A-7A AFCS: A Flight-Proved High-Gain System

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The automatic flight control system (AFCS) for the A-7A is a production version of a prototype system developed over the past three years, utilizing in its last phase an F-8D aircraft, which is quite similar to the A-7A in many aerodynamic and control characteristics. This paper presents the developmental philosophy that led to the selection of the final configuration: a completely dual, fixed-gain control-augmentation system, using series hydraulic servos and with attitude, altitude, heading-hold, and heading-select capabilities. Results of the Navy flight evaluation in the F-8D are presented along with capabilities of this type of system in providing improved airplane-handling qualities. The simple go-no-go cockpit self-test is discussed also.

1. Introduction

Although the automatic flight control system (AFCS) for the Ling-Temco-Vought (LTV) A-7A airplane only recently has flown in the A-7A, the system was in fact a highly developed and flight-proved system before installation. The A-7A AFCS is a production version of a prototype system developed by the Astronics Division of Lear Siegler Inc. (LSi) under BuWeps contract for high-performance fighter/-attack aircraft, such as the A-7A airplane. Preliminary flight testing of the system was accomplished in an F8U-1P (RF-8A) airplane, with prototype testing being accomplished in an F8U-2N (F-8D) airplane.

The LSi-Astronics AFCS features high, fixed-gain (inherently adaptive) dual channels, series servos, and control augmentation in addition to all the normal attitude and path-control functions. This paper discusses in detail the results and experiences of this development program, which dictated the final configuration for the A-7A. In addition, the capability of the control-augmentation feature to improve aircraft handling and control characteristics was investigated thoroughly at the Naval Air Test Center (NATC) in Patuxent River, Maryland, and the results are presented herein.

2. Control Augmentation

The heart of the AFCS for the A-7A is control augmentation, which differs from stability augmentation in that, with the former, the manual control system is augmented by electronic inputs emanating from a force sensor in the pilot's control stick to provide a closed-loop command of aircraft response. Control-augmentation signals from the pilot's stick-force sensor add to or subtract from the pilot's manual inputs as required in order to obtain the desired commanded response. The rudder axis remains a pure stability-augmentation system during the control-augmentation mode. Figure 1 is a simplified block schematic of the control-augmentation system.

There is one major advantage of a control-augmentation system that cannot be obtained with a manual control system, with or without stability augmentation; this is the amount of static stiffness that can be introduced into the airframe without deterioration of dynamic response. In normal aircraft design, maneuvering ability and performance are not compatible with stability requirements. In order to obtain the desired performance, it is usually necessary to make a sacrifice in stability. A simple stability-augmentation (damper) system can be used to minimize this compromise, but the damping ratio must be maintained closely (between 0.3 and 0.8) so that the damping does not adversely affect aircraft maneuverability.

This then results in an airframe with light static stiffness, which means that the airframe is easily disturbed by gusts or any configuration changes that change the aerodynamic forces acting on the airplane. The result is a compromise in the ability of the airframe to act as a stable weapons platform. With control augmentation, the airframe can be highly over-damped by electronic means to resist any external gusts, configuration changes, or aerodynamic forces. At the same time, the airplane can be maneuvered with the desired accelerations and rates inasmuch as the stick-force signal provides the means of biasing off this high damping signal so that the desired response can be obtained.

Thus, with control augmentation it is possible to provide an airframe with all the desired maneuverability as well as a heavy static stiffness to external gusts, configuration changes, and aerodynamic forces, and so obtain platform stability far in excess of that attainable by normal aircraft and stability control systems. This stiffness is especially desirable during the takeoff and landing phases and when configuration changes are being made (gear, flaps, speed brakes, variable geometry, external stores, and so forth). It also gives the pilot maximum confidence and maximum control of the airplane. Control augmentation is considered a major breakthrough in the state of the art towards the improvement of aircraft-handling qualities in high-performance aircraft. The control-augmentation system then becomes the basic automatic control system; the attitude and other path reference signals are added to it to provide the autopilot functions with little additional circuitry.

The control-augmentation signals originating at the pilot's stick provide control through series servos located directly at the primary control valves, bypassing all control frictions, nonlinearities, and hysteresis. High-authority series servos, e.g., $\pm 5°$ elevator, are thus a basic requirement of the control-augmentation system. (Parallel servos cause an objectionable feedback at the stick because the stick moves with servo movement.) The stick force signals, therefore, command a proportional airplane response independently of control effectivity or other aerodynamic effects. For this reason, the following advantages can be realized from a control-augmentation system: 1) A very simple manual control system can be designed; the basic manual control system is not the primary system and as such, needs only that complexity necessary to enable the pilot to control the airplane and land safely even though stick forces might be excessively high at some flight conditions. 2) The control-augmentation system will add to or subtract from manual input as required to command the desired airplane response; the control-augmentation system is therefore completely independent of

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manual control system characteristics. 3) The airplane control development task can be minimized. 4) Stability augmentation is provided with the basic control-augmentation system. 5) Any desired control-breakout force can be obtained. 6) Any desired static stick force vs airplane response can be obtained. 7) Any desired dynamic stick force vs airplane response can be obtained. And 8) complete control harmony can be obtained. All of the preceding characteristics can be varied at any time merely by readjusting gains or changing time constant values. This prevents costly control system changes after aircraft flight tests. Thus the automatic control-augmentation system can provide optimum aircraft control and handling characteristics; it is not a crutch in control-system design but an integral part of the aircraft control system.

3. Program History

The development program for the A-7A AFCS was initiated in September 1958 under a basic BuWeps contract. This preliminary system was installed in an RF-8A airplane; flight tests were conducted in early 1959 at the LSi flight-test facility in Ontario, Calif. The aircraft and system then were delivered to NATC at Patuxent River, Maryland, for further evaluation. The evaluation program was concluded in July 1959.

In September 1960, BuWeps awarded another contract to LSi-Astronics for a three-phase development program to develop further and flight test a production-prototype version of the system. The first phase of this program was to investigate existing electronic design techniques and AFCS components in order to obtain a desired system configuration to be fabricated under the second phase of the program. The final phase was a thorough flight evaluation of the system in an F-8D, again at Patuxent River. The program was officially concluded in September 1964; however, the system is still operational at NATC.

4. Preliminary Program

In 1959 there was considerable concern in the Navy about precisely what the optimum AFCS congfiuration should provide. The Navy was buying several aircraft, each of which had a different autopilot mechanization or configuration. It was very difficult to evaluate the merits of the various systems, because a certain function in one system might be considered objectionable not as a function but because of the mechanization peculiar to the airplane. Also, with the different autopilots being fabricated by different suppliers who used different electronic techniques, there was no common denominator for evaluation. Control stick steering was at that time coming into its own as a method of autopilot control; each system had a different stick steering mechanization. Therefore the Navy, LTV, and LSi-Astronics cooperated to configure a single autopilot system in such a manner that all the different functions and all the different modes and methods of mechanization could be evaluated on a single flight by a single pilot in an RF-8A Crusader. Figure 2 shows the cockpit installation.

At the top center of the pilot's instrument panel is the panel that furnished an indication of the mode being evaluated. At the bottom of the instrument panel is one of the three boxes which contained a total of 52 potentiometers to be used for inflight calibration. Figure 3 shows the pilot mode indicator panel with the different modes that were available for evaluation. Figure 4 shows the pilot mode-selector panel for selection of the various modes and functions during flight.

The system was configured to provide either parallel or series servo operation or a combination of parallel and series operation. In addition, four modes of control stick steering in the roll axis and six modes of control stick steering in the roll axis and six modes of control stick steering in pitch were available for investigation. The stick steering modes were: 1) control augmentation, a rate of command mode with no attitude information; 2) attitude control, wherein the attitude is disconnected with initial force, and rate control is obtained with synchronized attitude returning upon release of the force; 3) attitude control, wherein the stick force

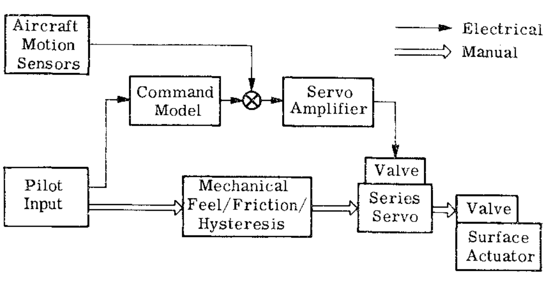

Fig. 1 Simplified block schematic of basic control-augmentation system.

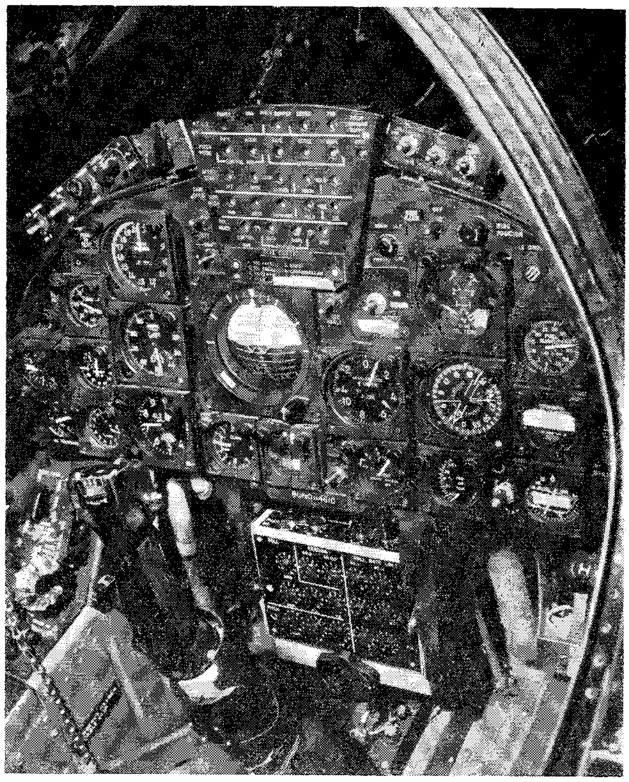

Fig. 2 Cockpit installation in RF-8A.

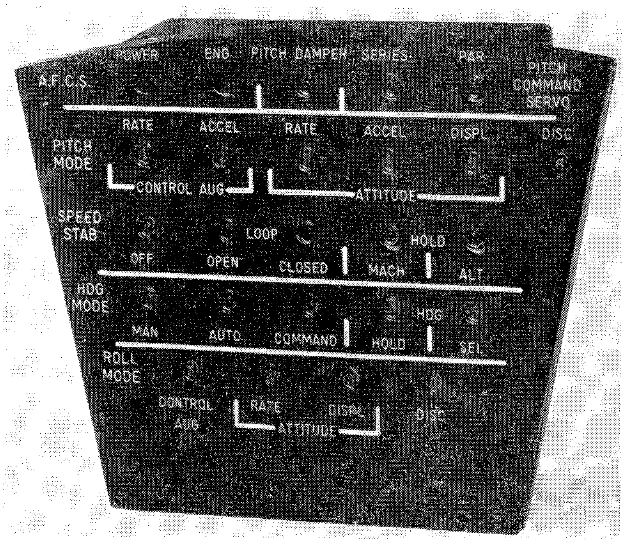

Fig. 3 Pilot's mode indication panel.

Fig. 4 Pilot's mode selector panel.

signal commands the pitch attitude synchronizer; and 4) attitude disconnect mode, in which the initial force applied at the stick disconnects the automatic control system and control reverts to manual until the force is released, at which time the attitude is re-engaged in a synchronous condition.

In the pitch axis two additional modes were available to provide normal acceleration control (command) in lieu of rate control in both the control-augmentation and the attitude modes. Three heading modes were provided: manual engagement of heading; automatic engagement of heading whenever the roll attitude was within 5° of wings-level and the pilot had no force on the control stick; the third mode allowed the pilot to command small heading changes through the control stick before force-disconnect.

It would seem that with all of these modes available it would be impossible to arrive at any sort of agreement among the various evaluation pilots as to which was the most desirable configuration. However, all of the pilots selected the same configuration: the one using all series servos with control augmentation as a basic function. Attitude command was obtained via the force stick, whereby the attitude was switched out with initial application of force and remained on synchronization until the pilot released force on the stick. For the heading mode it was decided that manual engagement of heading with heading-select capability was the most desirable.

The system as installed in the RF-8A was capable of fully demonstrating improvement of the manual control characteristics. This RF-8A was one of the first prototype airplanes, with an older type of control system which had very high breakout forces and frictions. In the longitudinal axis the manual breakout force was about 7 lb. The automatic system was designed to break out at about 1.5 lb with a gradient of about 3 to 16 lb/g. This meant that the airplane actually was being maneuvered most of the time without any manual input to the control valve as a result of the high breakout force. It was impossible for the pilot to determine, with the automatic mode engaged (even when making high g maneuvers), when the manual control system breakout occurred. The automatic system was capable of compensating for this nonlinearity in the manual control system without effect noticeable to the pilot.

To obtain a true evaluation of the merits of series vs parallel servos, a command function was provided in the cockpit which could introduce a 4 g command into the pitch axis of the automatic control system as a 1.5 second ramp. This was done to determine if there might be any pilot objection to large command inputs that had no resulting stick motion. All evaluation pilots agreed that there was no requirement for stick motion, inasmuch as the pilot always monitored the path command input; as long as the airplane reacted to the path command signal the pilot appeared to be completely satisfied without observing any stick motion. The WADC report stated, "It was found that the lack of stick motion while operating in internal command modes on series servos was not at all objectionable to any of the pilots."[1] During this program it was almost impossible to use the combination of parallel/series servos whereby the attitude and path command signals were introduced into the parallel servos, and the stabilization and control augmentation signals into the series servos because of the servos' differences in frequency response. From a practical standpoint, LSi-Astronics feels that it is almost impossible to obtain identical frequency response with parallel and series servos because the series servo has practically no force or inertial load, whereas the parallel servo had a comparatively high force and inertial load. All of the pilots approved the pure series servo configuration; and because it was the simplest mechanization, it seemed unnecessary to try to improve the mechanization of the parallel/series combination.

In order to provide adequate safety for the relatively high-authority series servo in the pitch axis, dual g limiters driving into dual series servos were installed. Each limiter had sufficient electrical authority to override the autopilot input. The limiters incorporated a dead zone in such a manner that no output was obtained until $+4.0\ g$ and $-1.5\ g$ were reached. The gradient of the limiter was such that full limiter output was obtained with an incremental 0.2 g after initial operation. In addition to the normal acceleration signal, a pitch rate signal was used for the necessary anticipation to prevent overshoot of the g limit. In operation the g limiter provided a very smooth and positive limit at the 4 g level which was independent of the rate at which the pilot approached the limit; this was due to the additional pitch rate signal. The g limiters were set so that when the pilot did not have a force on the stick, the maximum limit was 2 g's positive and 0 g negative. It was felt that the 4-g limit would be excessive if the pilot did not have his hand on the stick. However, the 4-g limit was necessary while the pilot was using the system for maneuvering. The limiters were set up in such a manner that at 4.2 g's the pilot could overpower the limiters by increasing force on the stick until the full authority of the series servo is overpowered. Thus, in an emergency, the pilot could pull additional g's but would be warned on reaching the 4-g limit. The NATC report states, "The employment of g limiters as a safety device in an AFCS is considered essential.

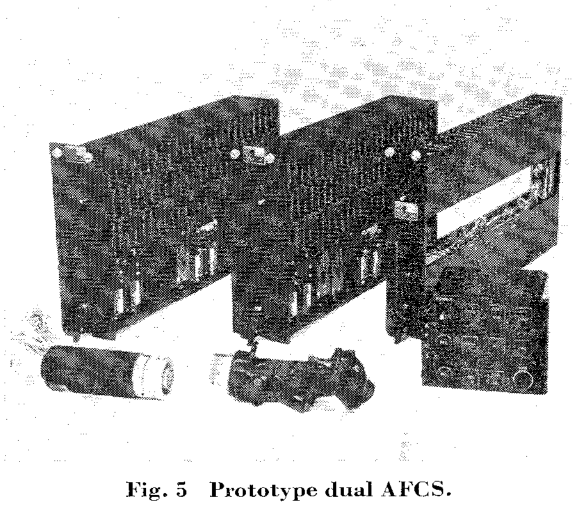

Fig. 5 Prototype dual AFCS.

The use of *g* limiters to prevent or warn the pilot of excessive *g* loads being imposed on the airplane during maneuvering is desirable."[2]

It therefore was determined that a control-augmentation mode utilizing series servos could appreciably improve handling qualities. In the control-augmentation mode the system was used from takeoff to landing as the primary control system. One of the other major considerations was the fact that heading select was a highly desirable feature but the heading-select maximum bank angle should be variable by the pilot. A fixed heading-select bank angle was inadequate inasmuch as the safe bank angle at low airspeeds would be too small for adequate maneuvering at high airspeeds. Bank-angle compensation with airspeed was provided, but this also was felt to be inadequate because in descending turns the pilot sometimes needed higher bank angles than in level turns. In addition, the desired maximum bank-angle limit appeared to be a function of the mission requirements.

5. Prototype Development Program

Because the Navy received such favorable reaction to the final system configuration from the evaluation pilots, and because the recommendation of NATC was to continue the development of this system, the Navy decided to go ahead with a three-phase program to develop a final production-prototype version.

Phase I

The first phase of the program was a study, investigation, and development phase during which all the different sensors and components were evaluated. The results of the evaluation were analyzed thoroughly so that the production-prototype system would reflect all of the recommendations, as well as correct any objectionable features of the preliminary system. It had been decided by the Navy to utilize a submodular functional packaging concept of the electronics. This submodular concept, designated "Millimin" by LSi-Astronics, was being utilized in the production AFCS for the Gyrodyne Drone Helicopter used by the Navy in the Drone Anti-Submarine Helicopter (DASH) program. The Navy felt that an AFCS could be designed around these functional submodules in such a manner that it would be possible to save future system-development costs on new aircraft by specifying these submodules for new systems. Thus with the final system mechanization and the electronic submodules specified, it would be possible to package any final system in the configuration necessary to satisfy a particular installation with minimum developmental costs.

During Phase I the decision was made to use a completely dual control-augmentation system (dual, including stick-force sensor electronics and series servos). It was felt that duality would provide the required safety for operation with high-authority series servos necessary to obtain adequate control throughout the maneuvering envelope. A dual stick-force sensor and a dual series electrohydraulic servo were designed for the final system as part of Phase I. Complete analog simulation of the final system using the high-gain servo loops with a typical high-performance aircraft verified the fact that the system was inherently self-adaptive and did not require any additional adaptive scheme or gain scheduling. This fixed-gain concept was possible as long as the manual control system of the airplane had a frequency response of at least 18 rad/sec.

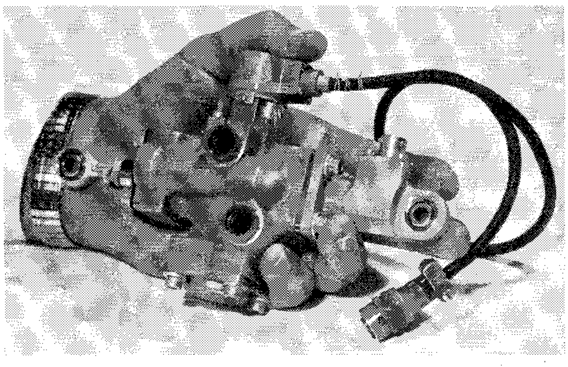

Fig. 6 Electro-hydraulic series servo.

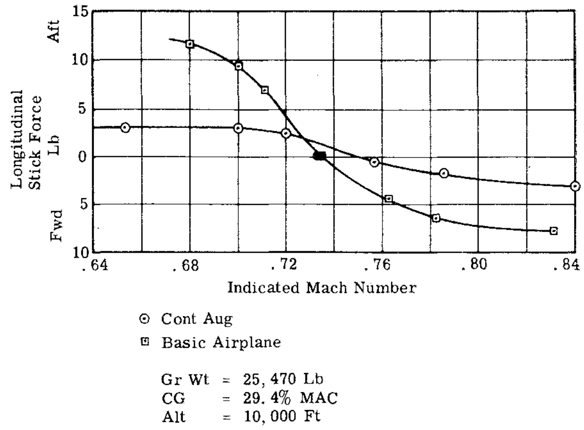

Fig. 7 Static longitudinal stability in configuration CR.

It was decided to provide a single attitude and path command loop for pitch and roll. To provide the desired safety, dual roll rate and pitch normal acceleration limiters were included. It was felt that the dual roll rate and normal acceleration limiters provided the same safety as a dual attitude and path command system in addition to providing a desirable warning feature during control-augmentation operation.

Phase II

The second phase included fabrication of a system for flight evaluation in the LTV F-8D. It was decided to package the dual pitch axis, the dual roll axis, and the dual yaw axis separately. Figure 5 is a photograph of the dual production-prototype system showing the three electronic packages, the stick-force sensor, and the pilot's mode-selector panel. Figure 6 is a photograph of the series servo, which was designed in such a manner that two can be bolted together to provide a dual series servo. The final system contained six of these servos.

Phase III

Flight test of the prototype system in an F8-D was designated Phase III. The primary interest of this flight evaluation was centered around the basic control-augmentation function and its relationship to improvement of aircraft-handling and control characteristics. These characteristics were evaluated during: 1) takeoff and landing, 2) instrument approaches and departures, 3) full aileron rolls, 4) wind-up and steady turns, and 5) various other typical fighter/attack maneuvers.

The initial flight evaluation consisted of 25 flights flown by seven Navy test pilots and three civilian test pilots. A complete complement of test instrumentation was installed in the airplane to obtain quantitative data. The flying qualities of the control-augmented aircraft were evaluated by use of the Cooper Rating Scale. Qualitatively it was determined that the gradient of longitudinal stick force with respect to airspeed appeared to be noticeably lower in the control-augmentation mode than when flying the basic manual airplane. Quantitative results supported these pilot opinions and are shown in Fig. 7.

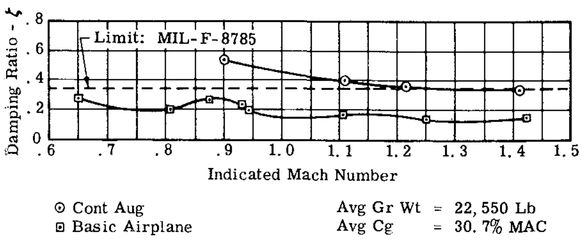

Fig. 8 Longitudinal damping ratio at 40,000 ft.

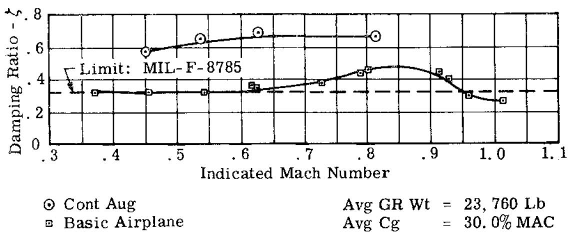

Fig. 9 Longitudinal damping ratio at 10,000 ft.

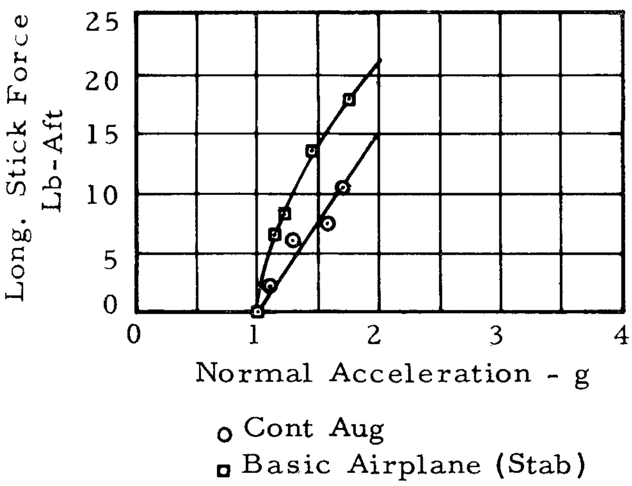

Fig. 10 Maneuvering longitudinal stability configuration CR (0.8 IMN at 40,000 ft).

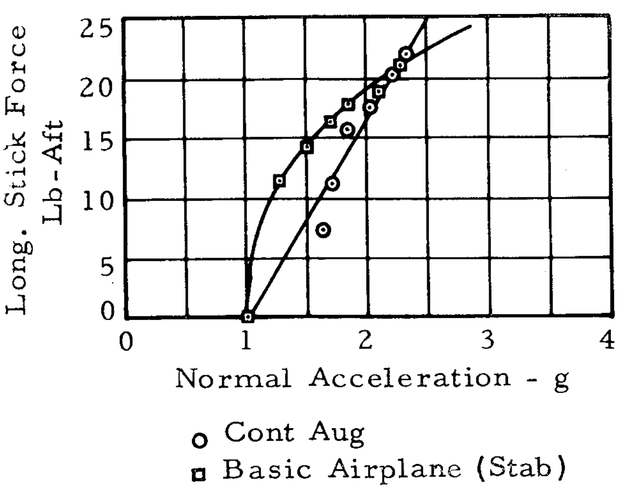

Fig. 11 Maneuvering longitudinal stability configuration P(A/B)(1.4 IMN at 40,000 ft).

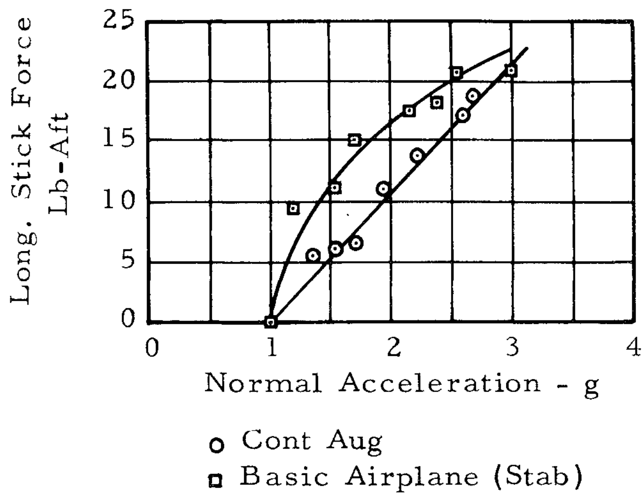

Fig. 12 Maneuvering longitudinal stability configuration CR (0.6 IMN at 10,000 ft).

Stick-free longitudinal stability tests were conducted at several flight conditions. The results showed that the stick-force gradient in the control-augmentation mode is about one-sixth of the manual aircraft in the cruise configuration, and one-half that of the manual aircraft in the powered approach (PA) configuration. The position of the horizontal stabilizer was identical for both the control-augmentation mode and the manual mode.

A comparison of the short-period dynamic longitudinal stability characteristics was made between the basic airplane and the control-augmentation system. Figures 8 and 9 show the difference in damping ratio at high and low altitudes. In both cases it can be seen that the control-augmentation system considerably improves the damping ratio of the basic airframe and will bring the airframe into specification limits.

It should be noted that, at the same time the control-augmentation system improves the damping ratio, it also increases the undamped natural frequency of the aircraft. Even though the undamped natural frequency was increased, it was not objectionable because the damping ratio was also increased. The net result is a much better responding airframe with improved damping characteristics. Results of these tests from the standpoint of qualitative considerations show that the pilots prefer an airplane that has relatively high damping ratios combined with an undamped natural frequency between 0.5 and 1.0 cps.

Test results of maneuvering stick-force gradients in the control-augmentation mode as compared to the basic airplane

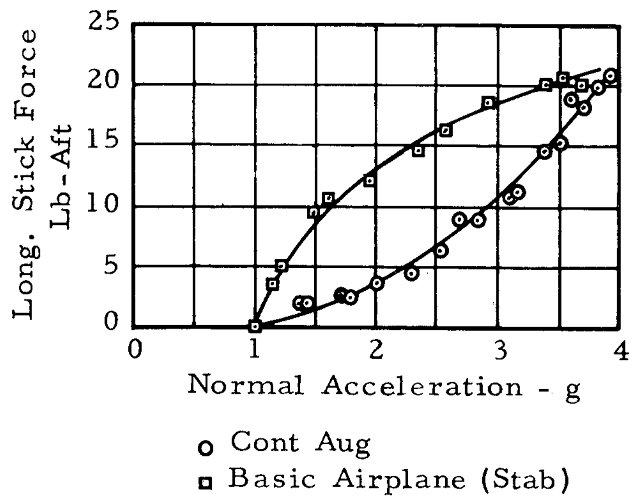

Fig. 13 Maneuvering longitudinal stability configuration CR (0.9 IMN at 10,000 ft).

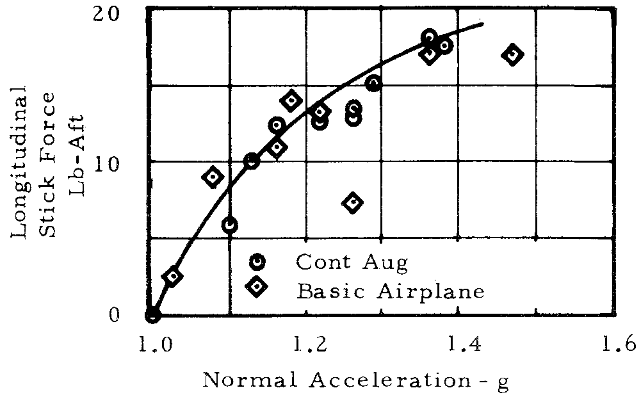

Fig. 14 Maneuvering longitudinal stability in configuration PA 160 KIAS, alt 5000 ft.

are shown in Figs. 10 through 14 for various flight conditions. The control-augmentation stick force gradient at small normal accelerations is linear and smaller than the basic airplane-maneuvering stick-force gradient. For relatively high normal acceleration, the maneuvering stick-force gradient of the pitch-control-augmented airplane is higher than that of the basic airplane. This is primarily because of the nonlinearity of the gradient of the basic airplane. In other words, the control-augmentation system tended to linearize the stick-force gradients regardless of the basic control-system gradient. It can be seen in Fig. 13, which shows the high-q condition at low altitude, that a very low maneuvering stick-force gradient at slight normal acceleration was obtained in the control-augmentation mode. This is due to the rather large increase in undamped natural frequency at this flight condition. As a result of this it was decided to incorporate a normal acceleration feedback in the pitch axis of the basic control-augmentation system.

Until this time the system was strictly a pitch-rate command control-augmentation system with the pitch-rate command being modified as a function of Mach number to obtain a close approximation of constant stick force/g. The addition of the normal acceleration feedback completely eliminated any dependence of the system on air data information and also greatly improved the airplane-handling qualities at the low-altitude high-q condition. The maneuvering longitudinal stability results obtained with the normal acceleration feedback as compared to the Mach compensated pitch-rate feedback system are shown in Figs. 15 through 18. It can be seen that the use of the normal acceleration feedback

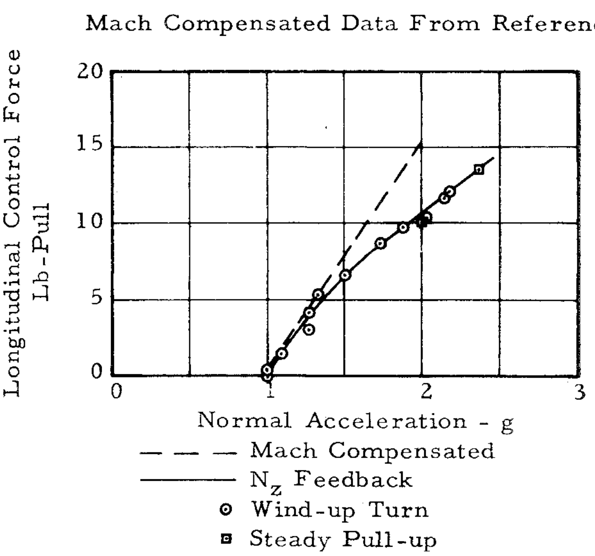

Fig. 15 Maneuvering longitudinal stability in configuration CR (0.8 IMN at 40,000 ft) control augmentation.

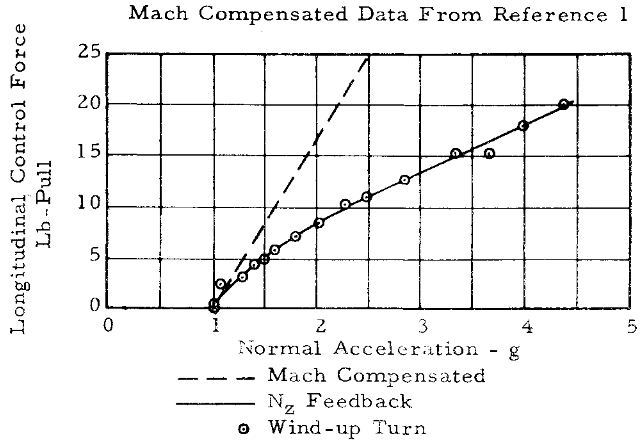

Fig. 16 Maneuvering longitudinal stability in configuration CR (1.4 IMN at 40,000 ft) control augmentation.

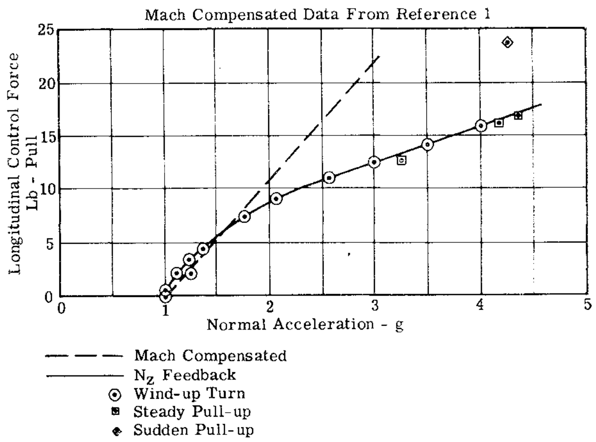

Fig. 17 Maneuvering longitudinal stability in configuration CR (0.6 IMN at 10,000 ft) control augmentation.

tends to flatten out the force gradient at the higher normal accelerations which, from pilot opinion, is felt to be a very desirable feature of any control system. Figure 19 shows this same condition to exist at the highest q tested, which gave almost identical results for wind-up turns or sudden pull-ups. With the normal acceleration feedback, the worst Cooper Rating of the control-augmentation system was 2.5, which was obtained in the low-altitude, high-speed regime.

The normal acceleration feedback system was actually a combination of normal acceleration and pitch rate, whose gains were set in such a manner that at about 250 knots

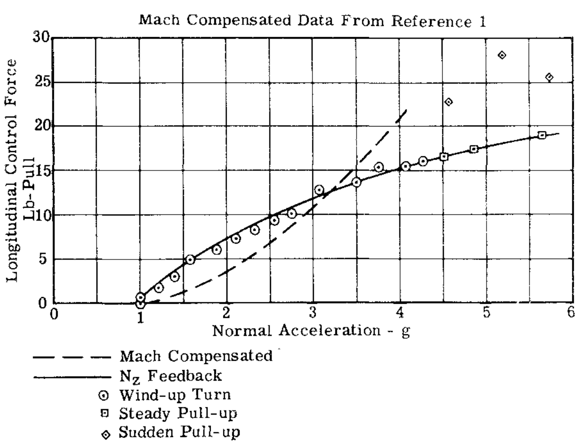

Fig. 18 Maneuvering longitudinal stability in configuration CR (0.9 IMN at 10,000 ft) control augmentation.

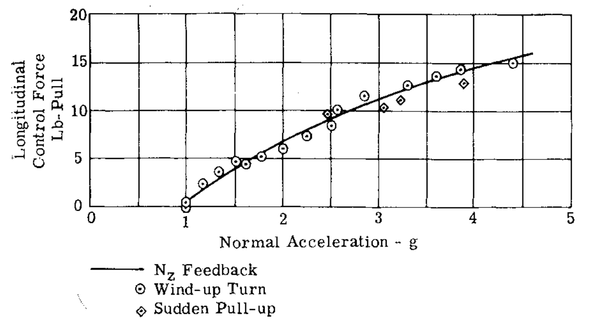

Fig. 19 Maneuvering longitudinal stability in configuration P(MIL) (0.94 IMN at 1000 ft) control augmentation.

indicated air speed (IAS) a crossover occurred. Thus, above 250 knots the control was partially pitch rate but became primarily normal acceleration as IAS increased. Below 250 knots the normal acceleration had diminishing effect and the pitch rate became the primary feedback command signal providing higher stick force/g in the PA configuration (see Fig. 20). This system, using a combination of pitch rate and normal acceleration, does not provide constant stick force/g; however, it appears to provide a stick-force gradient that is far more acceptable to the pilot than constant stick force/g.

It was determined that the command model has a major influence on aircraft-handling qualities. If the command model time constant is too short, there is an apparent decrease in damping. For a fighter/attack airplane this model was optimum as a first-order lag with a 0.4-to 0.5-sec time constant.

Although current specifications failed to provide standards for roll dynamics, a flight evaluation of the control-augmentation system in the roll axis was made. Roll sensitivity was satisfactory with a Cooper Rating of 2 to 3 for all test conditions. The best sensitivity was provided at 1.4 Mach number at 40,000 ft. Roll damping appeared to be adequate at all test conditions.

In addition to the control-augmentation evaluation, an evaluation of the basic autopilot mode and functions also was made. "All pilots who evaluated the autopilot functions considered the autopilot to be excellent. The high over-all pilot opinion was based on the smooth response to control signals, the lack of engagement and disengagement transients, and the very positive heading hold capabilities. Elimination of control stick movement as a result of automatic control actions (series servos) was considered to be a desirable feature."[3]

This evaluation showed that it was highly desirable to provide the pilot with the capability of increasing heading-select bank angle as desired by applying lateral stick forces. In other words, when the heading-select mode is engaged,

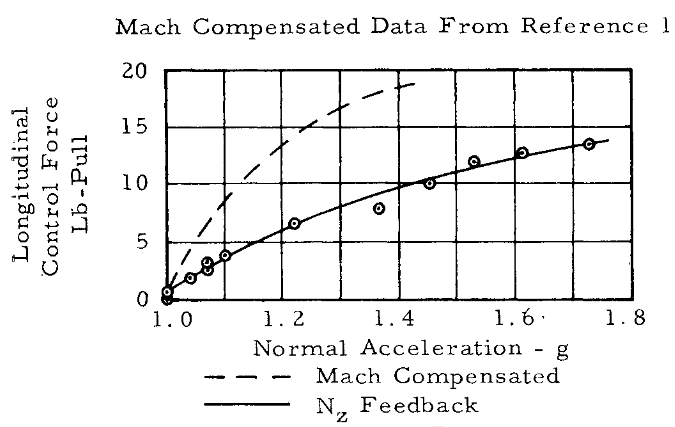

Fig. 20 Maneuvering longitudinal stability in configuration PA (160 KIAS at 5000 ft) control augmentation.

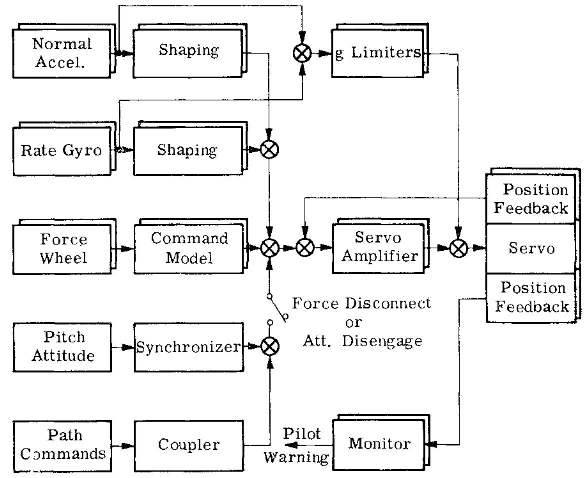

Fig. 21 Simplified block diagram of dual AFCS.

lateral stick forces increase the reference heading-select bank angle up to a maximum of 70°. This then provided the pilot the opportunity to adjust his heading-select bank angle to optimum for the particular mission requirements. The initial heading-select bank angle is maintained at a value which is safe under all conditions.

This program proved that the control-augmentation function is capable of substantially improving control handling characteristics of fighter/attack aircraft and should be a basic part of the AFCS. Figure 21 is a simplified block diagram of the dual AFCS.

6. A-7A AFCS

The AFCS for the A-7A aircraft is basically a dual control-augmentation system identical to the dual flight system evaluated in the F-8D airplane; however, it contains the following differences:

1) Dual pitch-attitude function in lieu of the single pitch-attitude function and dual g response limiters in the prototype system. From the standpoint of economy, it was felt that the dual pitch-attitude mechanization provided the necessary safety for the attitude modes with less complexity than the dual g response limiters, even though the response limiters have other desirable features as previously described. Altitude and path commands are single inputs, with safety being provided by dual signal limiters.

2) All roll axis attitude and path command signals are single-ended with safety provided by dual signal limiters that limit any hardover signal to a safe rolling rate.

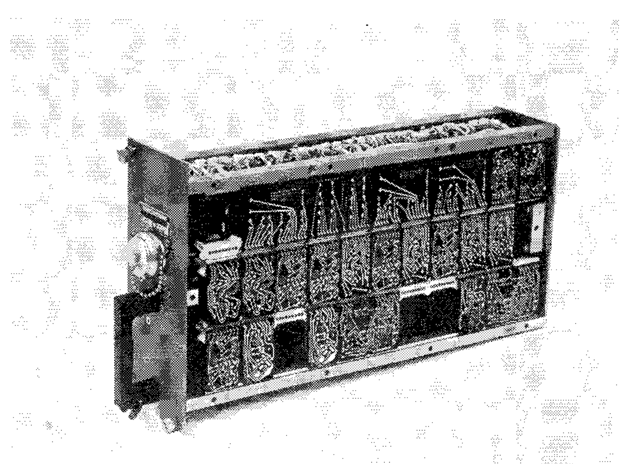

Fig. 22 Dual roll axis channel of production A-7A AFCS.

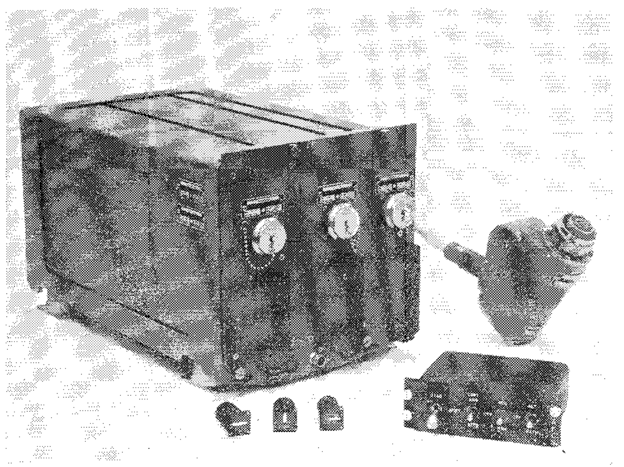

Fig. 23 A-7A production AFCS: pilot's controller, switch, dual electronics, and stick-force sensor.

3) The A-7A dual channel monitor supplies immediate axis-disconnect on disagreement. In the F-8D the monitor merely warns the pilot, and disconnect is a pilot option. Monitor-disconnect is an LTV requirement. The merits of monitor warning with pilot-disconnect are still being evaluated.

4) The A-7A dual series servos provide instantaneous (less than 50 msec) return to center on disconnect. The F-8D servos provide a slow return (1.5 to 2 sec) to neutral on disengagement. Again the fast return servo is an LTV dictate. The merits of the slow return to neutral are being evaluated because under certain disengagement conditions the slow return can prevent a system transient.

5) The pilot's manual-trim button provides a vernier command of pitch attitude; the prototype system used small stick-force signals. Several minor problems were encountered with the prototype mechanization, but the change in the A-7A system has corrected these. Otherwise, the system is identical to the F-8D system. The same submodular electronic construction is used. Figure 22 is a photograph of the A-7A dual roll axis unit showing this construction.

Figure 23 shows the complete dual three-axis electronics with dual stick-force sensor, trim indicators, and mode-selector panel. Considerable effort went into making the system as simple to operate as possible; note the simplicity of the pilot's mode-selector panel.

One of the major innovations of the A-7A AFCS is a simple go-no-go type of system check that can be accomplished in a matter of seconds. A separate test panel contains a switch with four positions. For system test the switch is turned to each position (rate gyro, accelerometer, altitude, and monitor), and a test button is momentarily depressed. Self-test rate gyros and accelerometers provide the test signal for two positions, whereas opening one leg of the altitude synchro provides the third position signal. If the system is functional, no monitor light will be obtained. The fourth position provides a signal to one channel only in order to test the monitor. To complete the system test the pilot need only apply a fore-aft and lateral forces on the stick and observe that no monitor light is obtained. The trim indicators (servo position) provide the pilot with the means of determining that his system is active. Satisfactory operation of the heading and attitude system can be obtained by observing the normal readouts in the cockpit instrumentation.

The production A-7A system was also "flown" on the A-7A controls simulator for more than 500 hours, and all results agree closely with the actual flight results obtained with the prototype system in the F-8D airplane. Thus the A-7A AFCS was a thoroughly developed and flight-tested system even before the actual flights in the A-7A.

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