An Automatic Stall Prevention Control for Supersonic Fighter Aircraft

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A number of supersonic fighter aircraft exhibit a tendency to "pitch up" as a result of reaching a full-stall condition. Recovery from the maneuver may be difficult and at higher speeds structural loads may be encountered which are beyond design limits of the aircraft. The flight test development program of an automatic system designed to protect the pilot and airframe from these undesirable characteristics is described. The system senses aircraft pitch rate and angle of attack and actuates a stick-shaker warning device followed by application of a corrective pitch control force if the warning is ignored and unsatisfactory conditions persist. Safety aspects of the test techniques were of paramount importance. The techniques developed for evaluation of system performance consisted of flights with lowered system boundary limits, 1-*g* stall approaches, wind-up turns, and rapid pull-ups. Tests were conducted with emphasis on reliability and system repeatability. A problem involving pilot-system interaction which caused cycling of the force system was solved by use of a minimum-time-on delay. Minimum reduction in maneuvering boundary was achieved by addition of a pitch-rate washout. System block diagrams and performance data are presented for several stages of development including the final system. Preflight and inflight checkout procedures to verify system operation are described, as well as design and switching considerations, which improve performance, reliability, and safety.

Introduction

EARLY wind-tunnel model tests predicted that the F-104 airplane would be subject to an uncontrollable pitch-up motion in the fully developed stall. The condition is caused primarily by downwash on the horizontal stabilizer resulting from high angles of attack as illustrated in Fig.1. Configuration changes that were effective in alleviating this problem were unacceptable for other reasons. Analytical and mock-up studies indicated that inadvertent entry to the stall could be successfully prevented by an automatic control system. The system utilized pitch rate and angle-of-attack information to sense approach to the stall boundary and responded to reduce these parameters by proper control motion. Flight testing confirmed the pitch-up predictions of the wind-tunnel tests; this paper describes the flight test program that confirmed the suitability of the automatic pitch control (APC) following the analytical and mock-up studies.

System Description

The system as proposed for flight testing was designed to provide the following essential requirements.

1) It would prevent entry into a fully developed stall. Figure 2 indicates the nature of pitching-moment characteristics of the airplane at high angles of attack. As shown, at 14° angle of attack the airplane is neutrally stable, and at higher angles it becomes increasingly unstable. To demonstrate the severity of the maneuver resulting from a penetration to a full-stall condition, Fig. 3 presents a time history following a 1-*g* stall entry at 40,000 ft at 0.6 Mach number. During the maneuver, sideslip angles of 40° were reached and there were rapid and extreme variations in angle of attack, stabilizer position, and c.g. normal acceleration. Although these were well within the structural capability of the airplane for this flight condition, the same maneuver at higher indicated airspeed could result in structural failure.

2) It would be reliable and fail safe. It was felt that this could best be provided by adequate testing of a suitable design. Achievement was to be proven by continued usage over a wide range of operating conditions with a thorough investigation and design correction of any malfunctions in any aspect of system operation.

3) It would not restrict the safe maneuvering capabilities of the airplane. The estimated angle of attack for neutral stability as a function of Mach number and a typical aircraft maneuver envelope (*M-n* diagram) are presented in Fig. 4; the *M-n* diagram is based on the coefficient of lift at neutral stability or by airplane structural capabilities. Any action of the system below these load factor limitations would represent an undesirable loss in maneuvering capabilities.

The system, called the automatic pitch control system, consisted of the following major components: 1) a gyro, sensing pitch rate; 2) a vane, sensing angle of attack, mounted on the nose of the aircraft; 3) a summing device for combining output from the rate gyro and the vane, providing an electrical signal that operated the control actuator; and 4) an electrohydraulic actuator that provided a forward-stick (nose-down stabilizer) motion that supplied a normal "breaking" stall characteristic in lieu of further penetration into the fully developed stall condition and subsequent pitch-up; stabilizer motion caused by the actuator is limited to approximately 1° nose down from the neutral trim position (the

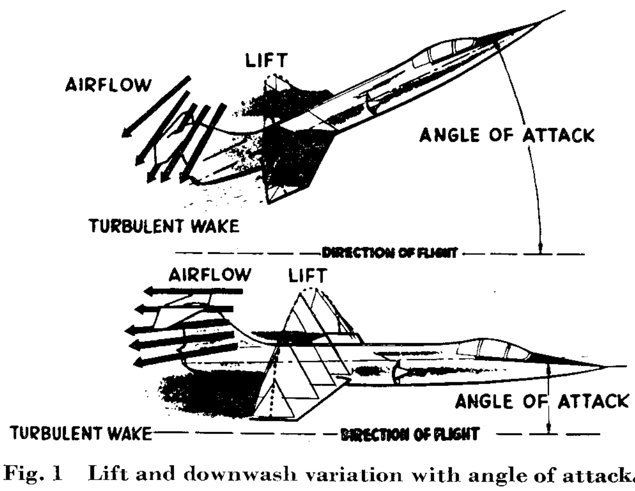

Fig. 1 Lift and downwash variation with angle of attack.

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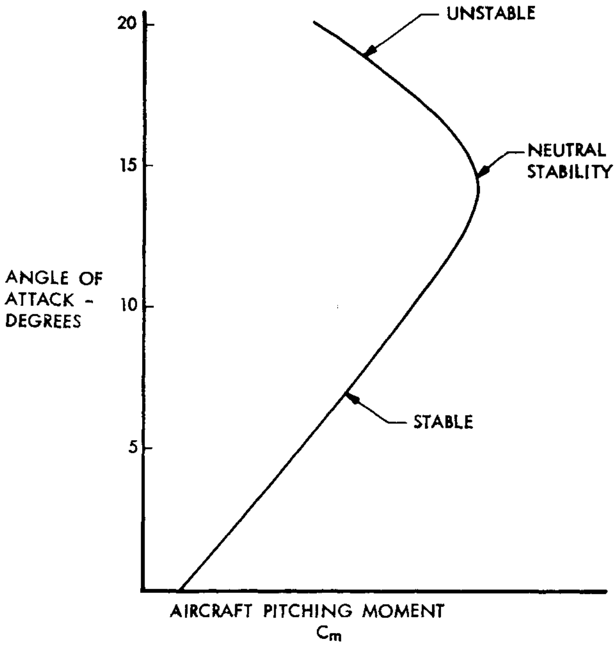

Fig. 2 Angle of attack vs aircraft pitching moment.

pilot can, if necessary, apply sufficient back-stick force to prevent the nose-down stabilizer movement).

A block diagram of the prototype APC system is shown in Fig. 5 to illustrate the circuit and component relationship. The system operates "open loop" with no direct feedback from the actuator to the summing point. In flight, aircraft motion closes the loop.

A typical operation boundary for the system is shown in Fig. 6. This boundary is generated by adjusting the gain controls to establish an actuation point in terms of vane angle of attack and gyro pitch rate. Once set, these values, or any combination of the outputs which reaches the boundary, will cause the system to operate. A signal from the summing amplifier causes a hydraulic actuator to apply a nominal 20-lb nose-down force to the stabilizer control system until the stabilizer reaches a position approximately 1° below the trimmed stabilizer angle. Figure 7 indicates the component locations in the aircraft and the two vane installations on opposite sides of the fuselage near the nose of the aircraft.

Operation of Proposed System

The angle of attack for neutral stability is depicted in Fig. 4. Since this boundary may be approached both slowly and

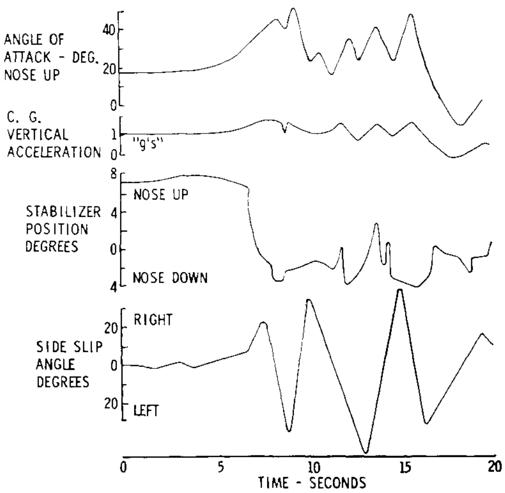

Fig. 3 Partial time history of full stall.

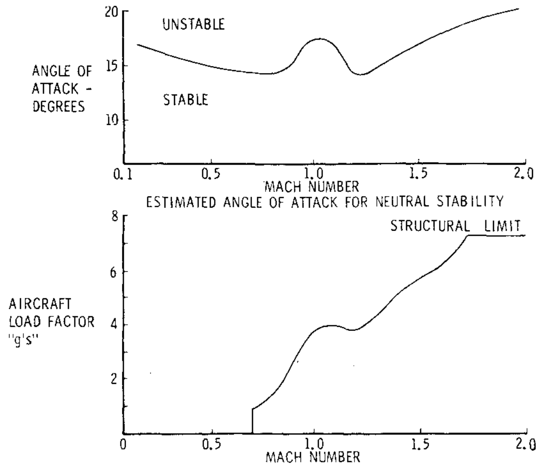

Fig. 4 *M-n* for neutral stability (typical).

quickly, there exists a necessity for the use of angle of attack and some dynamic measurement such as pitch rate for system operation. Angle of attack is the essential measurement in 1-*g* stall approaches and in steady turns, whereas pitch rate information is also necessary for anticipation in a rapid pull-up condition.

It was necessary that the selected settings protect the airplane from all possible combinations of entry conditions including rapid pull-up at high angle of attack. The stabilizer rate in all cases was to be limited only by the maximum rate of the stabilizer hydraulic actuator.

Figure 8 illustrates some typical flight variable paths in terms of pitch rate and angle of attack for different entry conditions. As shown for the fast pitch-rate pull-up at low speed and high angle of attack, the airplane continues beyond the point of neutral stability during the maneuver. How this can happen is explained by reference to Fig. 9. As the stick is pulled aft of the 1-*g* trim point, a new C_m vs α relation is established; as angle of attack and pitch rate increase, the APC actuation point is reached. The stabilizer then moves 1° forward of trim establishing another C_m vs α relation. Angle of attack over-shoots beyond the neutral stability point, but subsequently the airplane nose comes back down, and 1-*g* flight can be resumed. As can be seen, the angle of attack for neutral stability can be safely exceeded by several degrees as long as a nose-down or restoring moment is maintained.

In turning flight, a constant angle of attack is accompanied by a pitch rate dependent upon the speed and normal acceleration. Since the system is operated on the summation of pitch rate and angle of attack, any dynamic maneuver at other than 1 *g* could result in a premature actuation, i.e., at an angle of attack less than that at zero pitch rate. This results in a loss in maneuvering capability. This loss is even greater

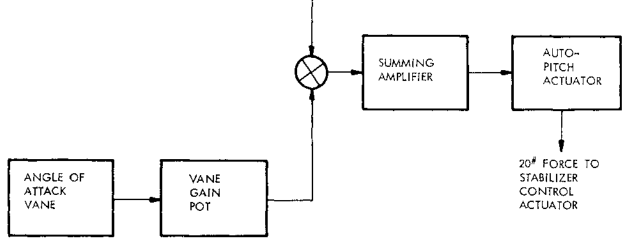

Fig. 5 Prototype autopitch system, F-104 A block diagram.

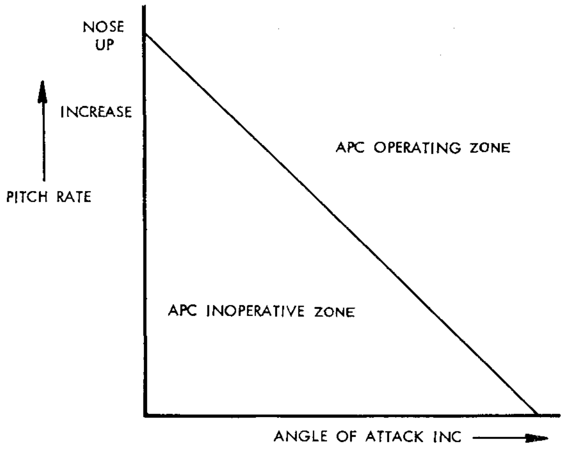

Fig. 6 Autopitch control operating variables.

at higher speeds because of the increased angle of attack available for maneuvering at higher speeds. As an example, if the system is to provide protection in a 1-g stall approach at 40,000 ft and 0.6 Mach number, the system must operate at 14° angle of attack. The pitch-rate contribution for this condition is assumed negligible. At 1.6 Mach number, at the same altitude, an angle of attack of 12.5° is necessary to reach load factor of 6.5 g; holding this load factor in a turn would require approximately 6.5°/sec pitch rate. With the angle-of-attack boundary setting of 14° for the subsonic case, it is apparent that the system would operate, with any nominal pitch-rate gain setting, at an angle of attack and pitch-rate combination considerably below the 14° angle-of-attack setting and the allowable 6.5°/sec pitch rate. The 14° boundary setting used in this illustration therefore prevents the full high-speed maneuvering performance of the aircraft from being realized before the APC operating point is reached.

The foregoing example made several things apparent.

1) The 1-g boundary setting must be as high as possible. All other flight conditions would be inherently less critical because the pitch-rate component effectively reduces the boundary.

2) It would be highly desirable to remove the steady pitch-rate signal component generated in steady turning flight, but to retain it for anticipation in rapid pull-up maneuvers.

3) Any vane location that yields a calibration proportional to the Mach-number/variant angle of attack for neutral stability would be of great benefit.

The test program was planned to test the proposed system to define the requirements necessary to overcome the forementioned problem areas and to determine if satisfactory repeatability and reliability would be obtained.

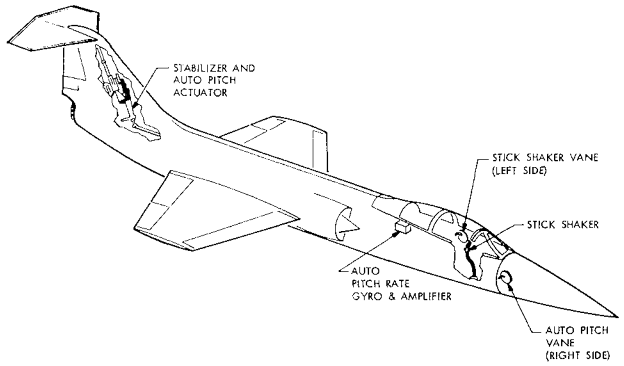

Fig. 7 F-104 prototype autopitch control system installation (typical).

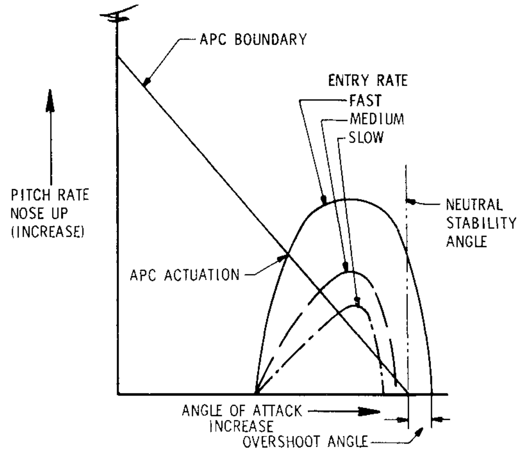

Fig. 8 APC operation characteristics at varied entry rates.

Flight Test Program

Test Techniques

Since the purpose of the APC was to protect the airplane from entering a dangerous flight condition, considerable thought was given to test techniques that would permit a safe evaluation of the operation, reliability, and repeatability of the system. The following procedures were established to permit this evaluation.

1. Operation check

With the boundary set well below the neutral stability boundary and in a flight condition below the safe broadside (structural limit) speed, steady turns and rapid pull-ups were made to check reliability and repeatability of operation with the preset boundary.

2. 1-g stall setting

Utilizing the data obtained from maneuvers in which the airplane had entered a full-stall condition from 1 g, it was possible to define the angle of attack at which rapid divergence in pitch commenced. For reasons of safety, pitch-ups were not made above Mach 1.0. Analysis of airplane pitching motion data from abrupt stabilizer inputs permitted the supersonic C_m vs α variation and the neutral stability angle of attack to be established. This technique was also used subsonically to confirm data from pitch-ups. The flight test data were then used to establish the neutral stability angle of attack as a function of Mach number, a variation similar to

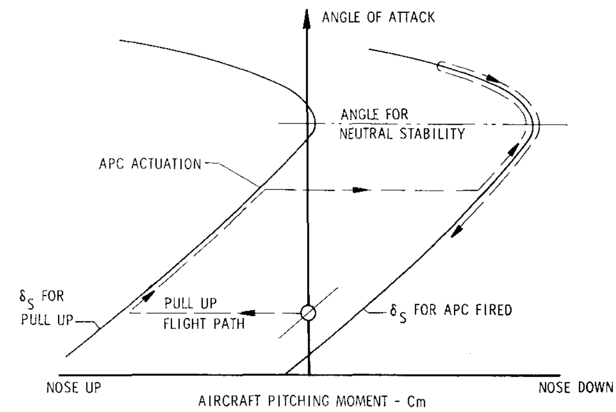

Fig. 9 Angle-of-attack pitching moment relationship in an abrupt pull-up to APC operation.

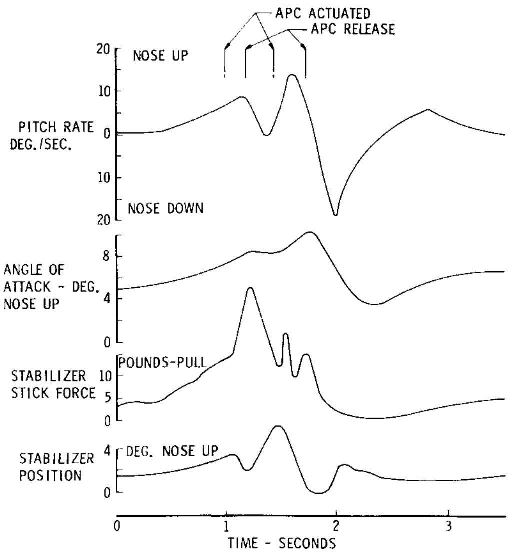

Fig. 10 Time history of quick pull-up for APC operation.

the wind-tunnel prediction shown in Fig. 4. These data permitted determination of a safe angle of attack at the zero-pitch-rate end of the APC boundary.

3. Pitch-rate setting

With the steady-state angle of attack setting determined, the pitch-rate gain setting was to be increased progressively with control checks made in rapid pull-ups to determine the overshoot in angle of attack. In addition, steady turns to APC actuation would be made to determine the extent of the available maneuvering boundary. These test techniques proved successful and were used continuously during the program with each major development change in the system calling for a recheck of the operation and repeatability of the system.

Since the angle-of-attack input for the APC system was sensed by vanes mounted on the fuselage side, it was necessary to calibrate the vanes against the true (airplane) angle of attack measured by a nose-boom-mounted vane. This was accomplished by "roller-coaster" maneuvers for various flight conditions.

Initial Problem Areas

Flight testing using the previous techniques revealed several areas requiring further development. With the system boundary settings at low values of angle of attack and pitch rate, nuisance actuations occurred during normal flight maneuvers and in turbulence. In addition, the airplane response was such that, after an APC actuation, the aircraft would return to the area below the setting boundary, the system would "relax," and the pilot, responding involuntarily to the nose-down stick force which had been applied by the APC system, would apply a nose-up stick force, which again would cause the aircraft to penetrate the boundary and repeat the sequence of events. In some cases, the cycle occurred several times before the pilot realized what was happening. Figure 10 illustrates a quick pull-up that resulted in double APC actuation of this type. For some very low boundary setting conditions this situation also occurred with no pilot force input.

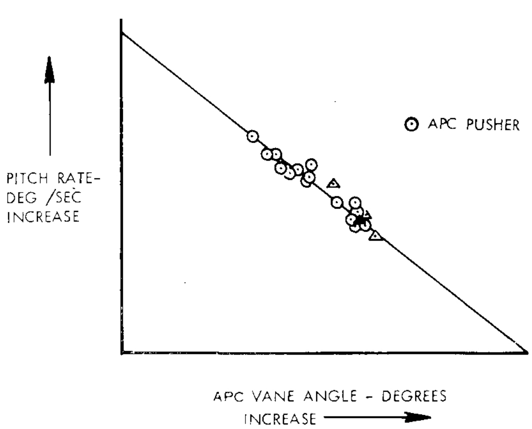

Fig. 11 Autopitch control operation, various conditions.

Immediate steps were taken to rectify this situation. The boundaries were advanced and a minimum-time-on function was added to the APC system. The nuisance actuations were eliminated, and with the minimum-time-on feature the pilot was able to reduce stick force consciously without cycling. Figure 11 indicates the results of further tests with this configuration at moderate boundary settings. The system operation was satisfactory and repeatable results were obtained over a wide range of conditions. With this configuration, pilot confidence and acceptance were readily obtained. The action of the system and the airplane response were natural and acceptable. However, it was felt at this time that, to complete the stall simulation, a stick-shaker warning should precede operation of the stick pusher. An additional vane was therefore mounted on the fuselage left side to operate the stick shaker from angle-of-attack data only. This shaker action would be representative of the usual stall approach, since in a rapid pull-up buffet is usually reduced.

APC Stick Force

In conjunction with the flight tests, investigations were made with a control system mock-up to determine the effects of the APC stick force on the time to reach maximum stabilizer rate. It was determined that a force at the stick of 15 to 25 lb provided maximum stabilizer rate capability; this force was deemed acceptable by the pilots. However, because of the possibility of a failure in the actuated position, two tests were made in which the airplane was flown and landed with the APC system actuated. In the two landings, the forces were 25 and 30 lb, respectively. Neither force was considered excessive by the pilot for this condition.

Vane Calibration Tailoring

Further tests were then made with boundary settings much closer to the neutral stability boundary. System operation was excellent, but aircraft maneuvering capabilities were not fully exploited, especially at higher speeds. It was obvious that a vane location that provided a calibration characteristic, which compensated for the variation of permissible maximum angle of attack with Mach number, would provide definite advantages. Several flights consisting of

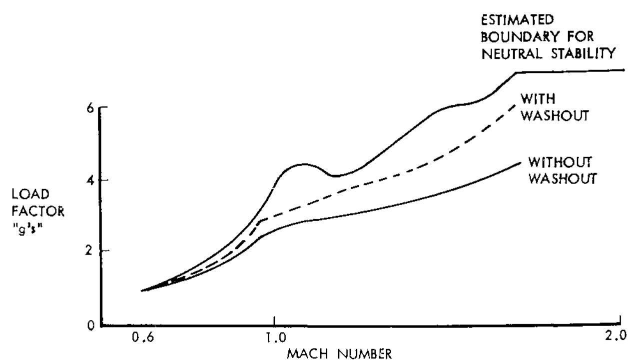

Fig. 12 APC boundary for horizontal turning flight.

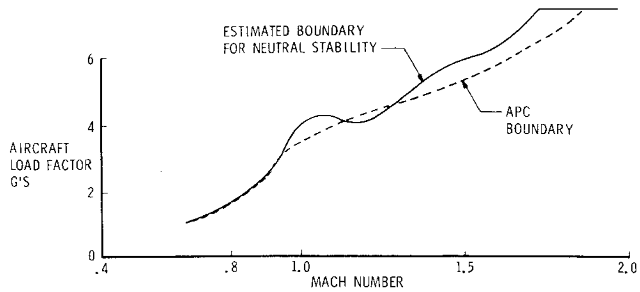

Fig. 13 Estimated boundary for neutral stability.

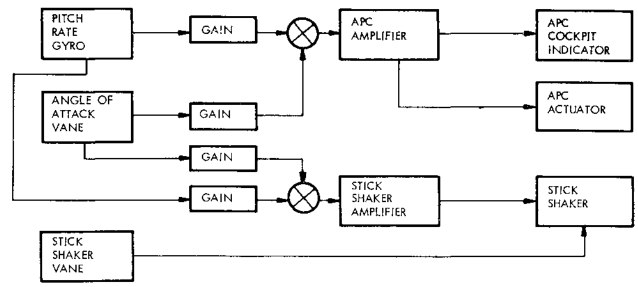

Fig. 14 Final APC system block diagram.

roller-coaster maneuvers were conducted in which various vane locations were calibrated against a boom mounted angle-of-attack vane. A satisfactory location was found and used for all subsequent tests.

At this stage of development, it was felt that, although system reliability and acceptance were excellent, the following problems remained.

1) Restrictions of maneuvering capabilities below that allowed by neutral stability. Tests in turning flight indicated that maneuvering was restricted as indicated by the lower curve of Fig. 12 because of the pitch-rate input to the APC system.

2) The stick-shaker operation was masked in heavy aerodynamic buffet at low (subsonic) airspeeds and did not provide warning of an impending APC action from all entry conditions, including maximum rate pull-ups.

Pitch-Rate Washout

To correct the first of these deficiencies a washout circuit (exponential signal decay) was added to operate on the pitch-rate signal. This served to eliminate the pitch-rate contribution during steady-state turns, and flight tests indicated an improvement in system operation for straight pull-ups as well. The boundary setting was reduced arbitrarily to provide a suitable safety factor for preliminary evaluation. Even with the reduced boundary, results were much improved over the operation without the washout. At this point, the time constant of the washout circuit was optimized. The tests revealed that the washout determined the peak angle of attack reached during the maneuver. The results further indicated that, with a time constant of 0.5 sec, regardless of the stabilizer rate, the peak angle of attack reached was approximately constant. That is, at low rate entries some washout occurred, allowing a higher angle to be reached before stick-pusher operation, whereas at high rate entries no washout occurred, and an earlier actuation prevented excessive overshoot.

The boundary was then raised to be more compatible with the maneuvering capabilities of the aircraft. Tests of this configuration provided essentially complete availability of the maneuvering envelope of the F-104A aircraft as indicated by the middle curve of Fig. 12. Although the steady ($\dot{\theta} = 0$) maneuvering boundary was considered satisfactory, the pilots felt that some increase in the allowable load factor in rapid evasive-type maneuvers would be beneficial. The pitch-rate setting was then increased to provide an additional 0.5-g maneuvering capability as shown in Fig. 13.

Stick-Shaker Development

Development of the stick-shaker warning device was carried out simultaneously with the flight testing of the APC washout circuit. In order to meet the requirements previously set forth, it was necessary to develop a more active stick shaker, which provided unmistakable signals in heavy natural aerodynamic buffet, but which were not objectionable under other flight conditions. The actuation of the stick shaker was added to the functions of the APC system; operation was similar to that of the APC system, but the shaker pitch-rate boundary setting was considerably reduced to increase the warning time before pusher operation for the high-rate pull-up condition. For steady flight conditions, it was found that the stick-shaker boundary could be flown by pulling to the point of intermittent shaker operation, a condition very similar to flying at the point of natural buffet. This proved advantageous by permitting full use of maneuvering capabilities of the airplane without reference to cockpit instruments.

Final APC System

The block diagram of the final APC system is shown in Fig. 14. It should be noted that a cockpit APC indicator is provided. This permits the pilot to check system and sensor operation in flight by noting indicator activity for slow and rapid pull-ups. It is also possible to make in-flight checks of system calibration by proper use of the meter. The indicator may also be used for ground checkout immediately before flight.

The system as installed in F-104 aircraft is isolated, monitored, and guarded insofar as possible against broken wires, disconnected plugs, and other malfunctions. Failures are indicated by warning light operation or by failure to the actuated condition. As a further backup, a separate stick-shaker vane input was provided, which controls the stick shaker directly as a function only of angle of attack through a mechanical switch. This provides a simple, positive backup to the normal system except for lack of pitch anticipation. Reliability in service has been excellent with no known case of malfunction not announced by the warning system, which permitted a fully developed stall to occur.

Summary

The final APC system in the F-104 provides satisfactory warning of the approach to a stall condition and protection from entering a full stall and possible pitch-up. It performs this function with minimal limitation in the aircraft maneuvering capabilities for all conditions of flight. The system operates on preset boundaries of angle of attack and pitch rate to 1) warn the pilot by a stick shaker of an approach to a stall condition, and 2) apply a nose-down force to the control system if corrective action is not taken by the pilot following the stick-shaker warning. Pilot acceptance and confidence in system operation is excellent. Reliability has proven to be excellent with no known case of malfunction, which permitted an inadvertent full-stall condition to occur.