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History of In-Flight Simulation at General Dynamics

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General Dynamics–Advanced Information Systems (GDAIS) (formerly Veridian) 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, the focus is on GDAIS 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. Early technologies that led to the development of variable stability aircraft and their earlier applications, are described first, followed by GDAIS'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. Specific case studies are presented that describe the development and distinctive features of each of the GDAIS in-flight simulators and some of the more significant applications of these unique tools are highlighted.

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 that 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) that 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 tests, 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 aircraft augmentation technologies to that. 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 General Dynamics–Advanced Information Systems (GDAIS) and its predecessors: the Cornell Aeronautical Laboratory (CAL), Calspan Corporation, and Veridian. IFS started at CAL in 1949 with the first flight of the single-axis (one-degree-of-freedom) yaw augmentation system on the F4U-5. (Throughout this paper the name by which the organization was known at the time of each development will be used.) This system essentially varied the yaw stability of the aircraft, hence the name variable stability aircraft, was coined. GDAIS 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 GDAIS operates four true in-flight simulators that do much more than just vary the stability of the aircraft.

Beginnings

The foundations of the variable stability aircraft and IFS have their roots in the science of the dynamic motion of aircraft, which dates back to the 1904 writings of Bryan and Williams in England[1] (also published in Ref. 2.). This was followed by other researchers in many countries, and the research was consolidated in the U.S. in two NACA reports by Zimmerman.[3,4] These latter reports put a highly theoretical and complex subject into a form that could be more readily 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 to produce an airplane that flew well. Two early reports on this subject were written by Soulé[5] and Gilruth.[6] The first U.S. military specifications for flying qualities were written for the U.S. Navy in 1942 (Ref. 7) and for the U.S. Army in 1943 (Ref. 8). This work was the genesis of the later U.S. military specifications for piloted airplanes that used IFS for much of their development and that culminated with MIL-F-8785 (Ref. 9) and MIL-STD-1797 (Ref. 10).

Existing airplanes were flown and evaluated to gain insight into their dynamics. However, to see how specific characteristics affected the flying qualities of the airplane, the physical configuration of the airplane had to be changed, for example, size of 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, augmentation or modification of the inherent yaw damping

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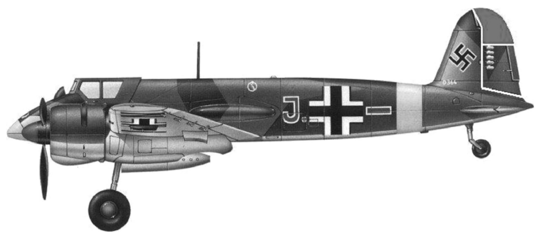

Fig. 1 Henschel HS-129.

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 of 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 U.S., but rather 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 (Fig. 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 U.S. researchers, but a few years later similar applications of feedback control resulted in the first variable stability airplanes in the U.S.

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, electromechanical devices were installed in the pitch axis of the large Bolm and Voss BV-222 flying boat to relieve pilot forces.[11] In the U.S., 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 U.S. Navy Ryan FR-1. Dihedral allows the pilot to pick up a low wing with rudder input. Also in 1947, CAL 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 Research Center 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 U.S. 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. 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 servoactuation of control surfaces (see Ref. 14). Kaufman 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.

Fig. 2 NACA F6F-3.

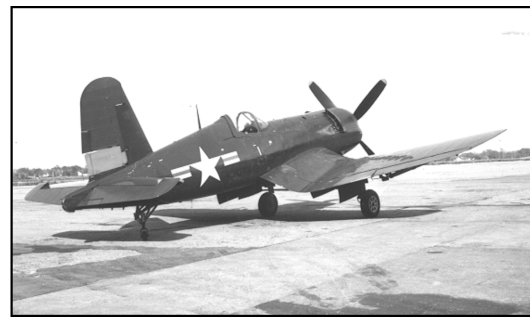

Fig. 3 CAL F4U-5.

NACA installed their first variable stability system in a Navy F6F-3 aircraft (Fig. 2). It initially incorporated a sideslip sensor fed to an aileron servomotor (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. The first flight of the system was in 1948. Soon afterward, 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 h were flown, and many lateral–directional flying qualities studies were performed.[15]

CAL F4U-5

Meanwhile, at CAL (and its predecessor Curtiss–Wright Research Laboratory) Milliken was doing research [started in 1944 under U.S. Air Force (USAF) sponsorship] on programmed automatic control inputs to measure aircraft stability derivatives [the beginning of what is now known 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 USAF sponsorship ended, CAL approached the U.S. Navy to continue the work.

The U.S. Navy, however, had a more pressing need to investigate the required level of yaw damping for landing of carrier-based fighters. After internal discussions, CAL determined that they could modify an aircraft with the equipment they were using for PID to achieve the U.S. Navy's research objectives. Their idea was to install a two-piece rudder on an airplane and to 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 U.S. Navy provided an F4U-5 (Fig. 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 CAL variable stability airplane flight was flown in March 1949. Soon afterward its capabilities were expanded with the addition of an auxiliary roll controller. The midspan flap was replaced with plane flaps that could go up or down [similar to what was done with the total in-flight simulator (TIFS) 20 years later]. They were driven by another autopilot servo. Roll-rate feedback was also added to both servos. Over the next two years, 172 h were flown, and many lateral–directional flying qualities studies were performed.[16,17] In 1951, the F4U-5 was transferred to the U.S. Naval Test Pilot School (NTPS), where it subsequently saw little use.

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 GDAIS 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, CAL, under the sponsorship of the All-Weather Branch of Wright Air Development Center, modified a C-45 with the first three-axis 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 USAF 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 U.S. Air Force Research Laboratory) also had CAL 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 (Fig. 4) and B-26 (Fig. 5) were chosen as base aircraft, primarily because of their availability. The T-33 was actually the preferred fighter choice (no afterburning 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 reconnected in flight to the elevator. The reason for retaining the 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.

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 the discovery 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 that "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, New York high school that taught airplane mechanics. It was subsequently donated to the Niagara Aerospace Museum–Ira Ross Center.

Fig. 4 F-94.

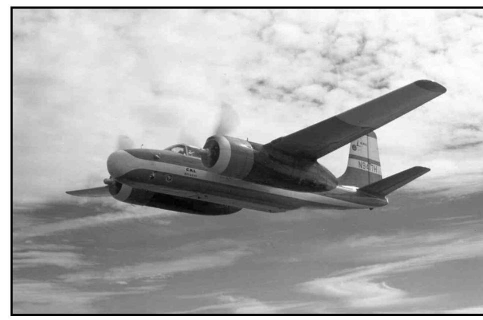

Fig. 5 B-26.

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 U.S. Air Force ended its sponsorship and donated this B-26, along with two others, to CAL. While continuing longitudinal research work in the B-26 for the U.S. Naval Air Test Center in 1960, the CAL Program Manager and pilot G. Bull showed the B-26's capabilities to the staff of the NTPS. They were struck with the unique capabilities of the VSS and how it might be able to be used as a flying classroom to demonstrate flying qualities that their students were learning on the ground. They incorporated a B-26 flight into a lecture that CAL pilots were giving at the NTPS, and it was an instant success. The U.S. Air Force Test Pilot School (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 to convert a second B-26 into another three-axis VSS aircraft. Both aircraft's upgrades were completed in 1963, and 40 years of TPS demonstration flights [in the B-26, NT-33, Learjet, and Variable Stability In-Flight Simulator and Test Aircraft (VISTA)] have continued since then. Similar demonstration and training programs have also been performed for the Federal Aviation Administration (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 test pilot school (TPS) efforts, the B-26s have been used for many other research programs. These have included 1) pilot primary controllers: various wheels, center, and side-sticks; 2) C-5A; 3) supersonic transport; 4) Piper Cheyenne accident investigation; 5) Saab ministick (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 Air Force Base. 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

Fig. 6 NT-33.

stability fighter aircraft and encouraged CAL to perform a conceptual design based on the T-33. A contract was received in July 1954 and the aircraft was delivered to CAL in October. The VSS electronics (vacuum tubes) would not fit in a normal T-33 nose, and so an F-94 nose was attached, increasing its volume by 50% (Fig. 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 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 Air Force Base, Edwards Air Force Base, and Andrews Air Force Base. 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 reentry, 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 s. 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 reentry and g loads, the safety pilot first put the NT-33 into a 0 g pushover, and then control was transferred to the evaluation pilot. He then flew under the hood, watching his attitude indicator, which was programmed to precess slowly. The pilot thought he was holding wings level and pulling g in the reentry maneuver, when he was actually in a highly banked turn (up to 75 deg) pulling up to 4 g simulating the high-speed, high g pull-out (Fig. 7).

Research into reentry vehicle flying qualities continued, but the capability to duplicate their very low lift/drag (L/D) characteristics was required. The drag of the NT-33 had to be greatly increased. At first, an underwing spoiler was proposed, but wind-tunnel tests showed it affected other aerodynamics too much. The CAL Project Engineer, 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 (Fig. 8) (Ref. 20). This configuration proved successful and with the drag petals fully deployed and speed brakes extended yielded $L/D = 2$. 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 (Ref. 21).

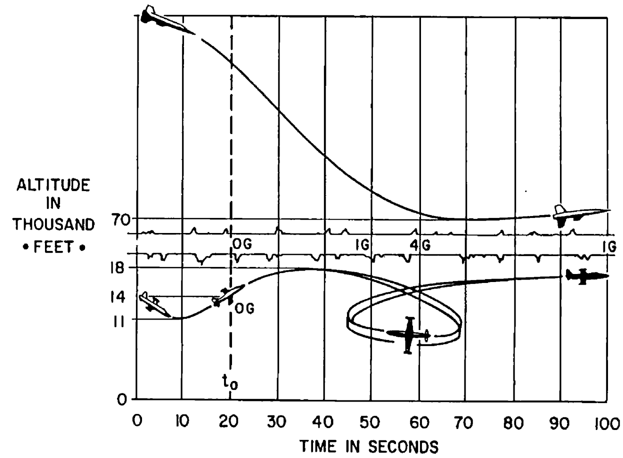

Fig. 7 NT-33/X-15 flight profile.

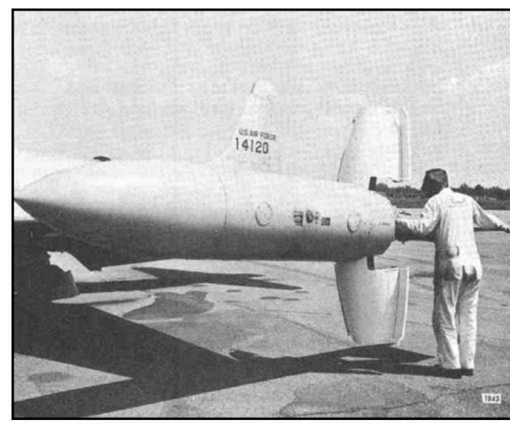

Fig. 8 NT-33 drag petals.

The NT-33 systems were continually updated, progressing from vacuum tubes and analog electronics to digital processors, including the addition of a programmable headup display (HUD). The aircraft was utilized to generate most of the database that was used to write the military flying qualities specifications,[9,10] and found its way to the AFTPS and NTPS to demonstrate flying qualities, advanced control systems, and HUD characteristics to their students. Harper, as an engineer, pilot, department head, and codeveloper 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 Air Force Base on 11 May 1997, where it was retired after 40 years and over 7900 research flight hours.

The following is a complete list of NT-33 simulation programs (not including generic flying qualities and TPS programs): 1) X-15; 2) M2F2 and X-24A lifting bodies; 3) A-9 and A-10; 4) F-15; 5) YF-16, YF-17, and F-18; 6) AFTI/F-16; 7) F-117; 8) British TSR.2 (1962 - first foreign use of a CAL IFS); 9) Israeli Lavi Fighter; 10) Indian Light Combat Aircraft (LCA); 11) Swedish JAS-39 Gripen; 12) YF-22; 13) side-force control evaluations; 14) side-stick evaluations; 15) control stick dynamics research; 16) ground simulator comparison research; 17) pilot-induced oscillation research; 18) actuator rate limiting research; 19) peripheral vision display research; 20) headup display research; and 21) VISTA tactile cuing evaluation.

X-22

The X-22 (Fig. 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 Triservice Research Aircraft program to develop a dual-tandem, tilting-ducted-propeller vertical/standard takeoff and landing (V/STOL). One attribute of this four-poster configuration was the large amount of control power available in

Fig. 9 X-22.

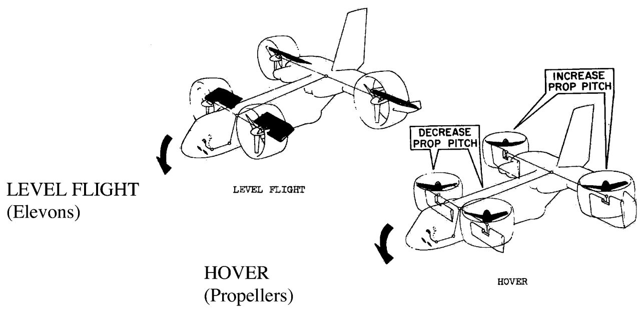

Fig. 10 X-22 pitch control.

the hovering mode. The program was managed by the U.S. Navy, and 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. CAL teamed with the Bell Aerosystems Company on the proposal. The contract was awarded to them in 1963, and CAL designed the VSS for the two prototypes that were built.

The 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 flightworthy. 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. CAL 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 rotation of 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 that summed the power output from the engines and drove the propellers equally. Loss of an engine would not cause asymmetric thrust. CAL designed the VSS, which included scheduling all of the gains as a function of duct angle. For example, in hover (ducts at 90 deg), pitch commands drove differential fore and aft propeller angles, whereas in horizontal flight (ducts at 0 deg) pitch commands drove elevons behind the ducted propellers (Fig. 10). A combination of commands to the propeller angles and elevons would be blended between the two extremes.

Two systems unique to the X-22 were developed by the CAL X-22 Program Manager, 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 Linear omnidirectional resolving airspeed system (LORAS). The primary sensing device of LORAS was a differential pressure gauge in the hub of rotating arm that sensed any differential pressure between the tips of the arm (Fig. 11). Each tip sensed its tangential rotational speed plus

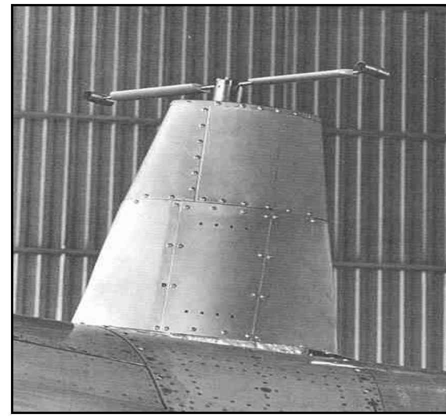

Fig. 11 Linear omnidirectional resolving airspeed system (LORAS).

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. Because of the rotating nature of the system, the output was a sine 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.

Over 13 years (1971–1984) 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 headup 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 TIFS with a separate cockpit had its beginnings in 1958 with discussions between Breuhaus of CAL and Havron of the Martin Company, who was then designing their entry for the proposed X-20 DynaSoar space-plane program.[13] Havron felt that they needed to simulate the unconventional dynamics and cockpit environment of the X-20, which were expected to affect its landing characteristics adversely. CAL 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 Company proposal, but The Boeing Company 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. CAL 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, and thrust) VSS. No thought was given to control of lift or side force because the lift-curve slope and size of the Convair were not too different than those of the new jet transports. CAL also called it an IFS (the first use of the name), rather than a variable stability aircraft, to better appeal to airlines and convey its broader usage beyond research. In 1960, CAL proposed this concept to the airline industry. Airlines were interested but did not want to sponsor its development.

All was not lost, however, because 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. CAL believed their IFS concept could be modified to include an SST cockpit and provide full six-degree-of-freedom

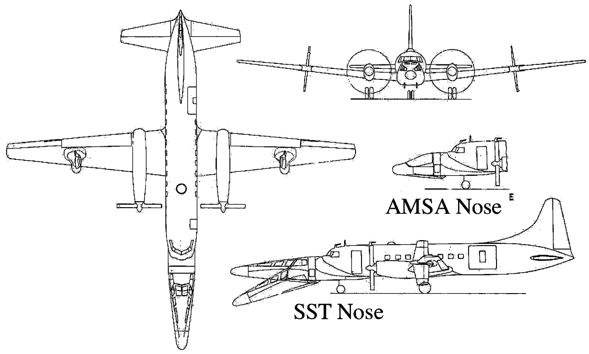

Fig. 12 TIFS 1966 concept.

simulation capability with added direct lift flaps and side-force generating surfaces on the wings. The idea was proposed to the FAA in 1963. CAL 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 that 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 droped 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 under way under the direction of CAL Program Manager P. Reynolds. The USAF provided a piston powered C-131B that was later converted to turboprops 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 (Fig. 12). However, the SST program was canceled before that nose was fabricated.

The aircraft was delivered to CAL 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 to have its turboprops 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 1969–1970. The first simulation systems checkout was flown in June 1970. The first actual TIFS IFS 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 autocode 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 Fig. 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 (1972–1985). To simulate the shuttle's low L/D configuration, the TIFS deployed its side-force surfaces ± 12 deg in a toe-out manner to generate enough drag to achieve a stabilized -15-deg flight-path angle at 275 Kn (Ref. 25). Its steep approach capabilities have been expanded by the use of larger side-force surface deflections (± 17 deg) to achieve a -18 deg flight-path angle in support of a recent X-40A simulation program.

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

Fig. 13 Current TIFS.

Fig. 14 ASTTA nose.

Fig. 15 Current TIFS simulation nose.

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 10 years at the AFTPS and NTPS to teach integrated radar/infrared sensor (IR) 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 (Fig. 14), and an operator's 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 (Fig. 15). This was developed for a NASA-sponsored synthetic/external visibility system program. Over 500 lb of equipment, including radar, high-definition TV cameras, monitors, projectors, servoed throttle handles, and other displays and instrumentation were installed in the nose.[27]

Early in 1999, the AFRL decided that it was no longer in their mission to operate research aircraft. Two of these aircraft were the IFS operated by Veridian 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, S. Markman, and Veridian management, a Cooperative Research and Development Agreement (CRADA) between AFRL and Veridian was established in July 2000 to continue operations of the TIFS.

Under the CRADA, the USAF retains ownership of the aircraft, but Veridian is responsible for all operations, including registering the aircraft with the FAA. After a 3-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 Synthetic Enhanced Visibility program for Rockwell Collins, as well as other systems test projects, are being planned.

The following is a complete list of TIFS simulation programs: 1) B-1; 2) B-2; 3) space shuttle; 4) concord/SST flying qualities; 5) compass cope RPV; 6) side-force control for crosswind landing; 7) control reconfiguration; 8) chemical defensive drug evaluation (C-130); 9) human motion sensory studies; 10) windshield distortion; 11) command flight-path display; 12) aeroelastic mode identification; 13) tacit blue; 14) X-29; 15) YF-23; 16) C-17; 17) C-141 display upgrade; 18) million-lb aircraft flying qualities; 19) Boeing 7J7 (777 fly-by-wire technologies); 20) McDonnell Douglas MD-12X; 21) The Netherlands, direct lift control flying qualities; 22) indonesian N250 FBW regional transport; 23) advanced high-speed civil transport; 24) flexible aircraft flying qualities programs; 25) external visibility and synthetic vision systems; 26) numerous flying qualities research programs (often used to generate portions of the database for the Military Specifications for Flying Qualities of Piloted Aircraft: MIL-F-8785 and MIL-STD-1797); 27) pilot-induced oscillation research; 28) control rate-limiting research; 29) TPS, ASTTA; 30) Martin Marietta smart weapons evaluation; and 31) X-40 integrated adaptive guidance and control.

Learjets

In the late 1970s, Calspan Corporation 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 Corporation 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 (Fig. 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 (4.4 g). An agreement was made with the AFTPS and NTPS that Calspan Corporation would buy the aircraft and the schools would fund the conversion to the variable stability configuration. Work commenced in 1979, with Calspan Corporation Project Engineer A. 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 because they were developing newer models. The aircraft arrived at Calspan Corporation in December 1979.

A three-degree-of-freedom VSS was designed based on fundamental technologies that were in the previous Calspan Corporation 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 because 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 show different flying qualities configurations quickly. 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 with 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]

Fig. 16 Learjet.

The Learjet 24 first flew in February 1981 and started training and demonstration flights at the TPS in July. Over the years, the Learjet program at the TPS grew until there was little time available for other programs. In the late 1980s, Calspan Corporation 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 Corporation in April 1990. A VSS similar to Learjet's first 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-U.S. TPS, in particular in Europe, but it 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 that has helped in these latter programs. Software is programmed in MATLAB® Simulink with a real-time autocode.

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 runaways, control jams, c.g. 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 recognize aircraft upsets quickly, as well as in recovery techniques.

The following is a complete list of Learjet programs: 1) USAF and NTPS, flying qualities and flight control training; 2) TPS student projects; 3) training programs for EPNER, Empire, International, and National TPS, NASA, Saab, DFVLR, Finland, India, Italy, Switzerland, Spain, Embraer, and Dornier; 4) FAA pilot-induced oscillations (PIO) workshops; 5) PIO research; 6) control rate-limiting research; 7) Wright Flyer (AFTPS project); 8) Swedish JAS-39 Gripen; 9) Indian LCA; 10) Saab 340 and 2000; 11) Cessna Citation X; 12) Bombardier Global Express; 13) Dornier 728JET; 14) Embraer 170; 15) Indonesian N250 FBW region transport; and 16) URT.

VISTA NF-16

The first mention of replacing the NT-33 with a newer fighter IFS was in 1965, when W. Breuhaus was visiting the Pentagon trying to raise interest in the TIFS. At one meeting, a USAF colonel voiced concern that the NT-33 (then flying for eight years) was also wearing out and that 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 Corporation did recognize the eventual need to replace the aircraft and conducted many internal conceptual design studies. As a result of these internal research and development studies, Calspan Corporation issued a report[32] in 1982 for a fighter TIFS and a subsequent proposal to the USAF. Calspan Corporation was then awarded a contract in August 1982

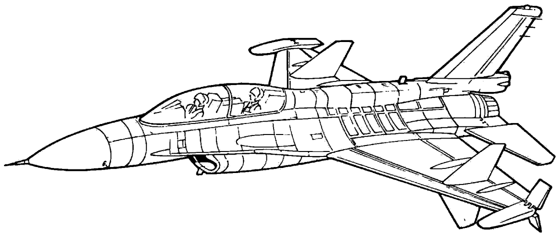

Fig. 17 Proposed six-DOF VISTA.

Fig. 18 F-16 VISTA.

to perform a comprehensive study to define the 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 of the production line. The study was completed in February 1986 with a design for a six-degree-of-freedom (DOF) simulator. It included side-force surfaces on the wings, as well as split drag petals on the wing tips (Fig. 17) (Ref. 33).

General Dynamics–Fort Worth (later to become part of Lockheed Martin) won the prime contract to develop the VISTA with Calspan Corporation as the subcontractor 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, 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 (Fig. 18) was completed in April 1992. A five-flight acceptance program was flown with first flight on 9 April 1992. For the next two years, the VISTA program was suspended due to funding problems. (Note that similar problems occurred 35 years earlier in 1957–1959 with the NT-33).

The aircraft was then turned over to General Dynamics–Fort Worth and General Electric in May 1992 for the multi-axis trust vector program. Flight testing occurred at Edwards Air Force Base from July 1993 through March 1994. By that time, additional funding was received and flight tests to complete the VISTA development resumed at Edwards Air Force Base in July 1994 and were completed in December 1994. On 28 January 1995, the VISTA was ferried to Buffalo, New York, 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 (Fig. 19) to complement its programmable headup display. A voice recognition system has also been installed that can be integrated with the simulation computers and other F-16 radar and weapon systems.

Fig. 19 Helmet-mounted display.

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

The following is a complete list of VISTA programs: 1) YF-22 and F-22; 2) Indian LCA; 3) JSF (X-35); 4) X-38 crew return vehicle; 5) headup display and helmet-mounted display research; 6) self-designing flight control; 7) voice recognition system; 8) PIO research; 9) USAF TPS, flying qualities, flight control, display training, and systems curriculum flights; 10) USAF TPS, test management programs; 11) numerous flying qualities research programs; 12) numerous display research programs; and 13) automatic air collision avoidance system.

Other Variable Stability Aircraft Built by GDAIS

In addition to the aircraft described, GDAIS has been involved with the development of six other IFSs: the NASA general purpose airborne simulator (GPAS) (based on a Lockheed Jetstar), a CH-46 VSS upgrade, and two SH-60 helicopter VSS built for the NTPS, a programmable feel system for a NASA Ames Research Center CH-47, and a programmable feel system for the British vectored thrust aircraft advanced control Harrier. Though these aircraft were not operated by GDAIS, they all utilized the technologies that were developed for other GDAIS simulators.

Conclusions

For over 55 years GDAIS (CAL, Calspan Corporation, and Veridian) has been involved in the development and operation of variable stability and IFS aircraft. Table A1 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-DOF IFSs. 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 IFSs to test and evaluate new concepts in a safe and efficient manner. The history of variable stability and IFS aircraft continues today with internal studies investigating candidate aircraft platforms, as well as advanced simulation and system concepts for the next-generation IFS.

Appendix: Locations of IFSs

Table A1 IFSs Operated by Cornell Aeronautical Laboratory–Calspan–Veridian–General Dynamics

Aircraft	Received	First flight	Last flight	Current location	Total hours[a]
F4U-5	28 Sept. 1948	7 March 1949	25 Oct. 1951	Scrapped by Navy	172
F-94	12 March 1952	Dec. 1953	July 1958	Aerospace Museum, Niagara Falls, NY	335
B-26 (17H)	12 June 1951	June 1952	3 March 1981	Destroyed	9,080
B-26 (46H)	12 Sept. 1958	Jan. 1963	19 Nov. 1986	USAF Museum, Edwards AFB	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	GDAIS, Buffalo, NY	~4,400
Learjet 24	13 Dec. 1979	16 Feb. 1981	Still flying	GDAIS, Buffalo, NY	~13,500
Learjet 25	1 Feb. 1990	8 March 1991	Still flying	GDAIS, Buffalo, NY	~3,700
VISTA	28 Jan. 1995	16 Feb. 1995	Still flying	AFTPS, Edwards AFB	~1,100

[a]Total flight hours, ~47,827.

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References

[1]Bryan, G. H., and Williams, W. E., "The Longitudinal Stability of Aerial Gliders," *Proceedings of the Aeronautical Sciences,* Vol. 73, 1904.

[2]Bryan, G. H., *Stability in Aviation*, Macmillan, London, 1911.

[3]Zimmerman, C. H., "An Analysis of Longitudinal Stability in Power-Off Flight with Charts for Use in Design," NACA Rept. 521, 1935.

[4]Zimmerman, C. H., "An Analysis of Lateral Stability in Power-Off Flight with Charts for Use in Design," NACA Rept. 589, 1937.

[5]Soulé, H. A., "Flight Measurements of the Dynamic Longitudinal Stability of Several Airplanes and a Correlation of the Measurements with Pilots' Observations of Handling Characteristics," NACA Rept. 578, 1936.

[6]Gilruth, R. R., "Requirements for Satisfactory Flying Qualities of Airplanes," NACA Rept. 755, 1943.

[7]"Specifications for Stability and Control Characteristics of Airplanes," Specification SR-119, Bureau of Aeronautics, U.S. Navy Department, Oct. 1942.

[8]"Stability and Control Requirements for Airplanes," Specification C-1815, U.S. Army Air Forces, Aug. 1943.

[9]"Military Specification, Flying Qualities of Piloted Airplanes," MIL-F-8785A, Dec. 1968.

[10]"Military Standard, Flying Qualities of Piloted Airplanes," MIL-STD-1797, March 1987.

[11]Hamel, P., "The Birth of Sweepback - Related Research at LFA in Germany," AIAA Paper 2003-5541, Aug. 2003.

[12]Sears, W. R., "Flying Wing Could Stealthily Reappear," *Aerospace America*, Vol. 25, No. 7, pp. 16–19.

[13]Breuhaus, W. O., "The Variable Stability Airplane, from a Historical Perspective," *Journal of the American Aviation Historical Society*, Spring 1991.

[14]Kaufman, W. M., Liddell, C. J., Smith, G. A., and Van Dyke, R. D., "An Apparatus for Varying Effective Dihedral in Flight, with Application to a Study of Tolerable Dihedral on a Conventional Fighter Airplane," NACA Rept. 948, 1949.

[15]Kaufman, W. M., and Drinkwater, F. J., "NACA Applications of Variable Stability Airplanes in Lateral Stability Research," *Aeronautical Engineering Review*, Vol. 14, Aug. 1955.

[16]Graham, F. D., and James, C. W., "A Flight Investigation of Minimum Acceptable Lateral Dynamic Stability," Cornell Aeronautical Lab., Rept. TB-574-F-3, April 1950.

[17]Bull, G., "A Flight Investigation of Acceptable Roll-to-Yaw Ratio of the Dutch Roll and Acceptable Spiral Divergence," Cornell Aeronautical Lab., Rept. TB-574-F-6, Feb. 1952.

[18]Chalk, C. R., "Flight Evaluations of Various Longitudinal Handling Qualities in a Variable Stability Jet Fighter," U.S. Air Force Wright Aeronautical Development Center, Rept. WADC-TR-57-719, July 1958.

[19]Harper, R. P., "In-Flight Simulation of the Lateral–Directional Handling Qualities of Entry Vehicles,"U.S. Air Force Wright Aeronautical Development Center, Rept. WADC-TR-61-147, Feb. 1961.

[20]Newell, F. D., Dolbin, B., and Schelhorn, A. E., "Development and Flight Calibration of a Variable Drag Device on a Variable Stability T-33 Airplane," U.S. Air Force Wright Aeronautical Development Center, Rept. ASD-TDR-62-910, Aug. 1963.

[21]Hall, G. W., and Weingarten, N. C., "An In-Flight Investigation of the Influence of Flying Qualities on Precision Weapons Delivery," U.S. Air Force Flight Dynamics Lab., Rept. AFFDL-TR-72-120, Oct. 1972.

[22]Cooper, G. E., and Harper, R. P., "The Use of Pilot Rating in the Evaluation of Airplane Handling Qualities," NASA Technical Note TN-D-5153, Apr. 1969.

[23]Radford, R. C., Andrisani, D., III, and Beilman, J. L., "An Experimental Investigation of VTOL Flying Qualities Requirements for Shipboard Landing," U.S. Naval Air Development Center, Rept. NADC-77318-60, Aug. 1981.

[24]Reynolds, P. A., et al., "Preliminary Design for a General Purpose Airborne Simulator," Calspan–Univ. at Buffalo Research Center, Rept. TE-1795-F-1, Buffalo, NY, Aug. 1963.

[25]Weingarten, N. C., "In-Flight Simulation of the Space Shuttle During Landing Approach and Touchdown in the TIFS," Calspan–Univ. at Buffalo Research Center, Rept. 6339-F-1, Buffalo, NY, Sept. 1978.

[26]Weingarten, N. C., Deazley, W., and Dittenhauser, J. D., "In-Flight Simulation of a Remotely Piloted Vehicle Performing Automatic Landings," Calspan–Univ. at Buffalo Research Center, Rept. AK-5280-F-9, Buffalo, NY, Sept. 1976.

[27]Schifferle, P. T., "T-2 Modification of the TIFS for the NASA High Speed Civil Transport (HSCT) External Visibility Systems (XVS) Program," Veridian, Total In-Flight Simulator Technical Memo. 1956, Buffalo, NY, Sept. 1998.

[28]Eckhart, F. F., "A Comparison of Selected Aircraft for a Variable Stability Airplane for the Military Test Pilot Schools," Calspan–Univ. at Buffalo Research Center, Flight Research Memo. 513, Buffalo, NY, Dec. 1975.

[29]Ductor, G. R., "Digital Configuration Controller Circuit Description," Calspan–Univ. at Buffalo Research Center, Learjet Technical Memo. 5, Buffalo, NY, March 1979.

[30]Schelhorn, A. E., Ductor, G. R., Siracuse, R. J., and Ball, J. F., "Learjet Variable Stability System Description, Capabilities, and Calibration Procedures," Calspan–Univ. at Buffalo Research Center, Learjet Technical Memo. 33, Buffalo, NY, Sept. 1982.

[31]Croft, J., "Inflight Upset Training Puts Muscle Behind the Book Work," *Aviation Week*, Vol. 157, No. 9, 2002, pp. 58–59.

[32]Chalk, C. R., "Study for a Fighter Total In-Flight Simulator" Calspan–Univ. at Buffalo Research Center, Flight Research Memo. 566, Buffalo, NY, July 1982.

[33]Chalk, C. R., Dittenhauser, J. D., and Schelhorn, A. E., "Study to Define the Variable Stability In-Flight Simulator and Test Aircraft (VISTA)," U.S. Air Force Wright Aeronautical Lab., AFWAL-TR-86-3021, Oct. 1986.