONCLUSIONS

The team approach to the problem of improving the flight fidelity of Operational Flight and Weapons System Trainers has proven very successful. The necessary members of the team are fleet pilots, test pilots, flight test engineers, computer specialists and simulator specialists, and a program manager.

Although the conventional flight test methods used by the team do not represent an advancement in technology, their application of flight fidelity improvement of simulators is long overdue.

Advanced test methods involving parameter identification techniques show great promise toward providing accuate data bases for simulator software programming in the future.

The most important conclusion to be gained from this work is the necessity for flight test personnel to become deeply involved in the acceptance of any new simulator for the Navy.

ABOUT THE AUTHORS

CDR MARLE D. HEWETT is Head of Flying Qualities and Performance Branch of the Flight Test Division of Naval Air Test Center, Patuxent River, Maryland. CDR Hewett is a Navy test pilot with 15 years of service. He holds a B.A.E. in Aeronautical Engineering from Rensselaer Polytechnic Institute, and an M.S. and Ph.D in Aeronautics from the Naval Postgraduate School.

MR. R. THOMAS GALLOWAY is an Aerospace Engineer in the Flying Qualities and Performance Branch of the Flight Test Division of Naval Air Test Center, Patuxent River, Maryland. Mr. Galloway holds a B.A.E. from Georgia Institute of Technology and a M.S. in Aerospace Engineering from Princeton.

CDR JAMES C. MURRAY is Advanced Systems Development Officer in the Plans and Programs Division, Chief of Naval Air Training, Corpus Christi, Texas. CDR Murray has flown the F4, A4, and A7 aircraft operationally in the attack carrier environment and has 19 years service. He holds a B.S. in Engineering Science from the Naval Postgraduate School.