THE UNITED STATES AIR FORCE'S USE OF IN-FLIGHT SIMULATION FOR AERONAUTICAL RESEARCH

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ABSTRACT

The United States Air Force has used in-flight simulation for research and development for over forty years. Often called a variable stability aircraft, the modern in-flight simulator duplicates the handling and flight characteristics of other vehicles. The Air Force's experience has covered the spectrum from single axis stability modification up to complete control of all six degrees of freedom. In-flight simulation is aiding the development of many new aircraft from concept through actual production.

In-flight simulation compliments ground-based simulation results, and offers a number of advantages, particularly in motion and visual cues and the psychology of flight. As a result, many flight control and handling qualities problems that went undetected using ground-based simulation have been found using in-flight simulation.

There are a number of in-flight simulators that have been used and are currently in use throughout the world. This paper discusses the United States Air Force's development and use of this unique type of research aircraft.

INTRODUCTION: WHAT IN-FLIGHT SIMULATORS ARE AND WHAT THEY DO

An in-flight simulator is an aircraft whose stability characteristics, flying qualities, and handling qualities can be changed to match those of another aircraft. The United States Air Force has taken advantage of this unique capability for over forty years. It sponsored the design, development, and operation of a variety of in-flight simulator aircraft over this period. The in-flight simulators that are probably best known are the Air Force's NF-16D Variable Stability In-Flight Simulator Test Aircraft, or VISTA, (Fig 1), the NC-131H Total In-Flight Simulator, commonly called TIFS (Fig 2), and the NT-33A (Fig 3).

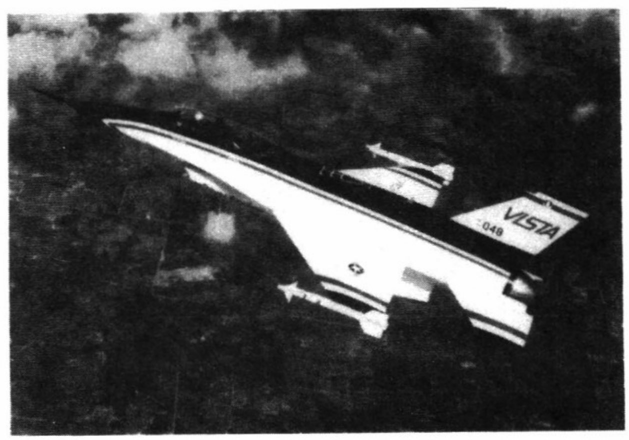

Fig. 1 - NF-16D Variable Stability In-Flight Simulator Test Aircraft (VISTA)

Fig. 2 - NC-131H Total In-Flight Simulator (TIFS)

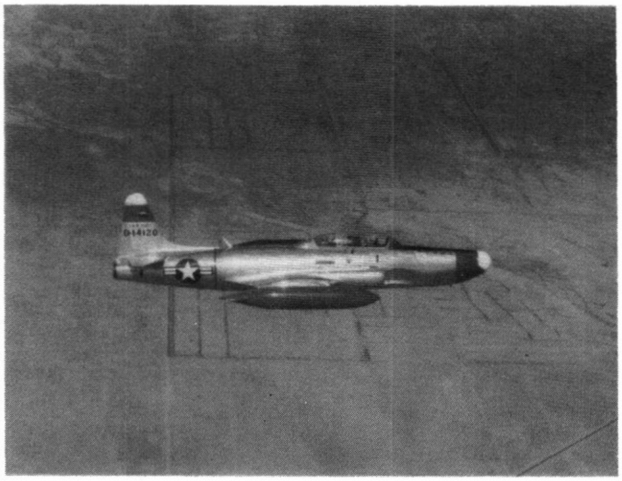

Fig 3 - NT-33A

Many aircraft that entered the Air Force inventory in recent years or are in development were simulated using one of these aircraft. Examples include the B-1, B-2, A-10, F-15, F-16, and F-22. Other programs that were supported include the Space Shuttle, Concorde supersonic transport, Navy F-18, Indian Light Combat Aircraft, and the Indonesian N250 regional airliner. Generic studies, such as handling qualities research, display symbology development, and bio-medical investigations have also been performed.

The in-flight simulator evolved from an older, but still commonly used concept, the variable stability aircraft. These two terms are often used interchangeably, since the difference is not distinct. In general, in a variable stability aircraft, a limited number of the host vehicle's stability derivatives can be changed. In an in-flight simulator, enough of the stability derivatives can be changed to duplicate the static and dynamic response of the aircraft being simulated. This other aircraft can be an existing or proposed one, or a generic aircraft. The aircraft can be simulated to whatever extent the aerodynamic data and flight control designs are known.

VARIABLE STABILITY IMPLEMENTATION

Two methods of implementing an in-flight simulation are in common use: response feedback and model following. Response feedback works by augmenting the stability derivatives of the host vehicle. It can be thought of as a programmable stability augmentation. Although simple in principal, response feedback is often difficult to implement because it is necessary to know the values of each stability parameter for the host aircraft. This process is complicated because each stability parameter often affects several flight characteristics, plus they often changes with flight condition. A considerable amount of in-flight calibration is required for each flight condition. The calibration process is largely a trial and error procedure in which all the variable stability system gains are systematically varied until the desired responses are achieved.

To reduce much of the time and expense required for calibration, another technique, called model following, was developed. Two computer functions are involved: a math model and a model following function. A mathematical model of each degree of freedom is programmed on the computer, just as with a ground-based simulator. The pilot's inputs are directed to the computer, and the model produces an appropriate response for the simulated aircraft. The model following computer then compares the model response to the host aircraft's orientation, and moves the control surfaces to force the host's motions to match those of the model. The model following concept is analogous to ground-based simulation, except that instead of moving a cockpit on the ground, the entire host aircraft moves.

Once the model following scheme has been developed and optimized for the host aircraft, virtually any model can be programmed on the model computer and checked out on the ground. A single verification flight to check all system operations is usually all that is required. This has proven to be one of model following's best features, especially with highly detailed models. The use of modern digital computers in the in-flight simulator allows the actual software model previously used in a ground-based simulation to be used with little modification.

One common feature of all in-flight simulator aircraft is that the evaluation pilot's controls are mechanically separated from the aircraft's normal flight control system. This is done so that the evaluation pilot will not be aware of the actual commands to the control surfaces, which are made by the computer. All stick forces and displacements are produced artificially, and to varying degrees of complexity, depending on the capability of the particular in-flight simulator. On aircraft such as the VISTA, TIFS, and NT-33A, the force gradients, breakout force, friction, freeplay, and damping can be programmed, as well as the effects of bob weights, bellows, and cable stretch.

IN-FLIGHT SIMULATOR DEVELOPMENT

The first two variable stability aircraft were developed about 1948. Ames Research Center of NASA used an F6F Hellcat to investigate the tendency of that class of aircraft to roll into an applied sideslip. An automatic control system was installed to deflect the aileron in an amount proportional to the sideslip. Almost simultaneously, the Navy awarded a contract to Cornell Aeronautical Laboratory (CAL), now the Calspan SRL Corporation, to study Dutch roll characteristics at high speed and high altitude. Using an F4U Corsair, CAL added an extra rudder surface at the base of the existing rudder. The extra surface could be deflected in an amount proportional to yaw rate and sideslip angle. Working independently of each other, each found the need to expand their capabilities. In continuing research, Ames added a rudder control system to their Hellcat and CAL added an aileron control system to their Corsair.

The flight experiments performed using these two variable stability aircraft are examples of early flying qualities research in which flying qualities were systematically changed to investigate pilot acceptability.

About 1950, the Air Force first became involved with variable stability aircraft when it developed a three degree of freedom variable stability C-45, the military version of the Beech 18 light utility transport. The purpose of this effort, which was done by CAL, was to incorporate a system that would make all the modes of the aircraft's motion non oscillatory and convergent. It also was to provide for automatic turn coordination, while keeping all control forces similar to those of the unmodified aircraft.

In 1951, the Air Force began another program specifically aimed at longitudinal flight and handling characteristics for fighter and bomber aircraft. Specifically, the Air Force wished to investigate the acceptable and optimum boundaries of stick force per g, stick to elevator gearing, short period and phugoid frequency and damping, and the significance of any combined effects.

Contracting with CAL, an F-94 and a B-26 were modified with similar variable stability systems in the pitch axis to give each the ability to augment these parameters. Because no actuators were capable of the extremely small elevator angles required for precise phugoid control while still being able to produce the gross deflections, small auxiliary surfaces were added to the aft fuselage of the B-26 and to the forward fuselage of the F-94 for this purpose. These auxiliary surfaces were eventually removed when high quality actuators capable of precise large and small movements became available.

On each aircraft, the ranges of short period frequency and damping, stick force/g, and elevator gearing were variable at least from one half to twice the normal values for each aircraft. Negative short period dampings were even achievable.

The F-94 was only used until 1959, when it was replaced by the NT-33A. The basic F-94 design precluded conversion into a 3 DOF system that would allow safe experimentation with less stable aircraft dynamics. In addition, the Air Force was planning to phase the F-94 series out of service and the aircraft would not have been supportable. One of the aircraft's most significant programs was the development of handling qualities criteria for the B-58 supersonic bomber.

The B-26 (Fig 4) was used extensively, and because of the high workload the Air Force supplied a second one to CAL in 1958. This aircraft was modified to a three axis system for control of pitch, roll, and yaw. Shortly thereafter, the original B-26 was upgraded to a 3-axis system. At about the same time, the second aircraft was provided to CAL, the Air Force was in the process of phasing the B-26's out of service, and allowed CAL to purchase them for $1.00 each. CAL continued to operate these aircraft for various research and development projects for both government and industry.

In 1960, CAL started demonstration flights for the Navy Test Pilot School at Patuxent River, Maryland, using the B-26. The purpose of these flights was to help new test pilots, who were already highly experienced naval aviators, to understand stability and control. These demonstrations capitalized on the B-26's ability to alter one variable at a time, while all others remained constant. By altering appropriate gains in the variable stability system, the relationship between theoritical and actual aircraft dynamics could be demonstrated quite realisstically. Then, by combining several parameters, the interrelationships between effects could be demonstrated. The demonstration flights were integrated with classroom lecturres and extensive pre and post flight briefings. In 1963, CAL began the same variable stability demonstrations for the Air Force Test Pilot School at Edwards AFB, California.

One of the B-26's was used to simulate the Lockheed Supersonic Transport entry in about 1964. For this program the aircraft was fitted with a model following system in the longitudinal axis. This was the first use of model following.

Both B-26's remained in service until 1981. One was destroyed in a tragic crash at the Air Force Test Pilot School in March 1981. It was ironic that the B-26 was performing its last session before being retired. The surviving B-26 was donated to the Air Force Museum and is on static display at Edwards AFB.

In 1957, again through a contract with CAL, the Air Force began operating the variable stability NT-33A. This aircraft featured an analog response feedback variable stability system that controlled pitch, roll, and yaw motions. In addition, the feel system was completely programmable. At this time, the NT-33A was the most advanced and highest performance in-flight simulator in existence.

The most noticeable modification to the aircraft was the replacement or the original nose with the larger one from an F-94. The increased volume provided space for all of the variable stability and feel system electronics.

At one time the aircraft had tip tank mounted drag brakes. These provided variable drag for reentry vehicle type approaches, and when used asymmetrically and combined with aileron and rudder deflections, provided for direct side force control and fuselage aiming. The drag brakes are no longer used as they were damaged beyond repair in a flutter incident in 1976.

Fig 4 - B-26 In-Flight Simulator in Calspan Markings

The NT-33A can also be fitted with an in-flight refueling probe. A high-workload flying task can be performed by requiring the evaluation to perform actual in-flight hookups with a tanker aircraft. Fuel cannot be transferred, but the probe is easily removed and reinstalled as needed.

System improvements over the years have resulted in expanded capability. A completely programmable sidestick was added and has been used when simulating fighters such as the F-16 and F-22. The variable stability system is currently in its fourth generation design (tubes, transistors, then integrated circuit analog, and now hybrid analog/digital). A heads up display (HUD) with a programmable display generator was added in 1979, and since then a significant amount of HUD and display research has been performed. The digital computer from the HUD system has been incorporated into the variable stability system to allow actual digital simulation of digital flight control systems.

Since 1957, the NT-33A simulated most fighter type aircraft that entered the Air Force inventory, plus a number of research aircraft (Fig 5). It also performed flight control and handling qualities research aimed at developing a handling qualities specification for sidestick controlled aircraft.

Fig 5 - Major Simulations Performed by the NT-33A

In 1976, the Air Force and Navy Test Pilot Schools each incorporated stability and control instruction flights using the NT-33 into their curricula. These flights initially were similar to the B-26 demos, expanding them to higher speed, altitude, and g's, and putting the pilot into the environment of a fighter cockpit. In later years, the instruction flights were oriented more toward HUD use and digital flight control system issues.

The NT-33A's most recent program was evaluating the flying qualities of the Indian Light Combat Aircraft during approach and landing. It remains in service despite introduction of the VISTA/NF-16D, which was intended to replace it. Occasional requirements for its use still arise. While not nearly as active as in its past, it is being kept in flyable condition. The NT-33A will be retired when it can no longer be supported or there is no longer a demand for it.

The first, and to date, the only six degree of freedom in-flight simulator the Air Force built is the NC-131H Total In-Flight Simulator, commonly called TIFS. Development began in 1966 and the first research program was flown five years later. As in previous aircraft, the pitch, roll, and yaw are controlled by the elevator, aileron, and rudder. A direct lift flap that can move 40 degrees up or down provides direct lift, and a movable side force surface on each wing produces side force. Fore and aft acceleration is provided by servo controls on the throttles. Both the model and the model following system are mechanized on a Silicon Graphics Onyx computer that was specially ruggedized for use on the TIFS. The Onyx computer can also produce a variety of instrument displays.

The evaluation pilots fly in a separate cockpit added to the front of the aircraft (Fig 6). The evaluation cockpit has side by side seating, and each pilot station can have flight controls and instruments. Because of the large volume, the evaluation cockpit can be modified relatively easily to suit the needs of any specific simulation. The windscreen was made large and can be masked as needed to duplicate the out-of-the-cockpit view.

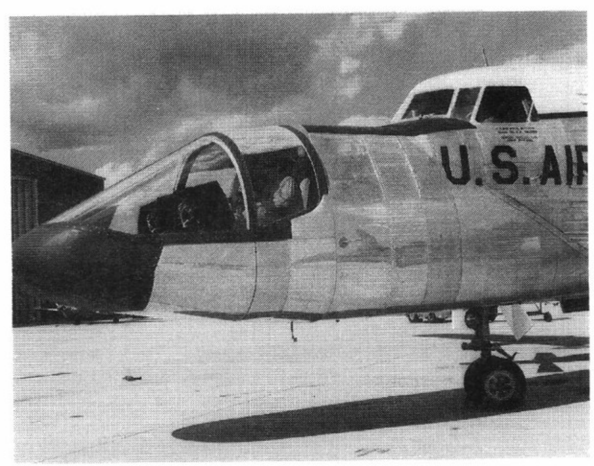

Fig 6 - TIFS Evaluation Cockpit

TIFS was developed initially to support supersonic transport and B-1 development. It provided data on handling qualities of large flexible supersonic aircraft in critical flight conditions, such as maneuvering flight and landing. An early research program utilized TIFS's unique side force surfaces to demonstrate the cancellation of cross wind effects during landing.

In other programs (Fig 7), TIFS simulated a remotely piloted vehicle and a pilot seated at a remote operator's console on the ground flew the TIFS to touchdown and a complete stop; simulated the Space Shuttle, including the steep approach, in an effort to improve handling qualities during final approach and landing; simulated several generic large aircraft, typical of the C-5 and 747 class, and smaller aircraft such as the X-29 and YF-23.

Other programs have taken advantage of the unique capabilities of TIFS. One was a motion perception study performed in 1980 for the Air Force Human Resources Laboratory, with the results being used to develop better acceleration cues for ground based simulators. This experiment had two subjects seated side by side, one with normal outside vision and the other with outside vision blocked. The aircraft was flown through a series of coordinated and uncoordinated maneuvers, plus single axis motions, such as pure heave oscillations and longitudinal accelerations and decelerations. The perceived motions, body movements, and head movements of the two subjects were compared. A program in 1986 investigated possible negative effects of protective drugs that pilots would take before flying into a chemical warfare area. The TIFS was used because in the event the subject pilot should be incapacitated and fall over the control wheel, the safety pilots could take over quickly and maintain control of the aircraft.

Fig 7 - Major TIFS Projects

In recent years, the Air Force has made unique, one-of-a-kind government-owned research facilities, such as TIFS, available for use by industry. In supporting this initiative, the TIFS was used to simulate commercial aircraft designs for Boeing, Douglas, and Nusantara Aircraft of Indonesia.

Another completely different mission for the TIFS is as an avionics test training aircraft (Fig 8). The simulation nose is removed and replaced with a radome housing radar, electro optical, and infrared units. The system also has inertial navigation, Global Positioning , and Loran systems. In this configuration, the TIFS was used at the Air Force and Navy test pilot schools to train new test pilots to perform avionics system testing. It has also been used to support the development of new avionics systems. While no longer used at the schools for this mission, the TIFS retains the capability to support this avionics training and test mission.

Fig 8 - TIFS/NC-131H in Avionics Test Training Configuration

The Variable Stability In-Flight Simulator Test Aircraft VISTA/NF-16D entered service in January 1995 to replace the NT-33A. The airframe consists of a mixture of F-16 production variants, plus the incorporation of the variable stability system. VISTA offers a substantial increase in performance over the NT-33A and other existing in-flight simulators.

VISTA features a five degree-of-freedom system that can control pitch, roll, yaw, direct lift, and longitudinal acceleration. Computations are performed on three Rolm Hawk 32 digital computers. The front cockpit has been modified extensively, including the installation of a programmable center stick and side stick.

VISTA was built brand new as an in-flight simulator. By doing this, the Air Force was able to take advantage of a wide variety of systems that already had been developed for many different F-16 models. The most noticeable exterior feature is the large dorsal housing that runs the length of the fuselage. This, too, was a previously-developed F-16 configuration. The computers, recording equipment, and other electronics are located in this area.

The aircraft made five acceptance flights in April 1992, then the program was placed on hold for financial reasons. Rather than leave the aircraft in storage, it was loaned to the Multi-Axis Thrust Vectoring (MATV) program, a joint effort between the Air Force, Lockheed, and General Electric. The purpose was to determine the feasibility and performance gains that could be obtained by adding thrust vectoring to an F-16. To perform this effort, the VISTA was demodified to make it functionally identical to a production F-16, including removing the variable stability system. The only major exterior change was the addition of a spin chute and some additional program markings (Fig 9).

The highly successful MATV program flew 95 flights between July 1993 and March 1994. It developed maneuvers that showed the effectiveness of thrust vectoring and post stall maneuvering for close-in air combat. In its final stage, the MATV program demonstrated the usefulness of this new technology by repeatedly winning in one-on-one and two-on-one aerial engagements.

Following completion of the MATV program in early 1994, and with VISTA's financial problems resolved, the aircraft was returned to its original configuration to complete development as an in-flight simulator. Development testing continued through January 1995, when the Air Force accepted the completed VISTA. It was flown to Buffalo, NY, where it is operated by the Calspan SRL corporation along with the TIFS/NC-131H and the NT-33A.

In its first year of operation, the VISTA flew training sessions at the Air Force and Navy test pilot schools. Its first research programs were flown in early 1996, simulating the F-22, Indian Light Combat Aircraft, and evaluating adaptive algorithms for a potential self-designing flight control system.

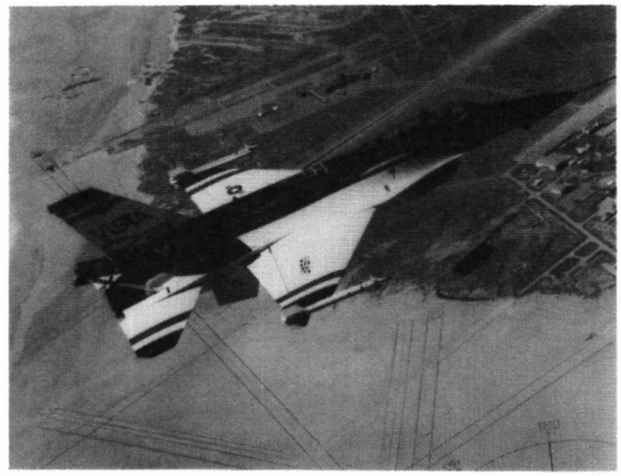

Fig 9 - VISTA/NF-16D During the MATV Program

The VISTA is currently down for its first major upgrade. The success of the MATV program did not go unnoticed. Wright Laboratory obtained funding to develop a permanent thrust vectoring capability for VISTA, along with a display system upgrade to allow the pilot to better-utilize the new maneuvering capability. When completed in September 1998, these enhancements will make VISTA the Air Force's premier thrust vectoring/post stall maneuvering research vehicle. In addition to other scheduled in-flight simulation programs and test pilot training, it will be used to further develop air combat maneuvering and high off-boresight missile tactics.

FUTURE DIRECTIONS

As the Air Force moved into the 1990s, new factors began to influence in-flight simulator use. Decreasing defense budgets resulted in fewer research programs and even fewer new aircraft to investigate. New business practices enacted throughout the Air Force require an accurate cost determination and that test sponsors pay all costs that can be attributed to their project. Expensive, unique research facilities not only must be technically justifiable, but economically justifiable. The Air Force can no longer afford to maintain facilities for convenience when similar ones that meet needs are available elsewhere. In-flight simulators were identified as a unique military facility with no comparable civilian capability. However, this does not assure their survival. Smaller budgets are here and likely will remain. Compounding the problem is lack of support funding, meaning customers must pay the full cost for using a facility.

In the new environment, survival depends on keeping these aircraft flying so that fixed costs do not become a burden. The realities of the 1990s will result in new users and missions being sought for the in-flight simulators.

Technology demonstration programs are not new for in-flight simulators, but they were not a significant use in the past. Many times another vehicle can be used for this purpose. An in-flight simulator may even be a far more expensive choice, especially if few of the unique capabilities are needed. However, with a shrinking pool of test aircraft available, the Air Force's in-flight simulators will certainly be called on in the future to perform this function.

One such use is the previously-mentioned thrust vectoring upgrade to the VISTA/NF-16D. While another aircraft could have been selected, this upgrade will make VISTA the Air Force's only thrust vectoring/high angle of attack research aircraft. By giving this new mission to VISTA, the simulation capability will also be greatly increased.

Another exciting new possibility is to serve as a testbed for developing new flight control system upgrades for aircraft with digital flight control systems. In production F-16s, for example, new software is simple to install in the field. However, developing, verifying, and flight testing the new code is a lengthy process. Proposed new code normally must undergo an extensive verification and validation (V&V) process before being tested in an aircraft to see if it fixes the original problem. Using the VISTA/NF-16D, proposed code that has not been V&V'd can be installed in the variable stability system and flight tested for proper operation. If the new code fixes the original problem, it can then be V&V'd for fleet-wide use. By duplicating other flight characteristics, VISTA can also be used in a similar manner for other aircraft.

SUMMARY

The United States Air Force is committed to the continued use of in-flight simulation for research and development. Combined with ground based simulation, in-flight simulation provides realism unattainable short of full scale vehicle flight testing. This allows thorough examination of flight characteristics, handling qualities, and performance of specific and generic airplanes. New missions for these aircraft will help keep them as valued test assets.

The Air Force's in-flight simulators evolved through over forty years of experience in this unique area of flight test. The recent introduction of VISTA demonstrates our commitment to this technology and gives the Air Force the capability to perform in-flight simulations in a flight environment representative of modern fighter aircraft.