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When In-Flight Simulation is Necessary

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As aircraft systems have become more complex, designers have depended more and more on ground simulation to optimize the aircraft's design. But when are the answers from ground simulators misleading or even erroneous? When is in-flight simulation (IFS) necessary? Previous IFS simulation programs and research experiments are reviewed and a set of guidelines for answering these questions is presented.

Introduction

AN in-flight simulator (IFS) uses hybrid technology. It is a ground simulator that flies and a test bed aircraft that plays make-believe. Many people think that IFS is unrelated to the ground test world since it must involve the flight testing part of the organization. Yet its utility during the ground-testing phase of a new aircraft's development has emerged strongly since the early 1970s.

This article draws a comparison between ground and IFS not often articulated. Its objective is to briefly document some of the case histories where both types of simulation have been used to mutual benefit and where lessons have been learned. From these examples, the authors have suggested some generalizations to apply in future simulation planning.

What distinguishes an IFS from a test bed aircraft? Test bed aircraft are numerous. Every major airframe developer has at least one. The Government has many. IFSs are rare in comparison, since they must have simulation capability combining the general ability to replicate another aircraft's dynamic response with cockpit controller force vs the position duplication and acceptable replication of the cockpit displays important to the task. The more powerful IFSs employ computer control of all six degrees of freedom (DOF), including the response to air turbulence and extensive capability to replicate a simulated aircraft's cockpit environment. The IFS must be programmed much like the ground simulator with, in some cases, a real-time dynamic model just as used in the ground simulator. Therefore, the user needs ground simulator expertise.

Up to the early 1970s, the U.S. Air Force (USAF) and others used their IFSs largely for handling qualities specification work and test pilot school training. Examples of specific aircraft development work were not nearly as plentiful as in the 1970s and 1980s. Now these simulators are accessible to users throughout the U.S. industry and to foreign governments, and it has become important to understand what roles they should play in aircraft design and evaluation.

Programs Using IFS

Supersonic Transport Simulation (1972)

The Federal Aviation Administration (FAA) tested a detailed approach and landing model of the unaugmented Concorde in the USAF total inflight simulator (TIFS; see Fig. 1) and the NASA/Ames flight simulator for advanced aircraft (FSAA). This experiment, to define the Cooper-Harper Level 2/3 boundary as c.g. is moved aft, was the first to attempt to compare complete six DOF ground simulation with IFS and with actual aircraft performance. Both simulators tended to predict the 6.5 boundary at the same value of time to double amplitude, although there was considerable scatter in the data.[13] Use of IFS gave the needed confidence to cope with the scatter and define the needed critical handling qualities to support a then anticipated U.S. certification of the Concorde. Concorde pilots were enthusiastic about how well IFS produced the Concorde handling qualities. They did report, however, that the ground effect was too abrupt and too large in both the TIFS and the FSAA.

YF-16 (1973)

In the evolution that yielded the USAF's primary lightweight fighter, the F-16 underwent a development process for its sidestick controller and flight-control system (FCS). This process included a fixed-base ground simulator for pilot-in-the-loop tests and evaluation prior to first flight. In addition, a short IFS was conducted in the USAF NT-33A Variable Stability Aircraft (see Fig. 2).

The F-16 fly-by-wire FCS and fixed sidestick were simulated in the landing, formation, and engine-failure flameout approaches. The results of the IFS indicated that 1) roll response was too sensitive and would lead to roll ratchet and roll pilot-induced oscillation (PIO) and 2) there was a pitch bobble (or PIO) tendency.[5]

The oil embargo halted evaluations after one week and the NT-33A was sent home. However, the YF-16 roll gearing was reduced by a factor of 2 as a result of the IFS evaluations. Soon after, an inadvertent YF-16 first flight resulted from roll PIO encountered during a high-speed taxi test. Control surface rate limiting was also a factor in the PIO. The aircraft's left and right stabilizer and right wing contacted the runway.

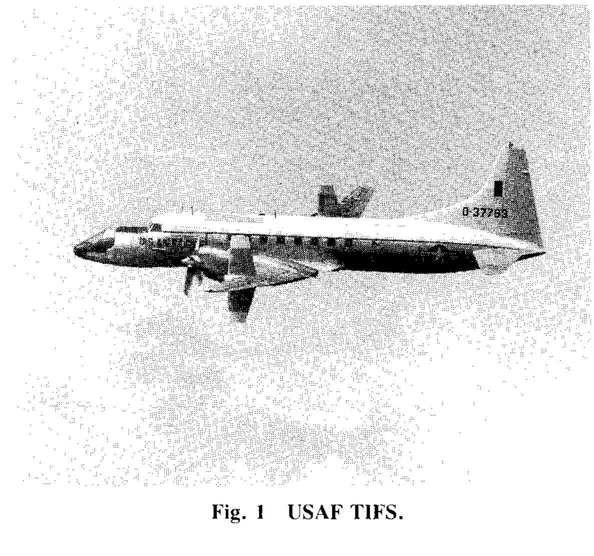

Fig. 1 USAF TIFS.

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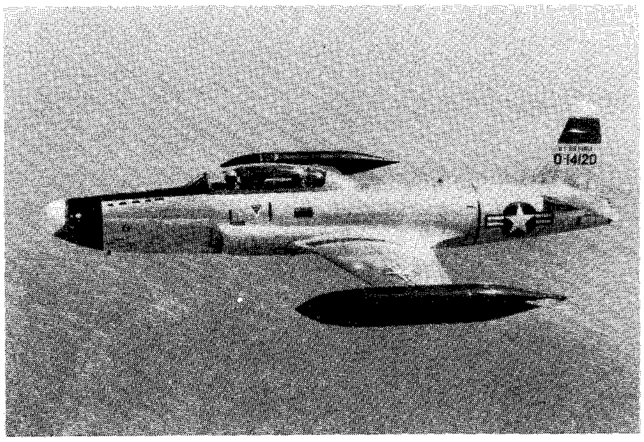

Fig. 2 USAF NT-33A.

The General Dynamics pilot saved the aircraft by completing the takeoff.

Following the incident, the NT-33A returned to Edwards Air Force Base for an additional F-16 IFS. As a result, the roll gearing was further reduced in the YF-16 and, subsequently, the "first" flight was successfully made. Ultimately, the YF-16 roll gearing was considerably reduced from the value selected as optimum in ground simulation.

During the YF-16 development testing, the NT-33A simulation was used to train and check out each pilot before flying the YF-16. Usually, three training flights were required. Emphasis was placed on familiarization with the sidestick-controlled handling qualities in landings and takeoffs and on simulated flameout landings to lake beds and runways. During YF-16 testing, several engine rollbacks to idle were experienced that required landing with reduced power. One Tactical Air Command (TAC) pilot assigned to the test force had this happen on his first flight in the YF-16. He made a successful landing, stating that his confidence in being able to land the YF-16 was a result of his NT-33A training. IFS training kept him from ejecting with the resultant loss of the airplane.

YF-17 (1973)

Ground simulation in a state-of-the-art moving base simulator was used during the YF-17 development program. IFS in the NT-33A occurred immediately prior to the YF-17's first flight. The flight phases simulated included landing, formation, air-to-air tracking, and engine-failure. The fly-by-wire FCS was replicated. The results indicated that 1) there was a tendency for divergent pitch PIO during landing flare making landing impossible and 2) there was an oscillatory but not divergent pitch response during tracking and formation. Neither of these results were reported in ground simulation.

A series of rapid changes and evaluations were performed in the next two weeks to improve the YF-17's FCS.[5] First the YF-17 pitch command prefilter was easily bypassed in the NT-33A by throwing a switch. No PIO occurred with the prefilter removed, but then the pitch response was too abrupt. Second, mathematical analysis predicted that a properly modified (less filtering; first-order rather than second-order) prefilter would cure the problem. The NT-33A was so modified (overnight) to simulate that prefilter, and subsequent IFS evaluations confirmed the predictions. Third, the YF-17 was modified accordingly, but only when the landing gear was down. When the gear was retracted, the control system reverted to the original prefilter. The YF-17 was then flown successfully on its first flight with good handling reported with gear down. When the gear was retracted (and the original prefilter inserted), the pitch response was oscillatory in tight tasks as predicted by the NT-33A IFS. After several confirming flights, the new prefilter was incorporated throughout the flight envelope.

Advanced Supersonic Transport (1977)

NASA performed IFS in the TIFS following development of the flight control system for the Advanced Supersonic Transport on a fixed-base ground simulator at NASA/Langley. The overall rating in the ground simulator was 2. In TIFS it was 7–8.[14] The reason for the poor flying qualities ratings during IFS was the high side acceleration at the cockpit due to rolling about the flight path, which was 36 ft below the pilot station in the approach condition. Side acceleration at the cockpit had been displayed to the pilot in the ground simulator, but the ball was driven with side acceleration at the c.g. The flight control designers' attention had not been attracted to time histories of the side acceleration. However, the motion cue was impossible to overlook in TIFS. The roll axis had been augmented with roll rate feedback and the sensitive roll command gain chosen yielded almost 0.1 g sideways acceleration per pound input. A second series of TIFS tests in 1978 yielded better flying qualities with a less sensitive roll axis.

F-18 (1978)

There was extensive ground simulation during the F-18 development program. IFS was performed in the NT-33A prior to first flight. This was the first IFS of a digital flight-control system. The primary emphasis was on Navy field carrier landings (but with a shallower approach angle due to NT-33A landing gear strength limits). Evaluation results[11] indicated 1) a tendency for divergent roll PIO to occur just prior to touchdown and 2) the sideslip rate estimator (to provide yaw damping) was incorrectly mechanized in the F-18 flight control computer leading to very poor flying qualities. NT-33A evaluation showed that the roll PIO tendency could be improved by reducing the transport time delay in roll axis and by reducing the roll gearing. Subsequently, the digital sampling rate was increased, the roll gearing was reduced, and the sideslip rate estimator algorithm was modified prior to first flight. There was significant improvement in the flying qualities.

Space Shuttle (1972–1985)

NASA requested IFS late in the Space Shuttle development program and funded five evaluation programs from 1972–1985. Each evaluation focused on the approach and landing task, including approach and preflare segments. TIFS was the IFS vehicle used throughout these evaluation programs. Early programs examined the basic Shuttle aerodynamics, handling, control laws, and rotational hand controller, with variations made to assess the effects of uncertainties in the expected characteristics.

Mathematical analysis of the mature Shuttle design predicted pitch PIO tendencies, although ground simulation did not support this conclusion. TIFS was not used to test the mature configuration. When pitch and roll PIOs were experienced during landing on approach and landing test 5, a TIFS simulation program was performed. That simulation reproduced the PIO tendency. TIFS was used to test and optimize a revised rate limiting scheme and a PIO-suppresser device that became a part of the operational Shuttle vehicles.[15]

Like the YF-16 takeoff incident, rate limiting was a factor in the PIO. The Shuttle has a priority rate limiting scheme on the elevons that determines how much pitch and roll control is available when the surfaces are rate limited. The pilot has reduced authority in one axis when there is excessive activity in the other axis. Predictions obtained from ground simulations of the control activity in a typical landing were not reliable.

NASA used the early TIFS simulations to give the opportunity to "fly the unpowered Shuttle to landing" with the real-world cues and environment, adding confidence that the job could really be done. These simulations included landings in actual instrument weather conditions, which have not yet been done with the real Shuttle. IFS (both the TIFS and the Shuttle training airplanes) enabled the pilots to develop control techniques that allow them to overcome the shortcomings in the Shuttle flying qualities.

Advanced Subsonic Transport (1980)

The Dutch National Aerospace Laboratory (NLR) conducted a moving-base ground-simulator program to examine fly-by-wire flight control on a derivative of the F-28. NLR then used TIFS to verify or "calibrate" the results, particularly in the flare and touchdown portion of the landing task. Touchdown sink rates averaged 4 fps on the ground simulator and 2 fps in TIFS. Speed control was a problem on both the ground and in-flight, but pilot complaints were more numerous and louder in-flight. Direct lift control gain increases on the ground produced a strongly favorable trend in pilot rating. In flight, this trend did not appear and even showed a mild reversal due to abrupt cockpit motions.[12]

Advanced Fighter Technology Integrator (AFTI/F-16) (1981)

No IFS was planned during the AFTI/F-16 development program. All development was done using a ground simulator. Prior to first flight, FDL requested and funded an NT-33A simulation. The NT-33A IFS focused on the landing phase with simulation of the primary FCS and the reconfiguration (backup) FCS modes. The results indicated that the pitch rate reconfiguration mode was unflyable for landing. The FCS was subsequently extensively revised.[6] The yaw rate reconfiguration was modified as a result of IFS.

To settle the considerable debate as to correct pitch time delay to represent the real AFTI, an additional simulation was performed using the NT-33A. In this IFS, the NT-33A simulated the F-16 with the new pitch-rate control system that was being flown at Edwards AFB. One USAF test pilot flew the F-16 and NT-33A simulation and stated that he couldn't see any difference between the two aircraft, giving credibility to IFS.

When the real AFTI/F-16 flew, the results had good correspondence with IFS except in one mode: pitch normal digital. Investigation showed that a prefilter had been incorrectly interchanged with a nonlinear gearing box in the NT-33A during the third simulation (done to permit in-flight variation of filter characteristics). This difference resulted in a higher time delay than in the real AFTI. The conclusion is that the face validity of IFS cuing must be backed by careful modeling. IFS flight dynamics checks should have caught this.

V/STOL Test Pilot Training (1983)

The Navy Test Pilot School used the X-22A (Fig. 3) as a training tool to acquaint students with thrust-vectored flight control. The X-22A was operated as a fixed-base ground simulator using the evaluation pilot's feel system, head-up display (HUD), and other displays driven by computer. Then, the same configurations were evaluated in-flight in the X-22A. Most pilots learned to perform the approach task quite well in the ground simulator with the exception of the rate-command flight-control configurations. They had so much difficulty that until the Spring of 1983, the rate systems were not attempted in-flight. The students from the Spring 1983 class decided to test the rate systems in-flight and found to everyone's surprise that they could achieve acceptable performance.[1] Again, ground and flight test results were opposite: a rate system that was uncontrollable in ground simulation was easy to use in-flight.

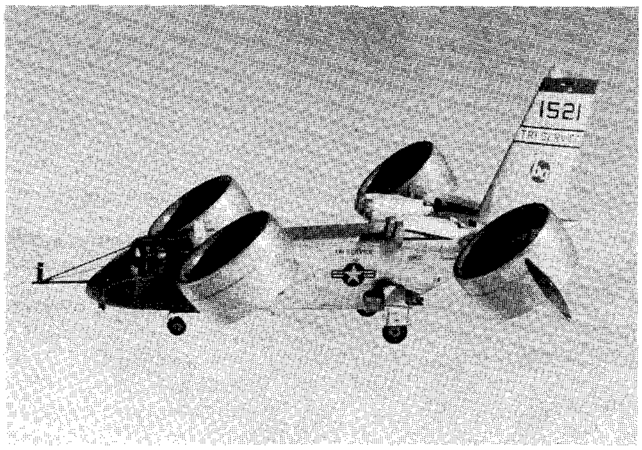

Fig. 3 X-22A.

Command Flight-Path Display (1983)

A pictorial-type pathway display was tested in TIFS. As part of the checkout procedure, the display was flown on the ground using the TIFS evaluation cockpit and the TIFS equations of motion in a computer. Both increased Dutch roll damping and reduced yaw due to ailerons were used on the ground to reduce the lateral excursions from the pathway. In flight the display was easy to fly and the Dutch roll damping increment was not needed.[3] Again, ground simulation results were not validated in flight test.

X-29 (1984)

IFS was not used for the X-29 development program initially. The FCS was developed in a fixed-base ground simulation and also tested in a motion-based simulation. In addition, IFS was requested and funded by FDL when the FCS development was mature. TIFS was used as the IFS for the X-29 because it could completely match the canard effects with its full six DOF simulation capability.

IFS evaluations uncovered roll PIO problems in landing in all three FCS modes. The problems were worst in the normal and backup digital modes. IFS evaluations also showed a tendency for the X-29 to float during landing that was not present in the ground simulator. Further IFS evaluations demonstrated that reducing the roll gearing by a factor of 2 eliminated the PIO problems and provided good roll handling. This change was made to X-29 FCS digital modes prior to first flight; the analog mode was left unchanged because of the high cost of modification at that point.

A flight test of the X-29 substantiated that there was no roll PIO in the modified digital modes. However, it also showed no PIO in the unmodified analog mode, contrary to TIFS prediction. Flight measurement of actual X-29 roll effectiveness was 30% less than the value used in all simulations. The lower control effectiveness had an effect similar to lowering the control gearing as had been done to fix the digital modes. The floating tendency predicted by IFS was substantiated by X-29 flight test.

Israel's Lavi Fighter (1984, 1985)

The initial control law development of the Lavi fighter was performed in ground simulation.[9] The resultant FCS was evaluated in IFS using the NT-33A. The IFS results caused significant modifications to be made to control laws. Some command gains were reduced. Furthermore, the IFS results enabled engineers to better interpret the subsequent ground simulation results. The first flight was flown in early 1987. The Lavi pilots indicated that the aircraft's flying qualities were excellent right from the start of flight testing.

Simulation Validation Experiment (1985)

Five configurations based on two sets of dynamics with time delay as the primary variable were flown in the NT-33A and the NASA Ames Vertical Motion Simulator (VMS).[8] The purpose of this experiment was to evaluate and compare configurations with PIO tendencies in an in-flight and a moving ground-base simulator. The same configurations were flown in the NT-33A and the VMS in December 1985 by the same

Table 1 Guidelines for IFS

Condition suggesting use of IFS	Supporting evidence
High gain task	Supersonic Transport
	YF-16 landing, formation and engine-failure flameout approaches
	YF-17 landing, formation, air-to-air tracking, and engine failure
	Space Shuttle approach and landing
	Simulation validation experiment with difficult landing
New controller	YF-16 side controller
	Space Shuttle rotational hand controller
Side acceleration	Advanced Supersonic Transport
New FCS	F-18 digital FCS
	AFTI/F-16 primary and reconfiguration FCS modes
	V/STOL test pilot training rate-command flight-control configuration
	Israel's Lavi fighter
	X-29 normal and backup digital FCS
Abrupt cockpit motion	Advanced Subsonic Transport
	F-16 MSIP
New flight director	Command flight-path display
Extensive cockpit changes	F-15E cockpit mechanization
Time-delay greater than 150 ms	Time delay study
Life threatening event	F-4 and A-7 heart-rate studies
Rate limiting	YF-16, FCS Space Shuttle FCS

pilots performing the same task (precision visual landing from an offset).

The best configuration was rated 3.5 on the average in-flight and on the ground (eight data points in-flight and six in the VMS using three pilots in each). The standard deviation was 1.3 in-flight and 0.5 in the VMS. The worst configuration (it was chosen to be the YF-17 data point of case 3) was rated 8.2 on the average in-flight and 6.5 in the VMS (six data points and three pilots in each). The standard deviation was 1.2 in-flight and 1.8 in the VMS. Four of the six ratings in-flight were 8 or worse with the same severe PIO tendencies as were observed 12 years previously. Only one rating in the VMS was 8 or worse. In each case the VMS indicated a better FCS than IFS.

The NASA/Ames conclusions, based on preliminary evaluation of the data and pilot comments, were 1) ratings of "PIO prone" configurations are extremely sensitive to task and to pilot control technique (aggressiveness), 2) in both the IFS and the VMS (for the standard lateral-offset approach, precision landing task), some pilots observed serious PIO tendencies while others did not, 3) tasks that require urgent or aggressive pilot control inputs more effectively expose latent flying qualities deficiencies, and 4) there is a need for a national program to acquire generic data to support military flying-qualities specification requirements. Both ground simulation and IFS are needed in a proper mix.

Time Delay Study (1986)

An in-flight experiment was performed in the NT-33A to investigate the effects of time delay on manual flight control and flying qualities. The in-flight time delay data were generated with full fidelity, unlimited range of motion cues. Using the same cockpit and a digital aerodynamic simulation, the in-flight experiment was completely replicated as a fixed-base ground simulation. For almost every value of added time delay, tracking error and the pilot rating were poorer in the ground-simulator mode than in the in-flight simulator mode.[4] As in cases 10 and 11, the full motion and visual cues made the configurations easier to fly.

F-4 Heart Rate

As part of an ongoing research effort to develop an in-flight physiological measure of workload, heart rate, eye blink, and evoked potentials were recorded during F-4 air-to-ground training missions and performance of a standard laboratory tracking tasks.[16] Heart rate and the number of eye blinks were higher in the air than on the ground. Specifically increased *g* forces resulted in a 15–20% increase in heart rate during flight. Also, in-flight, heart rate increased 20–50% from baseline heart rate; for the laboratory tracking task, this increase was only 10%. The authors state "this large difference in the dynamic range suggests that data from ground-based laboratory tasks may have limited utility in reference to actual flight situations." Blink rate was low during the tracking tasks, but increased 300–400% from baseline during flight. The amplitudes of the evoked potentials were smaller in-flight than on the ground. These results suggest that IFS or flight test are required to evaluate high-stress tasks.

A-7 Heart Rate

To assess the physiological and psychological stress associated with flight, heart rate, and heart-rate variability were recorded from eight A-7 pilots during a bird strike and a near midair collision in an A-7 aircraft and during two crashes in an A-7 simulator.[17] Heart rate increased 50% above baseline for both in-flight emergencies, but not for the simulated crashes. There was a greater decrease in heart-rate variability in-flight than in the simulator. IFS or flight test is required to evaluate emergency procedures.

Guidelines

The argument for IFS is at the same time persuasive and elusive. It always involves resources available and usually involves management policies. Our assertion is that there are objective guidelines for making engineering and management decisions on the use of IFS. These guidelines and their supporting evidence are given in Table 1.

Caveats

Simulation always involves some elements of make-believe, otherwise it would not be simulation. IFS attempts to maximize the components of reality in simulation of flying qualities, i.e., behavior of the pilot-airplane combination, the level of effort required to achieve that behavior, and the pilot's decision about the relationship between the two. Ground simulation attempts to do the same thing, sometimes quite successfully. The important question is when is the answer ground simulation gives not to be trusted? We hope this article has provided some guidance on when to believe and when to question.

Lessons Learned

Lesson 1, control sensitivities, such as roll rate or *g* per pound of stick force, are frequently chosen too light when the actual motion is appreciably attenuated or not present.

Lesson 2, the model can usually be simplified for flying-qualities tests, but simplifications must be justified.[10]

Lesson 3, important model parameters should be varied to determine their flying qualities sensitivity, especially if changes in the FCS are at issue late in the development cycle. With augmented vehicles, control surface effectiveness becomes more important. It can dominate flying qualities.[10]

Lesson 4, feel systems must accurately reflect what is in the real aircraft. They are not a detail to be treated with gross approximation.[10]

Lesson 5, displays need not be exact replicas, but they should include all the information important to the task presented in a similar manner.[10]

Lesson 6, excessive simulation time delay can cause PIOs or degraded pilot ratings. Use of feed forward techniques can reduce simulation time delay, in some cases to zero. Visual and motion cues should be synchronized.[10]

Lesson 7, the task should be defined in detail. If the real operational situation includes the likelihood of tight, closed-loop control, this should be part of the simulator task and difficult for the pilot to avoid by subtly changing the task.[10]

Lesson 8, pilot background and characteristics as a controller should be part of the experimental data. The pilots should receive the same briefing, and the briefing should emphasize the task, the rating scale use, and the comment card.[2]

Lesson 9, expect scatter in pilot ratings. Use repeat evaluations and other evaluation pilots to determine a consensus. Use the comment card to obtain insight on reasons for the rating, special control techniques developed, learning effects, and pilot confidence in the rating.[10]

Lesson 10, use the pilot in a real-time development mode. If some characteristic is objectionable, change it on the spot and get the reaction.[7]

Lesson 11, engineers should look at time histories of model motion (and cab motion, if present). They should remember that the pilot will feel complete cockpit motions in-flight, not washed out motions. They should become aware of how transient roll rates of 10 deg/s and side accelerations of 0.05 *g* feel when doing a landing approach. All six DOFs should be checked.[10]

Lesson 12, excessive control activity leading to rate limiting should be examined in an IFS matching the actual task as closely as possible.

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