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HISTORY OF IN-FLIGHT SIMULATION & FLYING QUALITIES RESEARCH AT CALSPAN

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Abstract

Calspan Corporation has been the primary innovator, developer, and operator of in-flight simulators in the United States as well as the rest of the world since 1947. Though other agencies and countries have developed their own in-flight simulators, this paper concentrates on Calspan accomplishments in this field. In-flight simulation puts the pilot in the real flight environment and has been used in the development of new aircraft, research of flying qualities and flight control systems, and training of pilots and engineers in these areas. More recent uses have been in the field of display systems and as avionics test beds. This paper starts with the early technologies that led to the development of variable stability aircraft and their earlier applications. It then describes Calspan's history in the development and utilization of in-flight simulation, starting in 1949 with the first flight of the F4U-5 and its auxiliary rudder surface up to the present with the five degree-of-freedom F-16 Variable Stability In-Flight Simulator and Test Aircraft (VISTA). Specific case studies are presented which describe the development and distinctive features of each of the Calspan in-flight simulators and highlight some of the more significant applications of these unique tools.

Introduction

The variable stability airplane was conceived as a device that would permit variation, in flight, of the characteristics or flying qualities of an airplane so a pilot could determine the suitability of these characteristics in actual flight. Today the concept of the variable stability airplane has progressed into true in-flight simulators (IFS) which are routinely used as an extension of ground-based simulators to the flight environment and its real-world cues. These applications include aircraft development, research of flying qualities, systems test, and special pilot training. In-flight simulators use some of the same technologies that go into ground simulators (modeling, control loaders, cockpit displays, and actuation systems) and add to that, aircraft augmentation technologies. IFS computers drive real responses of the aircraft instead of just displays and limited motion systems, and the outside visuals are the real world instead of computer generated. Although the technologies and development of the IFS have been advanced by many organizations, this paper will start with the early developments in augmented airplanes and then concentrate on IFS applications at Calspan. (Note: before 1972 Calspan was known as the Cornell Aeronautical Laboratory (CAL) and during an interim period as Veridian, and then was part of General Dynamics. In February 2005 it again became an independent company called Calspan. Throughout this paper the name Calspan will be used for all references to the company.) IFS started at Calspan in 1949 with the first flight of the single-axis (one-degree-of-freedom) yaw augmentation system on the F4U-5. This system essentially varied the yaw stability of the aircraft; hence the name, variable stability aircraft, was coined. Calspan has continued to use the term Variable Stability System (VSS) to describe all of its simulation systems since then. This technology has progressed to today, where Calspan operates five true in-flight simulators which do much more than just vary the stability of the aircraft.

The Beginnings

The foundations of the variable stability aircraft and IFS has its roots in the science of the dynamic motion of aircraft which dates back to the 1904 writings of Bryan, in England[1], which was also published in his 1911 book, Stability in Aviation[2]. This was followed by other researchers in many countries, and was consolidated in the US in two National Advisory Committee for Aeronautics (NACA) reports by Zimmerman in 1935[3] and 1936[4]. These latter reports put a highly theoretical and complex subject into a form that could more readily be understood and applied to aircraft design. Along with the understanding of aircraft dynamics came the question of what the pilot desired in terms of these dynamics in order to produce an airplane that flew well. Two early reports on this subject were written by Soulé in 1936[5] and Gilruth in 1943[6]. The first US military specifications for flying qualities were written for the Navy in 1942[7] and for the Army in 1943[8]. This work was the genesis of the later US military specifications for piloted airplanes which used IFS for much of their development, and culminated with MIL-F-8785[9] and MIL-STD-1797[10].

Existing airplanes were flown and evaluated in order to gain insight into the dynamics of airplanes. However, to see how specific characteristics affected the flying qualities of the airplane, the physical configuration of the airplane had to be changed (e.g. size if the tail or dihedral angle of the wing). Changes to the geometry would change the stability derivatives of the airplane. One can also change these stability derivatives by using the concept of feedback control. For example, augmenting or modifying the inherent yaw damping stability derivative, N_r, can be done by sensing yaw rate, r, and feeding that back to the rudder through a gain, dr/r. The product of the rudder yaw control derivative, N_{dr}, and the gain, dr/r, produces an increment to the natural yaw damping. This is now known as a yaw damper. All the stability derivatives of an airplane can be modified in the same manner; by feeding back the state of the airplane to the primary control surface for that axis.

The first practical use of feedback control to modify a dynamic characteristic of an airplane was not done in the US, but in Germany, during WWII. A recent paper by Hamel[11] describes the research of Heinkel and Fischel in 1940 that promoted the necessity and methods to produce artificial stability in their advanced aircraft. These advancements included sweepback and high speed flight. Hamel recounts how Doetsch and Friedrichs applied this technology in 1944 to the Henschel HS-129 aircraft which had annoying directional snaking oscillations during tracking tasks (now know as a lightly damped Dutch roll mode). They split the rudder into two separate surfaces (Figure 1): the lower surface was mechanically tied to the pilot's rudder pedals, and the upper surface was controlled with an electromechanical device fed by a yaw rate gyroscope. This was the first effective yaw damper. This work was unknown to US researchers, but a few years later similar applications of feedback control resulted in the first variable stability airplanes in the US.

Figure 1: Henschel HS-129

During WWII, as aircraft got larger and the control forces became unmanageable, it was recognized that there was a need to augment the pilot's forces through the aircraft's feel system. Again, first in Germany, electro-mechanical devices were installed in the pitch axis of the large Bolm & Voss BV-222 flying boat to relieve pilot forces[11]. In the US, artificial feel systems were first incorporated in the Northrop flying wings: N9M(1942), XB-35(1946), and the YB-49(1947)[12]. Artificial feel systems also eventually found their use in IFS.

First Generation Variable Stability Aircraft: F6F-3 and F4U-5

Work on two different problems by different organizations led to the first true variable stability aircraft. In 1947 NACA was investigating the lack of effective dihedral (L_β, roll due to sideslip) in the landing configuration of the Navy Ryan FR-1. Dihedral allows the pilot to pick up a low wing with rudder input. Also in 1947, Calspan was working with the Navy, investigating the poor Dutch roll characteristics during landing of new carrier-based fighter aircraft. Working independently, both organizations developed variable stability aircraft to help solve these problems. These variable stability aircraft had similar capabilities but achieved them by very different methods[13].

NACA F6F-3

NACA-Ames was assisting Ryan in the development of the FR-1, which had very little effective dihedral during landing with its flaps down. To determine the minimum amount of effective dihedral that would be acceptable to the pilot, the Navy built three separate prototypes, each with different fixed geometric dihedral angles in the wing attachment to the fuselage. Evaluation flights in each airplane were flown by pilots in rapid succession to determine their relative flying qualities. William Kaufman, an engineer at NACA who was not working on the FR-1 project, was developing a system for varying in flight the static and dynamic stability characteristics of an aircraft by means of servo actuation of control surfaces[14]. He was eventually awarded a patent for this device. After seeing the inefficiencies and expense of the FR-1 tests, he thought that an application of his new device could be used on this investigation.

NACA installed their first variable stability system in a Navy F6F-3 aircraft (Figure 2). It initially incorporated a sideslip sensor fed to an aileron servo motor (a B-29 gun-turret drive) on a modified aileron linkage. The servo moved a mechanical link that added to the pilot input but was not reflected back to the pilot's stick. This was accomplished with another servo on an aileron tab that balanced out the hinge moment due to servo commands. First flight of the system was in 1948. Soon afterwards, the rudder was modified with a similar servo arrangement and feedbacks of roll-rate and yaw-rate were added for both surfaces. Over the next few years 400 hours were flown and many lateral-directional flying qualities studies were performed[15].

Figure 2: NACA F6F-3

F4U-5

Meanwhile, at Calspan (and its predecessor Curtiss-Wright Research Laboratory) Bill Milliken was doing research (started in 1944 under Air Force sponsorship) on programmed automatic control inputs to measure aircraft stability derivatives (the beginning of what is now know as Parameter Identification, PID). This equipment was installed in a B-25, A-26, P-80, and N9M, and successfully used for PID studies. In 1947, after Air Force sponsorship ended, Calspan approached the Navy to continue the work.

The Navy, however, had a more pressing need to investigate the required level of yaw damping for landing of carrier-based fighters. After internal discussions, Calspan determined that they could modify an aircraft with the equipment they were using for PID, to achieve the Navy's research objectives. Their idea was to install a two-piece rudder on an airplane, and drive one section with pilot inputs, and the other with feedback signals through an autopilot servo (Sperry A-12). This was what the Germans had done with the HS-129, but that was not known at the time. The Navy provided an F4U-5 (Figure 3). A similar aircraft, the F2G-2, had a two-section rudder. This rudder was installed on the F4U-5. The upper surface was connected with mechanical linkage to the pilot's rudder pedals and the lower surface was driven by the servo with sideslip and yaw-rate feedbacks. This first Calspan variable stability airplane flight was flown in March 1949. Soon afterwards its capabilities were expanded with the addition of an auxiliary roll controller. The mid-span flap was replaced with plane flaps that could go up or down (similar to what was done with the TIFS twenty years later). They were driven by another autopilot servo. Roll-rate feedback was also added to both servos. Over the next two years 172 hours were flown and many lateral-directional flying qualities studies were performed[16,17]. In 1951 the F4U-5 was transferred to the Naval Test Pilot School (NTPS), where it subsequently saw little use.

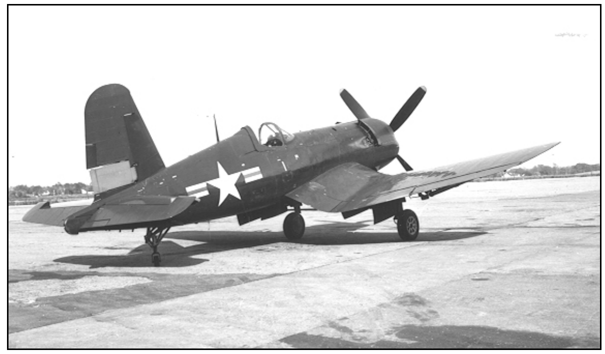

Figure 3: F4U-5

It is interesting to note some other similarities between these first two variable stability airplanes. Both were single pilot airplanes without a "safety" pilot, as was eventually used on all later Calspan IFSs. Both started with single axis control, but quickly expanded to full lateral-directional control. Finally, neither had the capability to modify feel characteristics, which was a feature that was added in all later IFSs.

Second Generation Variable Stability Aircraft: C-45, F-94, and B-26

The value of variable stability aircraft for flying qualities research was recognized soon after the development of, and experience gained from, the F6F and F4U. In 1951 Calspan, under the sponsorship of the All-Weather Branch of Wright Air Development Center modified a C-45 with the first 3-axes VSS. An augmented elevator control system with pitch rate and angle of attack feedbacks was added to the ailerons and rudder. Its purpose was to investigate minimum flying qualities for landing in instrument flight conditions. The left seat controls were separated from the right side and electrically fed to the command servos with their feedbacks. Hydraulic servo actuators were used to provide higher force and bandwidth capability than the electric autopilot servos. The right seat became the "safety pilot" with its controls remaining mechanically connected to the surfaces. Unfortunately, after delivery to the Air Force, the aircraft was damaged in a landing accident unrelated to the VSS, and was never used for flying qualities research. The primary contributions of the C-45 to IFS technologies were the development of hydraulically controlled surfaces and the concept of a safety pilot with an independent set of flight controls.

At the same time as the development of the C-45, the Office of Air Research (predecessor of the Air Force Research Laboratory) also had Calspan under contract to develop fighter and bomber IFSs for the purpose of investigating a myriad of longitudinal flying qualities issues.

F-94

The F-94 (Figure 4) and B-26 (Figure 5) were chosen as base aircraft primarily because of their availability. The T-33 was actually the preferred fighter choice (no after-burning engine), but was not available at that time. Initially, only the pitch axis was converted into the variable stability mode on these aircraft. (Later, we shall see that roll and yaw were added to the B-26). In the F-94, the front seat evaluation pilot controls were mechanically disconnected from the elevator in flight and drove the surface, along with feedback signals, through a hydraulic servo. After the simulation task was completed, the controls were re-connected in flight to the elevator. The reason for maintaining mechanical controls was that the rear safety pilot did not have rudder and brake controls and the evaluation pilot had to make all takeoffs and landings.

Figure 4: F-94

Figure 5: B-26

The first VSS flight of the F-94 was in December 1953. Significant longitudinal flying qualities research (including aircraft dynamics and feel characteristics) was performed during the life of the F-94 and the early years of the B-26. Most important was discovering that there was an acceptable range for the short period frequency; and that it depended on flight task, speed, loading, and lift-curve slope[18]. This was the origin of the Control Anticipation Parameter (CAP) that is now the primary longitudinal flying qualities criterion. Another interesting use of the F-94 was in simulating the pitch control system of the B-58 before its first flight. The Convair pilot who flew both the F-94 and the B-58 stated "It was like shaking hands with an old friend[13]." In later years, similar comments have been received from test pilots after their first flights in aircraft that have gone through in-flight simulation. The F-94 was retired in July 1958 after being flown for a total 335 research hours and was later donated to a Buffalo, NY high school that taught airplane mechanics. It was subsequently donated to the Niagara Aerospace Museum - Ira Ross Center.

B-26

The B-26 started flying in October 1952 and was also used for the longitudinal research work described in the F-94 section. In 1958 the Air Force ended its sponsorship and donated this B-26 along with two others to Calspan. While continuing longitudinal research work in the B-26 for the Naval Air Test Center in 1960, the Calspan Program Manager and pilot, Giff Bull showed the B-26's capabilities to the staff of the Naval Test Pilot School (NTPS). They were struck with the unique capabilities of the VSS and how it might be able to be used as a flying class room to demonstrate flying qualities that their students were learning on the ground. They incorporated a B-26 flight into a lecture that Calspan pilots were giving at the NTPS and it was an instant success. The AFTPS also added the B-26 demonstrations to their curriculum three years later. A decision was then made to add variable stability roll and yaw to the VSS, and convert a second B-26 into another 3-axis VSS aircraft. Both aircraft's upgrades were completed in 1963, and forty years of TPS demonstration flights (in the B-26, NT-33, Learjet, and VISTA) have continued since then. Similar demonstration and training programs have also been performed for the FAA, NASA, aircraft manufacturers, and foreign agencies. A closed-loop throttle servo was added to the B-26 in the mid 1960s for a Supersonic Transport simulation. This was the first application of a four degree-of-freedom simulation system.

In addition to the early longitudinal flying qualities research and TPS efforts, the B-26s have been used for many other research programs. These have included:

- Pilot Primary Controllers – various wheels, center and side-sticks
- C-5A
- Supersonic Transport
- Piper Cheyenne Accident Investigation
- Saab Mini-stick (early version of JAS-39 stick)

The B-26s continued flying at the AFTPS and NTPS until early 1981, when one of the aircraft suffered a wing structural failure that resulted in the loss of the aircraft and crew of three. The cause was an original manufacturing defect and not related to VSS operations. The second B-26 was then retired and now resides at the Air Museum at Edwards AFB. They were subsequently replaced by the variable stability Learjets.

NT-33

In 1953 during the early development of the F-94 and B-26, the USAF recognized the eventual need for a three-axis variable stability fighter aircraft and encouraged Calspan to perform a conceptual design based on the T-33. A contract was received in July 1954 and the aircraft was delivered to Calspan in October. The VSS electronics (vacuum tubes) would not fit in a normal T-33 nose, so an F-94 nose was attached, increasing its volume by 50% (Figure 6). The variable stability aircraft, now designated an NT-33 ("N" signifying permanently modified), first flew on 15 February 1957. Thus began the flight activity of the longest lived test aircraft in the world (in use for 40 years!). After a few months, however, checkout was suspended due to lack of funding. Responsibility for the program was then transferred to the USAF Flight Control Laboratory under the direction of Charles Westbrook who was responsible for flying qualities research. Funding was difficult to obtain because this was the dawn of the space age and the USAF had doubts about the need for further research for conventional manned aircraft. Struggling with problems with the highly unreliable vacuum tubes, the NT-33 was taken on a "road show" in early 1959 to Wright Patterson AFB, Edwards AFB, and Andrews AFB. Over 30 pilots flew the aircraft and were overwhelmingly impressed with its capabilities. It showed how one flight in a variable stability aircraft was more convincing than any amount of verbal or written descriptions. Soon after these demonstrations, more funding was received and the vacuum tubes were replaced by more reliable transistors. The NT-33 began flying with its upgraded VSS in September 1959.

The NT-33's first research program was a study on lateral-directional flying qualities for manned re-entry vehicles[19]. This led to a fascinating program simulating the X-15 in 1960. The X-15 flights were progressing to the edge of the atmosphere at hypersonic speeds. During re-entry the pilot would have the demanding task of flying a tight profile while the X-15's characteristics would be significantly changing over a period of 90 seconds. It was proposed that the NT-33 could simulate this maneuver and allow evaluation of the pilot's ability to perform this challenging task with various levels of augmentation. Analog circuits were programmed to automatically change all of the feedback gains in the VSS as a function of time. A side-stick controller similar to the X-15's was also installed. To simulate the re-entry and g-loads, the safety pilot first put the NT-33 into a zero-g push-over and then control was transferred to the evaluation pilot. He then flew "under the hood" watching his attitude indicator which was programmed to slowly precess. The pilot thought he was holding wings level and pulling "g" in the re-entry maneuver, when he was actually in a highly banked turn (up to 75°) pulling up to 4 g's simulating the high-speed, high-g pull-out (Figure 7).

Figure 6: NT-33

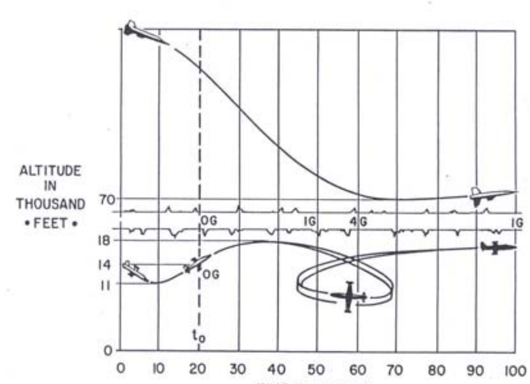

Figure 7: NT-33/X-15 Flight Profile

Research into re-entry vehicle flying qualities continued but the capability to duplicate their very low lift/drag characteristics (L/D) was required. The drag of the NT-33 had to be greatly increased. At first an under-wing spoiler was proposed, but wind tunnel tests showed it affected other aerodynamics too much. The Calspan project engineer, Fred Newell, then suggested modifying the wing-tip fuel tanks with the upper and lower surfaces of the aft portion hinged and controlled with a hydraulic actuator (Figure 8)[20]. This configuration proved successful, and with the "drag petals" fully deployed and speed brakes extended yielded an L/D of 2. Numerous flying qualities studies and the simulations of the M2F2 and X-24A lifting bodies benefited from this added feature. Later, the drag petals were modified to operate asymmetrically so that when used with the rudder they could produce direct side-force. This enabled flat turns for simulation of precision weapon delivery and was used in the A-9 and A-10 simulations in 1972[21].

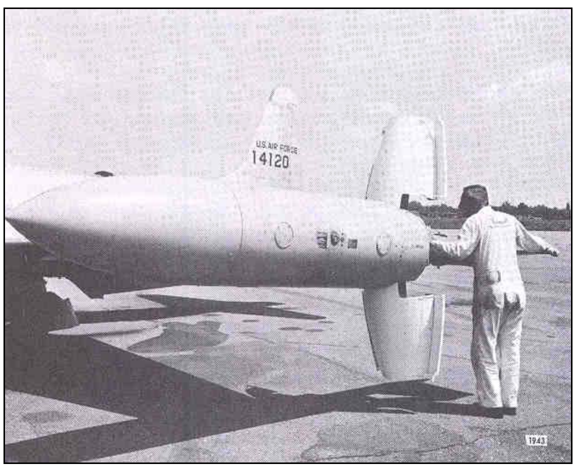

Figure 8: NT-33 Drag Petals

The NT-33 systems were continually updated, progressing from vacuum tubes and analog electronics to digital processors, including the addition of a programmable head-up display (HUD). The aircraft was utilized to generate most of the database that was used to write the military flying qualities specifications, MIL-F-8785[9] and MIL-STD-1797[10], and found its way to the AFTPS and NTPS to demonstrate flying qualities, advanced control systems, and HUD characteristics to their students. Bob Harper, as an engineer, pilot, Department Head, and co-developer of the Cooper-Harper Pilot Rating Scale[22] led many of these efforts on the NT-33. The NT-33's last flight was to the Air Force Museum at Wright Patterson AFB on 11 May 1997, where it was retired after 40 years and over 7,900 research flight-hours.

The following is a complete list of NT-33 simulation programs (not including generic flying qualities & TPS programs):

- X-15
- M2F2 & X-24A Lifting Bodies
- A-9 & A-10
- F-15
- YF-16, YF-17 & F-18
- AFTI/F-16
- F-117
- British TSR.2 (1962 - first foreign use of a Calspan IFS)
- Israeli Lavi Fighter
- Indian Light Combat Aircraft (LCA)
- Swedish JAS-39 Gripen
- YF-22
- Side-force Control Evaluations
- Side-stick Evaluations
- Control Stick Dynamics Research
- Ground Simulator Comparison Research
- Pilot-Induced-Oscillation Research
- Actuator Rate Limiting Research
- Peripheral Vision Display Research
- Head-Up Display Research
- VISTA Tactile Cuing Evaluation

X-22

The X-22 (Figure 9) was the only airplane that was conceived and designed to be a variable stability aircraft from its conception. The X-22 was developed for the Tri-Service Research Aircraft program to develop a dual-tandem, tilting-ducted-propeller V/STOL. One attribute of this "four-poster" configuration was the large amount of control power available in the hovering mode. The program was managed by the Navy, and Bill Koven of the Naval Weapons Stability and Control Section recognized the opportunity to capitalize on the large control power available to make a true research aircraft. He made a variable stability and control system one of the design requirements. The aircraft would then be capable of exploring V/STOL flying qualities and control issues. Calspan teamed with the Bell Aerosystems Company on the proposal. The contract was awarded to them in 1963 and Calspan designed the VSS for the two prototypes which were built.

Figure 9: X-22

First flight of the aircraft was in March 1966. The first prototype had a dual hydraulic system failure resulting in a hard landing with damage severe enough that it could not be made flight-worthy. The cockpit was retained and eventually served as the cockpit of an X-22 ground simulator. The second prototype was then flown in January 1967. Calspan was awarded the contract to operate and conduct research programs in the X-22 in July 1970 and first flew it in August 1971.

The X-22 was a four degree-of-freedom simulator, with control about its pitch, roll, yaw, and thrust axes. The thrust axis could be inclined by rotating the ducted propellers to allow the aircraft to go from vertical to horizontal flight. The propellers were driven by four aft-mounted turbine engines through a complex mechanical transmission which summed the power output from the engines and drove the propellers equally. Loss of an engine would not cause asymmetric thrust. Calspan designed the VSS which included scheduling all the gains as a function of duct angle. For example: in hover (ducts at 90°) pitch commands drove differential fore & aft propeller angles, while in horizontal flight (ducts at 0°) pitch commands drove elevons behind the ducted propellers (Figure 10). A combination of commands to the propeller angles and elevons would be blended between the two extremes.

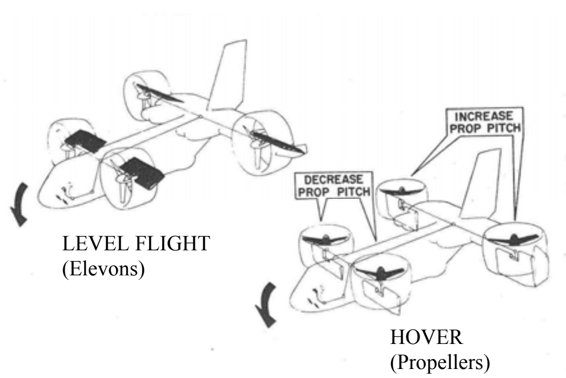

Figure 10: X-22 Pitch Control

Two systems unique to the X-22 were developed by the Calspan X-22 program manager, Jack Beilman. One was auxiliary, limited-authority hydraulic actuators that compensated for the natural hysteresis in the complex mechanical mixer in the VSS. The system compared actual positions of the propeller and elevons with their commanded positions and precisely moved them to zero out errors. The other was a very accurate low-airspeed sensor that was good down to vectorial-zero airspeed. This patented system was called LORAS (Linear Omnidirectional Resolving Airspeed System). The primary sensing device of LORAS was a differential pressure gauge in the hub of rotating arm which sensed any differential pressure between the tips of the arm (Figure 11). Each tip sensed its tangential rotational speed plus or minus a component of the relative wind or airspeed. The differential pressure – the measure of airspeed – was very accurate down to very low magnitudes. Due to the rotating nature of the system, the output was a sign-wave whose phasing represented the direction of the relative wind or airspeed. Two airspeed sensors were used: one mounted on the vertical tail rotated about the z-axis to give x-y speeds, the other mounted on a nose boom rotated about the y-axis that yielded x-z speeds.

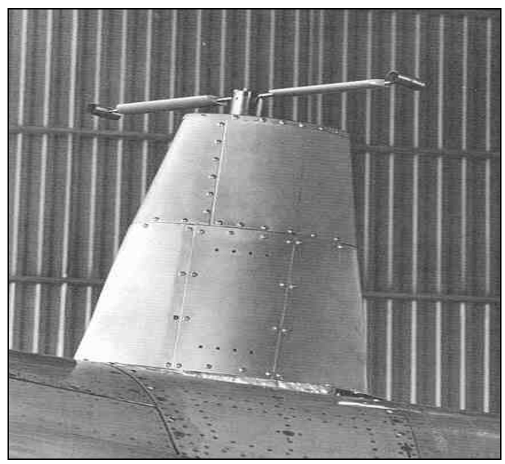

Figure 11: Linear Omnidirectional Resolving Airspeed System (LORAS)

Over the 13 years (1971-84) of operations, the X-22 was used for five major V/STOL flying qualities and control research programs. They included investigations of transition from vertical to forward flight. Studies were performed of different response-command systems, such as rate-, attitude-, and velocity-command in visual and instrument flight conditions. Various levels of sophistication of head-down and head-up displays were evaluated as well as an investigation of shipboard landing[23]. The X-22 was used to simulate the AV-8B Harrier and was used for many years by the NTPS to demonstrate transition characteristics and displays. The aircraft was last flown in 1984 after completing 273 research flights and 405 flight hours. It now resides in the Niagara Aerospace Museum - Ira Ross Center.

Total In-Flight Simulator

The concept for the Total In-flight Simulator (TIFS) with a separate cockpit had its beginnings in 1958 with discussions between Walt Breuhaus of Calspan and M.D. Havron of the Martin Company who was then designing their entry for the proposed X-20 DynaSoar space-plane program[13]. Havron felt they needed to simulate the unconventional dynamics and cockpit environment of the X-20 which were expected to adversely affect its landing characteristics. Calspan proposed to modify a second T-33 with an X-20 cockpit built into the aft seat. The lift curve slopes were the same and the L/D could be matched with drag devices. The T-33 X-20 simulator was made part of the Martin proposal, but Boeing won the contract.

However, the idea for an in-flight simulator with a separate cockpit did not die. In 1959 commercial jet transports were gaining acceptance, but significant flying time was required to transition pilots and several aircraft were lost during engine-out training. Calspan prepared a conceptual design of an airline training aircraft based on a modified Convair-340 with a jet transport cockpit attached to its nose. It had a four degree-of-freedom (pitch, roll, yaw, thrust) VSS. No thought was given to controlling lift or side-force, as the lift curve slope and size of the Convair were not too different than those of the new jet transports. Calspan also called it an "in-flight simulator" (the first use of the name) rather than a "variable stability" aircraft to better appeal to airlines and convey its broader usage than research. In 1960, Calspan proposed this concept to the airline industry. Airlines were interested but did not want to sponsor its development.

All was not lost, as the commercial Supersonic Transport (SST) was also being developed at this time. This aircraft would be very long, land at high pitch attitudes, have poor forward visibility, and unconventional (for commercial transports) flying qualities. Calspan believed their in-flight simulator concept could be modified to include an SST cockpit and provide full six degree-of-freedom simulation capability with added direct lift flaps and side-force generating surfaces on the wings. The idea was proposed to the FAA in 1963. Calspan also had to give it a name to convey its purpose and its acronym had to be easy to pronounce. One afternoon they came up with TIFS. The aircraft would simulate, in-flight, the pilot's total environment – cockpit, controls, displays, outside field of view, and six degrees-of-freedom. It was also at this time that the concept of a "model following" rather than "response feedback" type of simulation was developed. This would be much easier to calibrate and would provide a higher level of fidelity of simulation, especially for airplanes which were much different in size than the Convair, and take advantage of the six controllers being proposed[24].

Through the next three years the TIFS concept was further developed. The FAA and the Air Line Pilots Association were concerned about forward visibility for SST with its drooped-nose in the up position for landings. The USAF also became interested in the TIFS because of their Advanced Manned Strategic Aircraft (AMSA) program which eventually led to the B-1. By November 1966 the TIFS project, jointly sponsored by the USAF and FAA, was underway under the direction of Calspan Program Manager, Dr. Philip Reynolds. The Air Force provided a piston powered C-131B which was later converted to turbo-props and designated an NC-131H (Convair-580 commercial designation). The TIFS was to have two interchangeable noses – an SST nose and a general purpose nose for the AMSA (Figure 12). However, the SST program was canceled before that nose was fabricated.

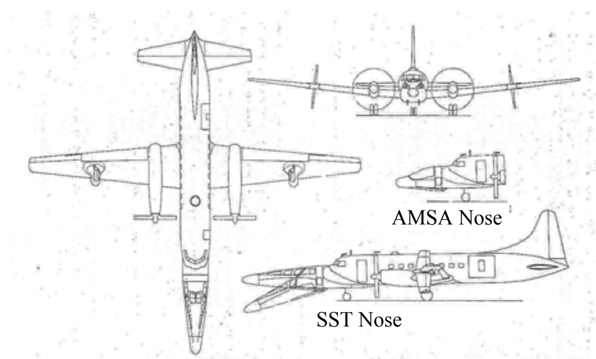

Figure 12: TIFS 1966 Concept

The aircraft was delivered to Calspan on 15 December 1966 and work began on the modifications. TIFS first flew on 6 December 1968 with only direct lift flaps installed and forward structure with a "ferry nose" attached. This was done to get the aircraft flown to Pacific Airmotive in order to have its turbo-props installed before that modification line was shut down. A serendipitous result of the ferry nose was that it was eventually used for programs where a simulation pilot was unneeded (such as unmanned vehicle and avionics test programs). The general purpose simulation cockpit, side-force surfaces, and simulation electronics were installed in 1969-70. The first simulation systems checkout was flown in June 1970. The first actual TIFS in-flight simulation program flight was on 10 June 1971 in support of the B-1 development. Throughout the years, the simulation systems have been continually upgraded: from analog modeling to digital computers with auto-code software, and from "steam gauge" displays to flat panel monitors. Wheel/column, center stick, and side-stick controllers have been installed. A recent photograph of the TIFS is shown in Figure 13.

A myriad of simulation, research, test, and training programs have been flown over the subsequent 32 years. Highlights include five programs during the development of the landing control system for the Space Shuttle (1972-85). In order to simulate the Shuttle's low L/D configuration, the TIFS deployed its side-force surfaces ±15° in a toe-out manner to generate enough drag to achieve a stabilized -15° flight path angle at 275Kt[25]. Its steep approach capabilities have been expanded by using larger side-force surface deflections (±22°) to achieve a -20° flight path angle in support of a recent X-40A simulation program.

Figure 13: Current TIFS

Another unique TIFS program was the Compass Cope Remotely Piloted Vehicle (RPV) program[26]. The objective of this program was to assist the USAF and manufacturers in the development of auto-takeoff, auto-land, and remote operator control for a large long-endurance RPV. The ferry nose configuration was used and telemetry linked the TIFS to an operator on the ground. Fully automatic takeoff and landings were performed.

The ferry nose configuration was also used for ten years at the AFTPS and NTPS to teach integrated radar/infrared-sensor operations in a flying classroom environment. This was called the Avionics Systems Test and Training Aircraft (ASTTA) program. An F-16 radar, IR turret, and Maverick missile were attached to the nose (Figure 14) and an operators' console was set up in the aft cabin for four students and an instructor.

The original general purpose simulation cockpit was replaced with a much larger volume canopy in 1998 (Figure 15). This was developed for a NASA-sponsored synthetic/external visibility system program. Over 500 pounds of equipment including radar, high definition TV cameras, monitors, projectors, servoed throttle handles, and other displays and instrumentation were installed in the nose[27].

Figure 14: ASTTA Nose

Figure 15: Current TIFS Simulation Nose

Early in 1999 The AFRL decided that it was no longer in their mission to operate research aircraft. Two of these aircraft were the in-flight simulators operated by Calspan under a task order contract: the TIFS and VISTA. As will be seen later, the VISTA was turned over to the AFTPS. Through the efforts of the USAF program manager, Steve Markman, and Calspan management, a Cooperative Research and Development Agreement (CRADA) between AFRL and Calspan was established in July 2000 to continue operations of the TIFS. Under the CRADA, the USAF retains ownership of the aircraft but Calspan is responsible for all operations including registering the aircraft with the FAA. After a three-year hiatus, the TIFS has resumed flight activities. The first program under the CRADA was the X-40 Integrated Adaptive Guidance and Control simulation. A sensor evaluation was flown for ITT, and a flying qualities program for Boeing is currently being planned.

The following is a complete list of TIFS simulation programs:

- B-1
- B-2
- Space Shuttle
- Concord / SST Flying Qualities
- Compass Cope - Remotely Piloted Vehicle
- Side-force Control for Crosswind Landing
- Control Reconfiguration
- Chemical Defensive Drug Evaluation (C-130)
- Human Motion Sensory Studies
- Windshield Distortion
- Command Flight Path Display
- Aeroelastic Mode Identification
- Tacit Blue
- X-29
- YF-23
- C-17
- C-141 Display Upgrade
- Million Pound Aircraft Flying Qualities
- Boeing 7J7 (777 Fly-by-Wire Technologies)
- McDonnell Douglas MD-12X
- Netherlands – Direct Lift Control Flying Qualities
- Indonesian N250 FBW Regional Transport
- Advanced High Speed Civil Transport
- Flexible Aircraft Flying Qualities Programs
- External Visibility and Synthetic Vision Systems
- Numerous Flying Qualities Research Programs
  (Many of these programs were used to generate portions of the database for the Military Specification for Flying Qualities of Piloted Aircraft: MIL-F-8785 and MIL-STD-1797)
- Pilot-Induced-Oscillation Research
- Control Rate-Limiting Research
- Test Pilot School – Avionics Systems Test & Training Aircraft (ASTTA)
- Martin Marietta Smart Weapons Evaluation
- X-40 Integrated Adaptive Guidance and Control
- ITT Natural Gas Leak Detector Evaluation

Learjets

In the late 1970s, Calspan realized that the B-26s were getting older and harder to maintain. These aircraft also lacked advanced capabilities and maneuverability that was required to train test pilots in modern aircraft dynamics and control. That, in addition to the less than high-technology impression that the WWII fighter-bombers gave to the students, led Calspan to the conclusion that a new variable stability aircraft was needed. It was decided that side-by-side seating should be maintained for its excellent training environment and room for at least two additional observers were desired. A study was performed in 1975 to investigate candidate aircraft[28]. As a result of this and other studies, it was decided to acquire a relatively new business jet. The Learjet (Figure 16) was chosen because it met these requirements and the earlier versions (Models 24 and 25) had wings that were designed for a Swiss fighter and were capable of relatively high normal accelerations (4.4g). An agreement was made with the Air Force and Naval Test Pilot Schools that Calspan would buy the aircraft and the schools would fund the conversion to the variable stability configuration. Work commenced in 1979, with Calspan project engineer, Arno Schelhorn, leading the effort. Learjet serial number 24-218 was purchased directly from the Learjet Company. The airframe had been used as a test aircraft for Learjet and was no longer need as they were developing newer models. The aircraft arrived at Calspan in December 1979.

Figure 16: Learjet

A three degree-of-freedom VSS was designed based on fundamental technologies that were in the previous Calspan variable stability aircraft but with updated servos and electronics. The main improvement put into the Learjet was the Configuration Control System (CCS)[29]. The CCS digitally set the 64 analog feel system and response feedback gains of the VSS. An all-digital VSS was not used at that time as it would have introduced unacceptable time delays. Pre-programmed sets of gains could be set with the push of one button. Individual gains could be called up and easily reset or slewed while still engaged to quickly show different flying qualities configurations. Gains could also be changed as a function of fuel load (critical for the Learjet whose roll inertia changes rapidly as fuel is burned from its tip tanks). New configurations that were setup in flight could be saved and recalled for future flights. This was a great improvement over the B-26 or NT-33 where up to 20 gains had to be manually set using potentiometers to change configurations. An analog computer with a programmable patch panel was also installed to provide the capability to simulate more complex control systems. In later years, a digital computer was installed to provide much greater modeling and display capabilities. A center-stick with programmable feel characteristics was installed as the primary controller, but a side-stick or wheel/column could also be used[30].

The Learjet 24 first flew in February 1981 and started training and demonstration flights at the Test Pilot Schools in July. Over the years the Learjet program at the Test Pilot Schools grew until there was little time available for other programs. In the late 1980s, Calspan determined that there was enough potential work to purchase and modify a second Learjet, all with company funds. A relative low-time Learjet Model 25 was bought and arrived at Calspan in April 1990. A VSS similar to first Learjet's was installed in the new aircraft. Its first flight was in March 1991. Its first flight program was for the French Test Pilot School (EPNER). The Learjet 25 has since been used primarily by other non-US test pilot schools, in particular in Europe, but also assists at the AFTPS and NTPS. It has been used to train test pilots and engineers at other agencies, such as NASA, FAA, and airframe manufacturers. The Learjet 25 has also been utilized in the development of new aircraft. A model-following simulation system has also been developed which has helped in these latter programs. Software is programmed in MATLAB Simulink® with real-time auto-code.

The most recent use of the Learjet is in the Upset Recovery Training (URT) program sponsored by the FAA[31]. The objective of this five-year program is to develop and optimize a URT program based on in-flight simulation to help reduce the incidence of loss-of-control accidents due to aircraft upset events. The simulation computers of the Learjet are programmed to produce responses that simulate actual aircraft upsets that have resulted in accidents. These upsets include wake turbulence, icing, trim run-aways, control jams, CG shifts, engine failures, and hydraulic failures. Real aircraft accelerations and actual out-the-window visuals produce pilot stresses that are hypothesized to result in a level of training that ground-based simulators can not achieve. During the course of this program, 2000 airline pilots will be trained to quickly recognize aircraft upsets and in recovery techniques.

As s flight activity has continued to increase in the Learjets, a third Learjet was purchased in February 2005 and is now being converted to an in-flight simulator. It will be operational in early 2006.

The following is a complete list of Learjet programs:

- USAF & Naval Test Pilot Schools – Flying Qualities and Flight Control Training
- Test Pilot School Student Projects
- Training programs for: French (EPNER), Empire, International, & National Test Pilot Schools; NASA, Saab, DFVLR, Finland, India, Italy, Switzerland, Spain, Embraer, Dornier
- FAA PIO Workshops
- Pilot-Induced-Oscillation Research
- Control Rate-Limiting Research
- Wright Flyer (AFTPS Project)
- Swedish JAS-39 Gripen
- Indian LCA
- Saab 340 & 2000
- Cessna Citation X
- Bombardier Global Express
- Dornier 728JET
- Embraer 170
- Indonesian N250 FBW Region Transport
- Upset Recovery Training
- FBW Control for Gulfstream

VISTA NF-16

The first mention of replacing the NT-33 with a newer fighter in-flight simulator was in 1965, when Walt Breuhaus was visiting the Pentagon trying to raise interest for the TIFS. At one meeting, a USAF colonel voiced concern that the NT-33 (then flying for eight years) was also wearing out and it would be desirable to replace it "in a couple of years." Needless to say, the NT-33 lasted a bit longer – 32 years after this meeting. However, Calspan did recognize the eventual need to replace the aircraft and conducted many internal conceptual design studies. As a result of these IR&D studies, Calspan issued a report[32] in 1982 for a "Fighter-TIFS" and a subsequent proposal to the USAF. Calspan was then awarded a contract in August 1982 to perform a comprehensive study to define the Variable Stability In-Flight Simulator Test Aircraft (VISTA) – a name and acronym given to the aircraft by the USAF. Candidate aircraft studied included: the T-2, F-5, F-20, T-45, F-16, and F-18. The study soon focused on the F-16 and F-18, and finally recommended the F-16D primarily because of the availability of a new aircraft off the production line. The study was completed in February 1986 with a design for a six degree-of-freedom simulator. It included side-force surfaces on the wings as well as split drag petals on the wing tips (Figure 17)[33].

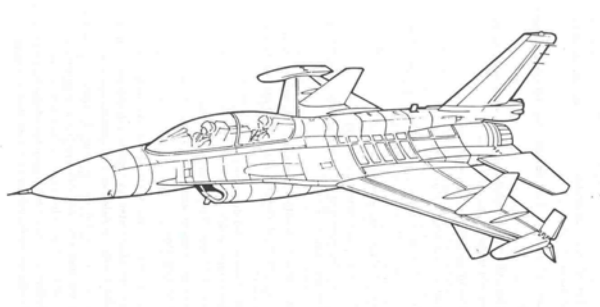

Figure 17: Proposed Six-DOF VISTA

General Dynamics (later to become part of Lockheed Martin) won the prime contract to develop the VISTA with Calspan as the sub-contractor to develop the simulation systems and provide test support. During contract negotiations, side-force surface and drag petal capabilities were eliminated due to cost constraints. Development of model following control laws was also deferred in favor of the simpler response feedback VSS control law structure. The development contract started in August 1988. An F-16D Block 30 airframe with Block 40 avionics (digital flight control computer) was selected. It had a Peace Marble II configuration with a large dorsal fairing for additional electronics; and high sink-rate landing gear. Higher capacity hydraulic and electrical power supply systems were added. The most significant advance in this in-flight simulator was the integration of the simulation computers and systems with the production F-16 fly-by-wire computers. Over 200 vehicle integrity monitors (VIMs), or automatic safety trips, were incorporated into the VSS. Programmable hydraulic feel systems included a center stick and a new side-stick capable of large deflections (developed for an F-22 simulation). The VISTA (Figure 18) was completed in April 1992. A five-flight acceptance program was flown with first flight on 9 April. For the next two years the VISTA program was suspended due to funding problems (it is interesting to note that similar problems occurred thirty-five years earlier in 1957-59 with the NT-33).

Figure 18: F-16 VISTA

The aircraft was then turned over to GD and GE in May 1992 for the Multi-Axis Trust Vector (MATV) program. Flight testing occurred at Edwards AFB from July 1993 through March 1994. By that time, additional funding was received and flight tests to complete the VISTA development resumed at Edwards AFB in July 1994 and were completed in December 1994. On 28 January 1995 the VISTA was ferried to Buffalo, NY where it was prepared for its first simulation programs (the Spring AFTPS demonstration flights and YF-22 programs).

The aircraft has since been used on many new aircraft development and other flying qualities research and systems development projects. Its capabilities have been enhanced with a programmable helmet-mounted display (Figure 19) to complement its programmable head-up display. A voice recognition system has also been installed which can be integrated with the simulation computers and other F-16 radar and weapon systems.

As was mentioned in the discussion on the TIFS, early in 1999 AFRL wanted to end its management of the VISTA. After many discussions, planning, and logistic preparations, the VISTA was transferred to the USAF Test Pilot School at Edwards AFB in October 2000. Calspan continues to support the aircraft with a permanent maintenance staff at Edwards, as well as technical support from Buffalo personnel. Research programs are developed and prepared in Buffalo on a "hot-bench" and transferred to the aircraft for ground checkout and flight activities.

Figure 19: Helmet Mounted Display

The following is a complete list of VISTA programs:

YF-22 & F-22
Indian Light Combat Aircraft (LCA)
JSF (X-35)

X-38 Crew Return Vehicle
Head-Up Display & Helmet-Mounted Display Research
Self Designing Flight Control
Voice Recognition System
Pilot-Induced-Oscillation Research
USAF Test Pilot School – Flying Qualities, Flight Control, Display Training, and Systems Curriculum Flights
USAF Test Pilot School – Test Management Programs
Numerous Flying Qualities Research Programs
Numerous Display Research Programs
Automatic Air Collision Avoidance System

Other Variable Stability Aircraft Built by Calspan

In addition to the aircraft described above, Calspan has been involved with the development of six other in-flight simulators: The NASA General Purpose Airborne Simulator - GPAS (based on a Lockheed Jetstar), a CH-46 VSS upgrade and two SH-60 helicopter variable stability systems built for the Naval Test Pilot School, a programmable feel system for a NASA-Ames CH-47, and a programmable feel system for the British Vectored Thrust Aircraft Advanced Control (VAAC) Harrier. Though these aircraft were not operated by Calspan, they all utilized the technologies that were developed for other Calspan simulators.

Concluding Remarks

For over fifty-five years Calspan has been involved in the development and operation of variable stability and in-flight simulator aircraft. Table 1 summarizes these aircraft, significant dates, and flight-hours. They have been instrumental in advancing the requisite technologies of aerodynamics, flight mechanics, control theory, mechanical controls, hydraulics, servos, sensors, augmentation electronics, airborne computers, feel systems, and displays. These aircraft have gone from augmented single-axis "variable stability" aircraft to full six degree-of-freedom "in-flight simulators." They have helped in the development of over 50 U.S. and foreign aircraft programs. Countless research programs have been flown to help in the generation of aircraft flying qualities specifications and requirements. Literally thousands of test pilots and engineers have been trained in stability and control concepts. In addition, many systems test and development programs have utilized these in-flight simulators to test and evaluate new concepts in a safe and efficient manner. The history of variable stability and in-flight simulator aircraft continues today with internal studies investigating candidate aircraft platforms as well as advanced simulation and system concepts for the "next generation" in-flight-simulator.

Acknowledgment

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Table 1 In-Flight Simulators Operated by Calspan

Aircraft	Received	First Flight	Last Flight	Current Location	Total Hours
F4U-5	28 Sep 1948	7 Mar 1949	25 Oct 1951	Scrapped by Navy	172
F-94	12 Mar 1952	Dec 1953	Jul 1958	Aerospace Museum, Niagara Falls, NY	335
B-26 (17H)	12 Jun 1951	Jun 1952	3 Mar 1981	Destroyed	9,080
B-26 (46H)	12 Sep 1958	Jan 1963	19 Nov 1986	USAF Museum, Edwards	7,193
NT-33	14 Oct 1954	15 Feb 1957	11 May 1997	USAF Museum, WPAFB	7,942
X-22	21 Jan 1971	17 Aug 1971	29 Oct 1984	Aerospace Museum, Niagara Falls, NY	405
TIFS	15 Dec 1966	6 Dec 1968	*Still Flying*	Calspan - Niagara Falls, NY	~4,400
Learjet #1	13 Dec 1979	16 Feb 1981	*Still Flying*	Calspan - Niagara Falls, NY	~13,500
Learjet #2	1 Feb 1990	8 Mar 1991	*Still Flying*	Calspan - Niagara Falls, NY	~3,700
Learjet #3	** Mar 2005	Not yet	*Still Flying*	Calspan - Niagara Falls, NY	0
VISTA	28 Jan 1995	16 Feb 1995	*Still Flying*	AFTPS, Edwards AFB	~1,100
				TOTAL Fight Hours	~47,827

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