Flight Test of General Electric Self-Adaptive Control

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The General Electric self-adaptive control (GESAC) was flight tested at the Naval Air Test Center in an F-4A aircraft. In addition to three axis self-adaptive control, system features included solid-state gain error integrators in each axis and proportional force maneuvering in the pitch and roll axes. The objective of the program was to achieve essentially invariant dynamic response over the complete flight envelope without use of programed gain changes. The system received a generally high level of pilot acceptance using the Cooper rating sytsem. The system provided basically constant and linear variation of roll rate with lateral control force. Adverse yaw caused by roll was eliminated. The high gain in the roll and yaw stability augmentation loops essentially eliminated aerodynamic coupling between the roll and yaw axes. The aircraft thus appeared to have zero dihedral effect. The pitch axis high gain proportional force maneuvering and automatic trim system relieved the pilot of trim adjustments during takeoff, during configuration changes, rapid accelerations, and bombing runs. It did give the effect of apparent neutral static stability which was considered undesirable during air-to-air combat maneuvers at high altitude and landing approaches. Results of the program will yield future flight control performance improvements.

Introduction

IN February 1964, the Naval Air Test Center and the General Electric Company completed flight test of the GESAC in an F-4A aircraft. The system included three-axis self-adaptive control, solid-state gain error integrators in each axis, and proportional force maneuvering in the pitch and roll axes. The objective of the program was to achieve essentially invariant dynamic response over the complete flight envelope without use of programed gain changes. The flight test program furnished information on flying characteristics of high gain command maneuvering systems which differ from basic aircraft qualities. This paper discusses the changes in airframe handling characteristics with full-time stability augmentation and proportional force maneuvering. Pilot ratings of the system were generally high.

System Description

Pitch Axis

Stability augmentation

A block diagram of the pitch channel is shown in Fig. 1. The stability augmentation in the pitch channel includes pitch rate plus normal acceleration command maneuvering.[1] The command signal originates from the pilot input to the stick force transducer assembly. This signal is compared to the rate and normal acceleration feedbacks. The resultant signal is fed through the gain changer and on to the series actuator servoloop. The series actuator then moves the stabilator through the power actuator. The pilot input to the stick also controls the stabilator through the aircraft manual control system. In operation, the series actuator adds to, or subtracts from, the manual control system as necessary to obtain the desired aircraft response. If the loop gain is sufficiently high, the closed-loop response will be the inverse of the feedback model response. For this reason, the desired response (a frequency of 4 rad/sec with a damping ratio of 0.7) is seen to be in the numerator of the feedback model. The desired response was determined from the plot of acceptable short-period frequencies and damping ratios shown in Fig. 2. Figure 2 was derived from a study by Cornell Aeronautical Laboratory.[2]

The adaptive sensor is used to maintain the loop gain at the highest value consistent with loop stability. An "adaptive" mode of oscillation, having a frequency of approximately 20 rad/sec, is monitored and the gain is adjusted to maintain the damping ratio of this mode at approximately 0.3. The adaptive mode is normally imperceptible to the pilot.

Use of normal acceleration, in addition to rate feedback, allows elimination of air data gain scheduling of the stick force transducer output. The ratio of normal acceleration feedback to rate feedback was

$$3.0\ \frac{\mathrm{v}/g}{\mathrm{v/deg/sec}}$$

This was chosen for two reasons: 1) It gives a satisfactory stick force per g and rate gradient over flight envelope; and 2) Higher ratios of g-to-rate yield a less favorable adaptive mode. It is recommended that lower ratios of g-to-rate be studied, since this will reduce structural feedback problems introduced by large normal accelerometer loop gains.

Automatic trim is provided to keep the series actuator operating around its center position. This permits maximum value of the $\pm 2°$ authority used during this flight test program. This authority is insufficient on some of the larger and more abrupt maneuvers. The automatic trim speed is one-third the manual speed. To prevent stick movement by automatic trim while in a maneuver, it is recommended that, if larger authority is available, automatic trim be made inoperative when pitch stick force exceeds 2.2 lb.

The system has capability of introducing electrical bump commands for general test purposes. This was used as one means of evaluating system operation.

An automatic stability augmentation g disconnect is provided. If the series actuator moves 90% of its authority in the stabilator leading-edge-down direction and $+4g$ is exceeded, stability augmentation will disengage. If the series actuator moves 90% of its authority in the stabilator leading-edge-up direction and $-1g$ is exceeded, stability

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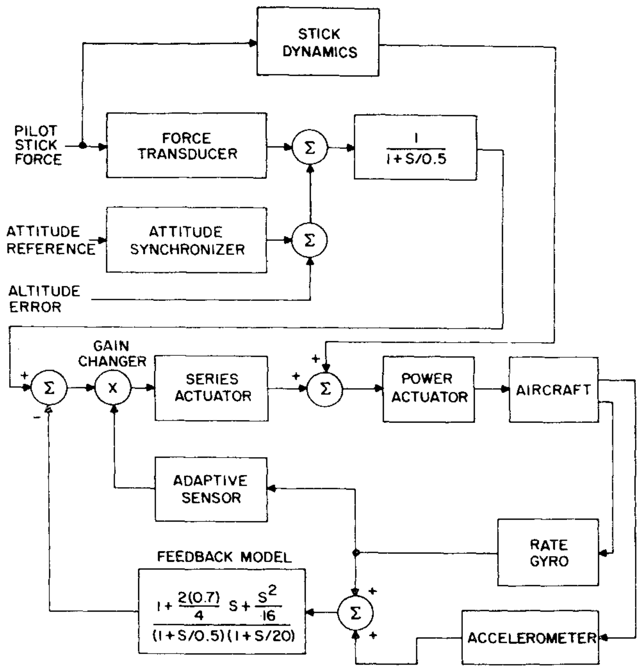

Fig. 1 Pitch channel block diagram.

augmentation will disengage. The g limit accelerometer is mounted in the nose wheel well; therefore, a pitch acceleration factor is included in the measurement.

Attitude hold

Pitch attitude hold is operable up to pitch attitudes of $\pm 70°$, providing roll attitude is under $\pm 70°$. Pitch attitude hold is automatically deactivated when pilot pitch stick force exceeds 2.2 lb, which indicates pilot desire to maneuver the aircraft. When the stick force is decreased below 2.2 lb, pitch attitude hold is automatically re-engaged on the new existing pitch attitude. In the pitch attitude hold mode, an attitude error signal is fed in, as the rate/g command, in place of the stick force transducer output. Automatic trim is provided in this mode. If -1 or $+4g$ is exceeded, the attitude mode will disengage and manual re-engagement is required. This does not drop out stability augmentation unless the added conditions specified in that section also are met.

Altitude hold

Altitude hold is operable up to roll attitudes of 70°. During altitude hold, pitch attitude feedback is used to assist in stabilizing the loop. The altitude error signal is fed into the loop as a rate/g command to maintain the aircraft on the reference altitude. Altitude hold is deactivated by pitch stick force above 2.2 lb, by altitude engage switch, by turning off attitude mode, or by turning off stability augmentation. Automatic trim is provided in this mode.

Roll Axis

Roll channel stability augmentation

The roll stability augmentation control, Fig. 3, includes a rate maneuvering system as an integral part. The command signal originates from the pilot input to the stick force transducer. The signal is compared with the roll rate feedback. The resultant signal is fed through the gain changer, and on to the two series actuator servoloops. The series actuator moves the ailerons and spoilers through power actuators. The pilot input to the stick also controls the ailerons and spoilers through the aircraft manual control system. In operation, the series actuator adds to, or subtracts from, the manual control system as necessary to obtain the desired aircraft response. The desired response is built into the feedback model, and is further shaped by the manual-electrical command relationship. The feedback model consists of a lag circuit, straight-through gain, and canceller.

The series actuator authority is $\pm 7°$ aileron. The electrical command deadband is ± 2.0 lb which matches the manual control system. The system has the capability of introducing electrical bump commands for general test purposes.

Roll attitude hold

Roll attitude hold is operable up to roll attitudes of $\pm 70°$, providing pitch attitude is under $\pm 70°$. Roll attitude hold is automatically deactivated when pilot lateral stick force exceeds 2.0 lb, which indicates pilot desire to maneuver the aircraft in roll. When the lateral stick force is decreased below 2.0 lb, roll attitude is automatically re-engaged on the new pilot anticipated roll attitude. The pilot anticipated roll attitude is computed by feeding roll rate into the roll attitude synchronizing unit. This causes the roll synchronizer to lead the actual roll attitude by a factor proportional to roll rate. This approach also is used in the production F-4 aircraft. Its prime purpose is to prevent roll rebound. Pilot comments indicate that the amount of lead should be reduced for the GESAC application.

Yaw Axis

The yaw channel differs from the pitch and roll channels in that it is a normal damper loop rather than a rate command loop. The primary function of the yaw channel is to provide yaw stability augmentation and side-slip control. For this purpose, yaw rate and lateral acceleration sensor signals are utilized as shown in Fig. 4.

The feedback model approach is used in order to provide a means of tailoring the yaw response. The feedback model is located at 2 rad/sec and a damping factor of 0.7. The lateral acceleration to yaw rate ratio is

$$16.0 \frac{\mathrm{v}/g}{\mathrm{v/deg/sec}}$$

Operational Characteristics

Apparent Neutral Static Longitudinal Stability

Aircraft with neutral static longitudinal stability exhibit no tendency to return to trim conditions following a dis-

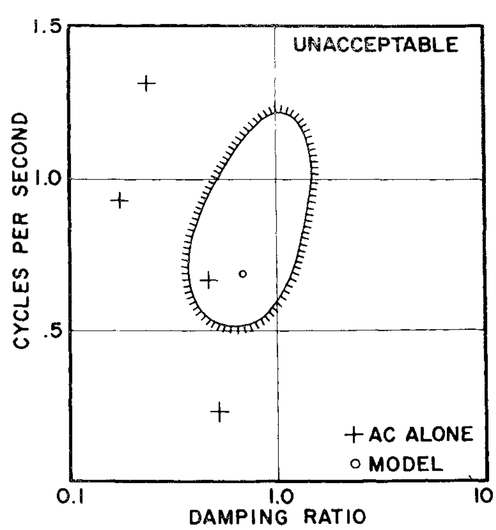

Fig. 2 Acceptable frequency and damping.

turbance or a control input. In addition, excessive response (controllability) may result from control inputs.

A high gain rate/g maneuvering system will maintain nearly zero rate/g in the absence of a command input and will therefore maintain any attitude into which it is maneuvered by the pilot.[3,4] In this respect it appears to have neutral static longitudinal stability. However, the controllability of an aircraft with a high gain rate/g command maneuvering system is determined by the command maneuvering system, and is independent (within control power limitations) of static stability considerations. The attitude of an aircraft with this type of system also is insensitive to disturbances. This characteristic, along with automatic pitch trim, relieves the pilot of the necessity of making trim adjustments. This feature is particularly useful after takeoff, during configuration changes, rapid accelerations, and bombing runs.

However, the effects of apparent neutral static stability were considered undesirable during the performance of air-to-air combat maneuvers at high altitude. Here, the pilot could no longer judge pitch attitude in terms of stick force or use static stability to change the airplane attitude when stick force is relaxed. This lack of attitude and stick force relationship also was found undesirable during the landing approach whenever no external pitch attitude reference was available, or during maneuvers that diverted pilot attention from altitude, airspeed, and pitch control.

The characteristics cited certainly differ from basic airframe handling characteristics. On the other hand, the rate/g command maneuvering improves aircraft response and relieves the pilot of the manual trim task. When optimum response is required, can the pilot adapt to these new handling qualities? The tradeoff should be made carefully since stick command maneuvering does alter some characteristics on which pilots have placed heavy reliance.

Trim Operation

During this program, the pitch trim actuator was used to supplement the series actuator because of the latter's limited authority. This resulted in stick position changes during steady rate commands, such as in a turn. This position change during stick force maneuvering can be eliminated by deactivating trim operation during maneuvers if sufficient series actuator authority is available.

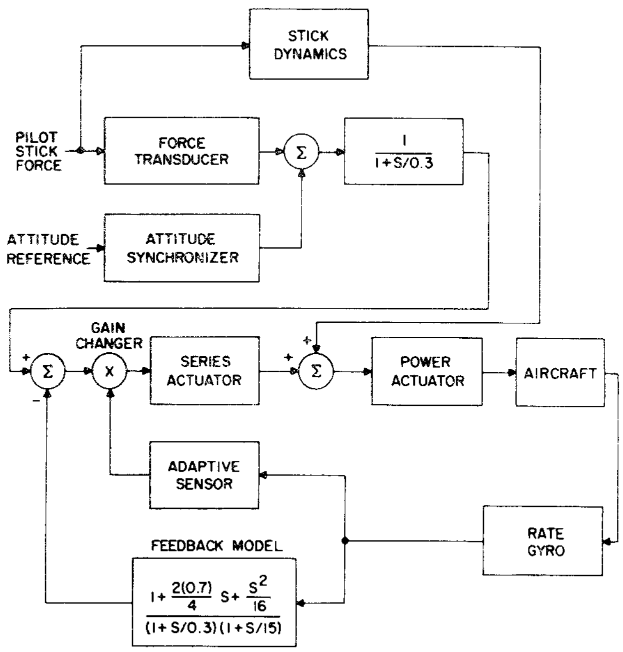

Fig. 3 Roll channel block diagram.

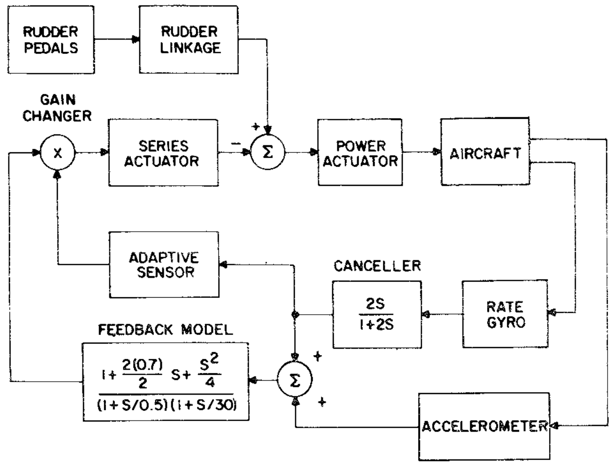

Fig. 4 Yaw channel block diagram.

Trim for Steady-State Turns

The tested system, a rate/g command mechanization, required aft stick force for steady turns except when in attitude hold operation. This aft force requirement was felt more desirable than a mechanization that requires manual trim into the flight control system, even though this is required of the basic aircraft. However, further evaluation of the desirability of providing means of trimming into pitch maneuvers should be made.

Invariant Response

One of the initial goals of the self-adaptive system was to provide invariant response. Although complete invariant response is not obtainable, since this would require infinite open-loop gain, it is possible to obtain response that feels essentially invariant to the pilot. However, pilot opinion indicated some change in transient response is desirable in that change in handling qualities serves as an indication of changing flight conditions. In particular, airspeed can be sensed with fair accuracy during tactical maneuvers and changes in flying qualities are used to warn of impending stall or excessive speed. Invariant response is not necessarily the ultimate in aircraft performance because some variance appears desirable. The prime requirement currently being placed on flight control systems is that performance fall within certain boundaries.

Modification of Aircraft Frequency and Damping

One of the prime features noted in the flight test program was the ability of the GESAC system to control both the apparent aircraft short-period frequency and damping. Desired ranges of frequency and damping have been investigated by means of simulators and variable stability aircraft.[2] For flight conditions with a lower short-period damping and a higher short-period natural frequency than indicated in Fig. 2 as most desirable, increasing the damping and decreasing the frequency resulted in a very significant improvement in pilot opinion.

For flight conditions where both damping and frequency are lower than indicated by Fig. 2 as most desirable, increasing damping and natural frequency improved pilot opinion, but not as much as might be expected. This is believed to be due to the fact that the F-4, as is typical of a high-performance swept-wing aircraft, has a much lower L_α than the F-94 used in the variable stability tests which were the basis of Fig. 2.

The approximate transfer function for pitch rate/stabilizer deflection is

$$\frac{\dot{\theta}}{\delta} = \frac{K_{\dot{\theta}}(1 + S/L_\alpha)}{1 + (2\zeta/\omega_n S + (S^2/\omega_n^2)}$$

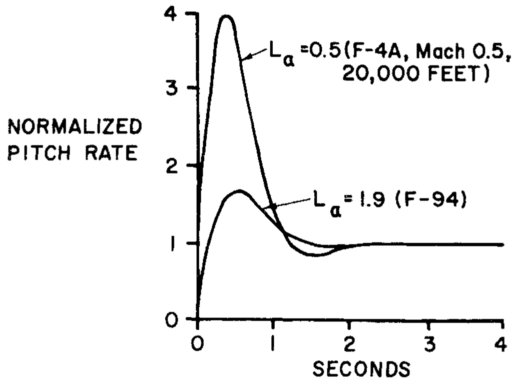

Fig. 5 Effect of L_α on pitch rate response.

The pitch rate response to a step stabilizer input for two different values of L_α is shown in Fig. 5. The short-period damping (ζ = 0.7) and frequency (ω_n = 4 rad/sec) are the same for both curves, and are well within the most desirable area of Fig. 2. As shown in Fig. 5, the pitch rate overshoot for L_α = 0.5 (F-4A, Mach 0.5, 20,000 ft) far exceeds the pitch rate overshoot for L_α = 1.9, which is typical of the F-94 at the velocity used for the variable stability tests. The effect of a large overshoot in pitch rate was called pitch rebound, or drop back, and was most noticeable when making small pitch attitude changes. Upon releasing stick force, the system calls for zero pitch rate and $1g$. The flight control system, in bringing the normal acceleration to the $1g$ level, causes the rate to reverse polarity from that used in the maneuver. This, in turn, causes the attitude to rebound toward the attitude from which the maneuver was initiated. Figure 6 illustrates this effect. The cross-hatched area below the axis in Fig. 6 represents the magnitude of the pitch attitude rebound. The effect is somewhat exaggerated, in Fig. 6, since the response to a step input is shown, and it is not normal practice to make small attitude changes by means of step inputs. However, the rebound can be large enough to be objectionable, even with the smoothing introduced by the pilot. Caution should be exercised in artificially increasing the short-period frequency of aircraft with low L_α in order to meet criteria based on Fig. 2. Report ASD-TDR-63-399 should be consulted for a more complete discussion of the effect of L_α on flying qualities.[5]

Stall Warning and Recovery

The control system reduced the stall warning usually apparent from deteriorating longitudinal and lateral flying qualities. This was not considered objectionable to the pilot, since adequate artificial warning was provided. It does illustrate that the control system improves performance up to stall warning area. It also points out the desirability of adequate artificial warning.

In the pitch axis, the characteristic nose drop at stall was less than that of the basic aircraft. The high lateral gain delayed the onset of wing rock oscillations normally experienced during approach to stall. Essentially, no wing rock occurs until the lateral series actuators reach the limit of their authority. After this occurs, nonlinear damping gives jerky roll motion. Prior to this, the artificial stall warning was present and, normally, this flight area should not be entered.

In a stall, correction of a wing drop should be accomplished by use of the rudder. Use of the aileron to pick up a wing is likely to cause a spin. Since the roll channel of the automatic flight control system (AFCS) controls only the ailerons and spoilers, stall recoveries were made with the flight control system off to avoid possible undesirable control surface movement as a result of the rate command and stability augmentation system. From the operational standpoint, it would be desirable if it were not a requirement to disengage stability augmentation. A possible solution to this problem would be to fade out the roll authority near stall angle of attack and/or displace the rudder as a function of roll error.

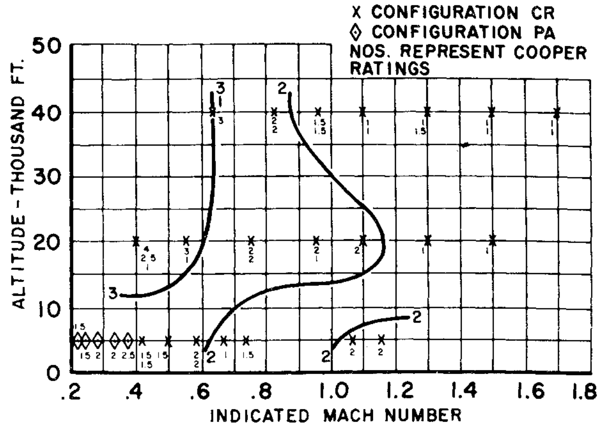

Fig. 7 Qualitative pitch response.

Dihedral

The high gain in the roll and yaw rate stability augmentation loops essentially eliminates aerodynamic coupling between the roll and yaw axes. The high roll gain removed all roll caused by yaw. The aircraft thus appeared to have zero dihedral effect. Operation of the rudder did not give any roll attitude change as experienced on the basic aircraft. This effect eliminated the use of the rudder in banking the aircraft during landing. If roll attitude changes are desired, they must be made with lateral stick force. An appropriate dihedral effect can be introduced by electrical coupling between the yaw and roll channels, if desired.

Adverse Yaw

The yaw channel mechanization eliminated adverse yaw caused by roll. Full lateral control reversals, with

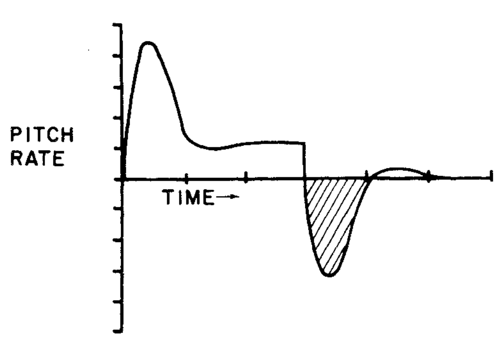

Fig. 6 Pitch rebound.

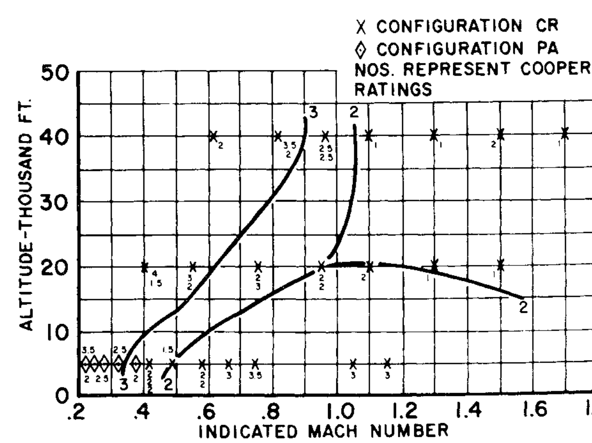

Fig. 8 Qualitative roll response.

Table 1 Cooper ratings

Operating conditions	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[a]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[a]	No	Doubtful
		8	Unacceptable—dangerous	No	No
		9	Unacceptable—uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[a] Failure of stability augmentor.

rudder free, were made without producing discernable amount of adverse yaw. This produced one of the best lateral-directional flying qualities ever experienced by the test pilots.

Steady-State Sideslip

Steady-state sideslip could be performed with rudder deflection. As mentioned previously, operation of the rudder does not give a roll attitude change. Thus, no lateral stick force is required for steady-state side slips.

Stick Force to Roll Rate Gradient

The rate command as mechanized in Fig. 3 provided essentially constant lateral control effectiveness over the complete flight regime. This existence of basically constant and linear variation of roll rate with lateral control force was given an excellent rating by the flight evaluation team. If the roll response to a basic airframe needs improvement, a roll rate command augmentation system is recommended.

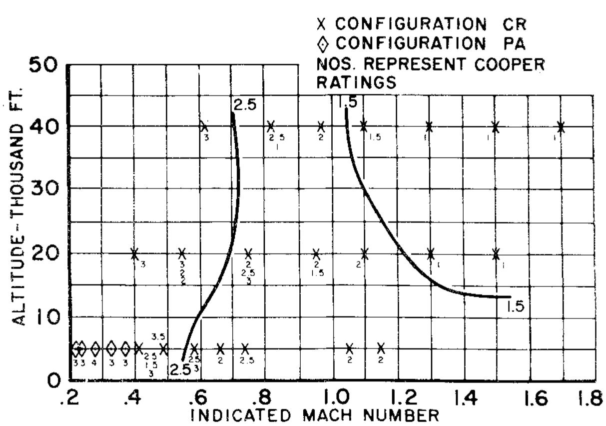

Fig. 9 Qualitative yaw response.

Conclusions

The over-all qualitative evaluation of the system described in this paper was very good. This is illustrated by the pilot qualitative ratings shown in Fig. 7–9 for the pitch, roll, and yaw axes, respectively. The ratings were based on the Cooper rating system, which is described in Table 1. The three figures show Cooper ratings as a function of altitude and indicated Mach number. Lines of constant Cooper rating are drawn to relate flight area where performance fell into the various Cooper rating levels. Although flying qualities were altered as described, the generally high level of ratings obtained indicates that the control system tested has features considered desirable by the pilot. These features can be used to design improved flight control systems for current and future applications.

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