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EFFECTS OF A SIMPLE STABILITY AUGMENTATION SYSTEM ON THE PERFORMANCE OF NON-INSTRUMENT-QUALIFIED LIGHT-AIRCRAFT PILOTS DURING INSTRUMENT FLIGHT

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

Many general aviation accidents are attributed to loss of control or disorientation of the non-instrument-rated pilot during an attempt to fly in instrument conditions. Simple low-cost wing-leveling systems are available which show promise of affording a measure of safety in this situation. A flight investigation has been conducted to evaluate the performance characteristics of one such system, and its effect on the capability of the non-instrument-rated pilot to maintain flight during instrument conditions.

Experienced research pilots evaluated a mechanical-pneumatic rate-gyro-controlled lateral stability augmentation system installed in a retractable gear, low-wing, personal-owner aircraft. The effects of various tilt angles of the gyro-spin-axis on system characteristics were investigated. The system was found to be capable of maintaining the aircraft in wings-level flight and on a relatively constant heading. Roll recovery after a disturbance was found to be acceptable; however, a slightly higher roll rate to match the pilot's normal rate during visual flying was desired. Results indicate that a simple pneumatic system will provide acceptable roll-recovery characteristics, with a proper gyro tilt angle. The system was adjudged to be a benefit to the pilot during either visual or instrument cross-country flying.

Non-instrument-rated private pilots were not able to operate the basic aircraft (without lateral-stability augmentation) in instrument conditions, and also to perform limited navigation. With the aid of the lateral-stability augmentation system, the non-instrument-rated pilot was capable of sustained instrument flight and limited radio navigation. Flight could be performed in a sufficiently safe manner to permit recovery to visual flight conditions from an inadvertent instrument situation.

INTRODUCTION

A major factor in general aviation accidents apparently lies in the encounter of instrument flying weather by the non-instrument-flight-qualified pilot. An analysis of

accident statistics available in references 1 and 2 indicates that weather is a contributing factor in approximately 25 percent of all in-flight accidents. Reference 3 shows that 85 percent of all general aviation pilots are not qualified for instrument flight.

The specific problem facing the non-instrument-qualified pilot who has disregarded or failed to comprehend available weather information and is forced to attempt instrument flight is to maintain a wings-level attitude or a steady turn at a controlled altitude to navigate to an area clear of clouds. Although most light aircraft manufactured today are equipped with suitable flight instrumentation and navigation equipment to permit at least limited instrument flight, considerable training and experience are necessary to interpret these instruments properly and to maintain orientation and aircraft control. This task is made even more difficult by the tendency of the aircraft to enter a descending spiral if subject to a lateral out-of-trim condition. This out-of-trim condition is almost always present because of aerodynamic or loading asymmetry, power changes, or control friction. The non-instrument-qualified pilot attempting instrument flight will then most probably enter a descending spiral as demonstrated in the simulator study reported in reference 4. Because of a lack of instrument flying skill, the pilot may not be able to recover properly from this spiral prior to ground impact or may cause in-flight structural failure of the aircraft by incorrect recovery procedures.

The problem of preventing this loss of aircraft control has been attacked by seeking mechanical means of inhibiting the spiral tendency through the use of simple, low-cost systems designed to maintain the aircraft in wings-level flight, or to return the aircraft to the wings-level flight when disturbed. Several experimental systems have been studied and are reported in references 5 and 6. More recently, a number of wing-leveling systems have become commercially available. This paper presents the results of an evaluation of one such system, and the effect of this system on the instrument flight performance of the non-instrument-qualified pilot.

SYMBOLS

Quantities given in brackets are values of respective coefficients estimated (measured in the case of K_F and K_S) for the test airplane and used in computations of airplane motion characteristics. Quantities in terms of International System of units (SI) are shown in parentheses where appropriate.

b   wing span

C_L lift coefficient, $\dfrac{\text{Lift}}{qS}$

C_l rolling-moment coefficient, $\dfrac{\text{Rolling moment}}{qSb}$

C_{l_p} variation of rolling-moment coefficient with rolling angular-velocity factor, $\dfrac{\partial C_l}{\partial \frac{pb}{2V}}$, $\left[-0.50 \text{ second/radian}\right]$

C_{l_r} variation of rolling-moment coefficient with yawing angular-velocity factor, $\dfrac{\partial C_l}{\partial \frac{rb}{2V}}$, $\left[0.278 C_L \text{ second/radian}\right]$

$C_{l_{\delta_a}}$ variation of rolling-moment coefficient with aileron deflection, $\dfrac{\partial C_l}{\partial \delta_a}$, $\left[-0.103/\text{radian}\right]$

D operator, $\dfrac{d}{dt}$

F aileron control force

g acceleration due to gravity

K_S stabilization system gain, $\dfrac{\partial F}{\partial \omega_g}$, $\left[260 \text{ lb-sec (1157 Newtons-second)}\right]$

K_F inverse of control-force gradient with aileron deflection, $q\dfrac{\partial \delta_a}{\partial F}$, $\left[0.796 \text{ radian/square foot (8.57 radians/meter}^2)\right]$

K_x ratio of radius of gyration about X-axis to span, $\left[0.10\right]$

p rolling velocity, radians/second

q dynamic pressure, $\frac{1}{2}\rho V^2$

r yawing velocity, radians/second

S wing area

t time, second

V indicated airspeed (IAS)

α angle of attack of longitudinal reference axis of airplane, radians

δ_a total aileron deflection

θ_g tilt angle of spin axis of rate gyro relative to longitudinal reference axis in airplane, radians

ω_g angular velocity sensed by gyro, radians/second

τ time constant of stabilization system, second

μ airplane relative-density coefficient, $\dfrac{\text{Mass}}{\rho Sb}$, [6.1]

ρ air density

ϕ angle of roll, radians

ψ angle of yaw or heading change, radians

TEST VEHICLE, LATERAL STABILITY AUGMENTATION SYSTEM, AND INSTRUMENTATION

Test Vehicle

The test vehicle was a typical modern single-engine personal-owner aircraft. Test aircraft specifications are shown in table I. Aileron and rudder control surfaces

TABLE I.- TEST AIRCRAFT SPECIFICATIONS

Wing span	35.0 ft (10.7 m)
Length	23.2 ft (7.1 m)
Height	8.4 ft (2.6 m)
Wing area	167 sq ft (15.5 m^2)
Wing loading	15.4 lb/sq ft (737.4 N/m^2)
Aspect ratio	7.34
Wing taper ratio	0.51
Aileron span	0.3b/2
Aileron area	11.1 sq ft (1.03 m^2)
Passenger and crew capacity	4
Maximum gross weight	2575 lb (11 454 N)

were fitted with a ground adjustable fixed tab for trimming at a selected flight condition. These fixed tabs were adjusted by the manufacturer prior to the evaluation. In-flight adjustment of longitudinal trim was provided. With the lateral stability system in operation, a small degree of lateral trimming was available by vacuum bleed through the system.

Lateral Stability Augmentation System

The lateral stability augmentation system incorporated in the test aircraft is shown schematically in figure 1. The system is entirely mechanical-pneumatic, power for system control and actuation being supplied by the engine-driven vacuum pump which is provided on almost all current light aircraft for operation of the attitude and directional gyro flight instruments. A simple rate gyro, which is normally tilted forward 35° in a commercial installation but which can be tilted to other angles, is used as the sensing element. The precession force of the gyro in response to rolling and yawing motions is applied mechanically to a valve mounted in the gyro assembly. This valve controls vacuum application to four control-surface bellows-type vacuum servos. Surface movement is then provided by these servos which are attached directly to aileron bell cranks and rudder pushrods. Altitude effects were found to be negligible over the normal operating range of the aircraft, as the vacuum system provided a constant operating pressure differential. The system can be overpowered by the pilot by applying wheel forces in excess of those developed by the servos or temporarily disengaged by a hold-down button on the pilot's control wheel.

A theoretical analysis of the effect of system lag and of the angle of tilt of the gyro axis on aircraft performance is presented in the appendix.

Instrumentation

Sufficient flight and navigation instruments were available to meet the instrument flight requirements of instrument-qualified pilots. These instruments are an attitude gyro (artificial horizon), directional gyro (compass), airspeed indicator, altimeter, vertical speed (rate of climb) indicator, turn and bank indicator, omnirange navigation course indicator, clock, navigation radio, and communications radio. (See fig. 2.)

NASA recording instrumentation was installed in the aircraft to record normal flying qualities parameters. Indicating instruments were installed to allow observation of system performance parameters. A NASA recording package and film recorder were used to record aircraft flight parameters as follows:

Airspeed   Longitudinal acceleration
Altitude   Aileron position
Roll angular rate   Rudder position
Yaw angular rate   Elevator position
Pitch angular rate   Stabilizer trim position
Normal acceleration   Time
Transverse acceleration

Indicating instruments were installed to permit the following information to be recorded:
control gyro rotor vacuum, control servo actuating vacuum, and normal acceleration.

TESTS

The flight evaluation consisted of two phases. During the first phase, experienced research pilots evaluated the performance and force characteristics of the lateral-stability system. Tests were performed at a pressure altitude of 5000 feet at indicated airspeed (approach and cruising speeds, respectively) of 78 and 135 knots for values of the tilt angle of the gyro axis of 0°, 15°, 35°, 55°, and 90°. Some of the tests were made by placing the aircraft in a constant-altitude 30° banked turn, releasing the controls, and recording a return to wings-level condition or a spiral divergence. The effect on system performance of operating as a single axis (aileron only) system was investigated by disconnecting the rudder control servos. Research pilots also evaluated the desirability of the system during instrument flight by flying the aircraft during simulated instrument flight in cruising, descent, and instrument landing approach (ILS) conditions. Simulated instrument conditions were obtained with the standard blue-orange filter system.

The second phase consisted of the evaluation of the instrument flight performance of two private pilots who were not qualified for instrument flight. Each pilot had approximately 250 hours of visual flight time, each owned his own aircraft, and each was actively engaged in cross-country flying. These pilots had no previous formal instrument training, but each displayed some knowledge of proper instrument flight techniques during preflight briefings. After a short period of visual familiarization flying, the pilots were subjected to simulated instrument conditions. Three tasks were attempted which are considered to be appropriate for the inexperienced instrument pilot inadvertently flying into instrument weather. The first task was the 180° turn followed by 2 minutes of straight and level flight; this task represented the procedure to return the aircraft to visual conditions. The second task was a descent through a simulated overcast from visual conditions above to visual conditions below. The third task represented an attempt to continue a cross-country flight after encountering instrument conditions; this task required radio navigation and communication. All flights during this phase were made with a gyro tilt angle of 35° and two-axis augmentation.

RESULTS AND DISCUSSION

Lateral-Stability-System Performance

Roll recovery.- The motion of the aircraft after the control release during a constant-altitude 30° banked turn at cruise airspeed is shown in figure 3. The basic aircraft, as illustrated by the upper curve, entered a steepening spiral. This increasing bank was caused by a lateral out-of-trim condition. In a period of 10 seconds from control release, the bank angle reached 38°, and the heading was approximately 50° from that at the time of control release. Figure 3 also shows the recovery from a similar turn under manual control of the pilot. As may be seen, the aircraft was returned to wings-level altitude in 8 seconds.

With the lateral-stability system operating, the wings were returned to the level condition in 10.5 seconds with a 14° change in heading. This performance was obtained with the commercially available system, which has a gyro tilt angle of 35°, and two-axis (roll and yaw) control. The return to wings-level condition provided by the stabilization system was somewhat slower than when the pilot controlled and was considered to be moderately sluggish (for visual flight) by research pilots. As an aid to the instrument pilot, this return rate is adequate.

Gyro axis tilt.- Roll rates and damping produced by the system can be altered by changing the tilt angle of the gyro spin axis. The gyro is tilted as shown in figure 1 in order to sense both yaw and roll rates. As discussed in the appendix, the tilting of the gyro axis counteracts the destabilizing effect of the lag of the low pressure pneumatic system. The results of roll-recovery tests made with gyro tilt angles of 0°, 35°, and 55° are shown in figure 4. Calculated aircraft motions, as computed in the appendix, for 0° and 35° tilt angles are shown in figure 5. The calculations show reasonable agreement with flight data and indicate similar trends. Theoretical results (fig. 6) indicate that a gyro angle of approximately 21° at the approach and cruise speeds of the test aircraft will result in critical damping. Computations of figure 6 indicate that a 14° gyro tilt angle will result in a damping ratio of 0.7 which has been found to be optimum in some systems. For the 15° gyro tilt angle used in the flight-test system, performance was improved in the cruise condition by a more rapid roll response with little or no noticeable bank angle overshoot or oscillation. In the approach condition, however, the performance was rated as unsatisfactory inasmuch as it resulted in a residual, neutrally damped roll oscillation.

Control forces.- The control forces developed by the system are applied directly to the control linkage and therefore to the pilot's wheel. To accomplish a steady turn with the lateral-stability system operating, the pilot must oppose the restoring forces of the system. As indicated in figure 7, the forces developed were a function of turning

rate and therefore bank angle in a steady turn. These forces are average forces, as trimming bleed vacuum is also applied through the same servos, which, if being used, will bias the force. Although these forces are unnatural to the experienced pilot, they were considered to be acceptable although slightly high. This relationship between control force and bank angle will be discussed further in respect to the instrument flight performance of the non-instrument-qualified pilot.

Control-system friction.- Control-system friction will prevent a control surface from returning to a trimmed (zero force) position after a system- or pilot-caused deflection. Low control-system friction is a requirement for small heading drift rates with a system which produces forces in proportion to the rate sensed.

On the ground, the test aircraft had static friction breakout forces of 9 inch-pounds (1.02 m-N) of wheel force. This friction had a negligible effect in flight when aerodynamic turbulence and aircraft vibration were present. Heading drift rate was less than 2^O per minute in smooth or turbulent air with a 35° gyro tilt angle.

Single-axis tests.- The lateral-stability system evaluated provided control inputs to both the ailerons and the rudder. During some tests the aircraft was flown with a single-axis system $\theta_g = 15^O$, 35°, and 55° by disconnecting the rudder servos. Roll-recovery performance was unchanged from that of the complete system. The most noticeable degradation of performance was the inability of the system to damp Dutch roll oscillations at low speed in the approach configuration. The research pilots considered these flight characteristics to be undesirable; however, the basic safety aspect of the system, the capability of maintaining the aircraft in wings-level flight, was not affected. At high speeds the absence of rudder inputs was not noticed.

Instrument flight.- Experienced research pilots found the stabilization system to be beneficial during both visual and instrument cross-country flying. The aircraft maintained heading within acceptable limits with no pilot attention during flight in smooth or turbulent air and greatly reduced pilot workload. Instrument approaches to a landing also proved the system to be desirable in that the aircraft would maintain a heading with less pilot effort. The fact that maneuvering forces were higher than without the system was more than compensated for by the fewer control movements required.

Performance of Non-Instrument-Qualified Pilot

During Instrument Flight

Turns.- The non-instrument-qualified pilot inadvertently entering instrument flight conditions should immediately return to an area clear of clouds. To duplicate this situation, the initial maneuver attempted by each pilot was a level 180° turn followed by 2 minutes of straight and level flight. The bank angle which will result in a standard-rate turn

(3° per second) at the cruise airspeed of the evaluation aircraft was 20°. This bank angle should not have been exceeded by the evaluation pilot because of the increased difficulty of maneuvering at steeper bank angles. The turn and bank indicator, a familiar instrument to the non-instrument-qualified pilot, was available to indicate this proper rate of turn. The first attempts at this turn, both with and without the stability system operating, resulted in bank angles as high as 65°, altitude changes exceeding 1000 feet, and airspeed variations which had to be controlled by the safety pilot to prevent structural damage to the aircraft or to prevent a stall. After several practice turns, the average bank angle used with the system inoperative was 35°. This steep bank angle resulted in higher than desired turning rates and high pitch sensitivity to small elevator-control-force changes. Planned 180° turns often resulted in 90° to 360° turns as the pilot was forced to concentrate on bank angle or altitude corrections. Airspeed and altitude variations could be controlled by the pilot within tolerable limits.

With the stability system operating, the average bank angle used by the pilot, after several practice turns, was 15° to 20°. This improved control of bank angle was due to the stability system opposing the pilot's attempts to overcontrol, and also to the fact that the pilot quickly recognized that the wheel force exerted by the stabilization system was related to bank angle and hence could be used as a cue to obtain the proper bank angle. The wheel-restoring force developed by the system during a steady turn is illustrated in figure 7. The bank angle was easily obtained, easy to maintain, and was repeatable. The slower turn rate resulted in most turns being completed within 10° of the desired heading, and a large reduction in altitude and airspeed variations.

Apart from the stabilizing effect of the system, the control wheel force in a steady turn, as illustrated in figure 7, was a necessary aid for the non-instrument-qualified pilot. This force provided: (1) a force gradient in the control system for the pilot to hold against in a steady turn and thus prevented overcontrolling, (2) an additional attitude sense to the pilot who quickly realized that wheel force and bank angle were related, and (3) assurance to the pilot that he could recover to wings-level flight whenever desired by releasing the controls.

Straight and level flight.- Straight and level flight, with the stability system inoperative, required complete pilot attention to attitude control. The pilot was unable to attend adequately to navigation or communications tasks. Any distraction from attitude control usually resulted in turning and climbing or descending flight. Each deviation from the desired flight path required the pilot to level the wings to stop the heading change, to make pitch adjustments to stop the altitude change, to estimate the correction necessary to return the aircraft to the desired flight path, and to initiate the correction. Because of the pilot's lack of ability to judge the required correction properly and to perform it with precision, a continuous series of corrections was required.

In descents through an overcast, control difficulties experienced with the system off were similar to those experienced in straight and level flight. With the system on, descent presented little problem inasmuch as pilot attention could be focused on (pitch) control of altitude and airspeed.

Pilot workload.- The primary difference between system off and on flight was pilot workload. With the system on, straight and level flight presented few problems. Heading was maintained by the system; thus, the largest workload item was removed. The pilot could concentrate on control of the pitch attitude and properly trim the aircraft for flight. Navigation, communication, engine operation, and flight-path corrections could receive more pilot attention and be performed more effectively.

Navigation.- The pilot who elects to continue a cross-country flight into an area of instrument conditions must navigate by radio or radar information. The ground track of a cross-country flight in actual instrument weather, flown by a non-instrument-qualified pilot with a safety pilot, is shown in figure 8. The task was to follow designated omnirange airways and ground radar vectoring along the course depicted by the dashed line. The pilot had preplanned the flight and therefore was at an advantage over the pilot who might inadvertently enter instrument weather while navigating by landmarks.

During the initial portion of the flight, from A to D, the stability system was engaged. After level-off, the point-to-point ground speed was 147 knots. During this part of the flight, the pilot became progressively more relaxed and confident. Longitudinal pitch trim was concentrated on and stabilized; the pilot was unconsciously controlling the aircraft with light finger-tip pressure on the control wheel; and was maintaining altitude within 100 feet of the assigned altitude. Deviations from course occurred slowly and could be easily recognized, studied, and corrected. An awareness of flight progress was maintained by frequent map reference. The pilot would disregard aircraft control for as much as 45 seconds to accomplish navigation tasks, little heading or altitude change occurring. Radio stations were tuned and identified, and the proper cross-bearing for airway interceptions at points C and D were obtained.

After the turn at point D the stability system was turned off. During the portion of the flight from point D to omnirange station F, the only required pilot task was to follow an airway as had been done on the previous portion of the flight. No additional requirement of radio tuning or map reference existed. The correction to the airway following the turn at D required a distraction from attitude control, during which the pilot allowed the aircraft to enter a turn away from the desired track. A series of corrective turns followed as the pilot attempted to establish the aircraft on the airway. During this part of the flight, the safety pilot was required to intervene to prevent altitude excursions from exceeding 500 feet from the assigned altitude to comply with instrument traffic restrictions. The control and navigation workload quickly exceeded the non-instrument-pilots'

capability. Simple and familiar tasks, such as throttle adjustment, were performed hurriedly, which often resulted in errors that required further attention. The pilot became less attentive to radio communications and would respond to only one-half of the radio transmissions directed to the flight. On one occasion, the distraction caused by radio instructions to turn 70° resulted in a turn of 140° in the opposite direction.

The constantly turning flight resulted in progress along the flight path being reduced from 147 knots to 88 knots. The pilot was unable to maintain an awareness of ground position or progress. At point E, the pilot was asked to estimate his position. By map reference and omnibearings, he erroneously estimated his position at E', and would have attempted to fly a heading away from the station had he not been corrected. On a previous flight, with the system operating, the pilot had tended to make a similar error. With more time to study the problem, because of attitude stability of the aircraft, he immediately realized and corrected this error. The pilot was not aware that he had completed a circle at point E while attempting to estimate his position.

The stability system was returned to operation as it passed the radio station at point F. The pilot was then able to follow ground radar guidance information accurately. Attention to radio communications or throttle adjustments caused no problems. An instrument descent and ground-controlled radar approach (GCA) were performed at the destination airport even though the pilot was unfamiliar with instrument approach procedures.

CONCLUSIONS

A flight investigation has been conducted to determine the effect of a simple lateral-directional stability-augmentation device on the instrument flight performance of a non-instrument-rated pilot. The system was first evaluated by research pilots to determine the basic flight characteristics. On the basis of this investigation, the following conclusions can be made:

1. A simple wing-leveling system affords the non-instrument-rated pilot the attitude stability necessary to allow him to maintain control and successfully cope with an inadvertent instrument flight situation.

2. The wheel force provided by the system as a function of bank angle is a definite aid to the inexperienced instrument pilot during instrument flight.

3. The wing-leveling system affords relief to the pilot while flying visually or during instrument weather by maintaining the aircraft in a wings-level attitude without pilot attention.

4. Roll rates produced by the stability-augmenting system during recovery from turns should approximate those considered to be comfortable during visual flights.

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   National Aeronautics and Space Administration,
      Langley Station, Hampton, Va., July 21, 1966,
         126-16-02-06-23.

APPENDIX

ANALYSIS OF AIRCRAFT LATERAL MOTION CHARACTERISTICS
WITH A SIMPLE STABILIZATION SYSTEM

The function of a system of this type is to sense turning rate and apply aileron and rudder to null this rate. A limited theoretical analysis of system operation was undertaken to gain some insight into the factors which influence system performance.

It appears from the character of the system that the transfer function (the time relationship between sensed aircraft motion and opposing control movement) can be approximated by a first-order equation. When the equations of motion of the stabilized aircraft were derived, it was assumed that the motion consisted only of coordinated level turning and banking flight with no sideslip. Short-period modes were ignored in view of the relatively long period of the motion of interest. The stabilization system was assumed to act only through the ailerons. The dynamics of the basic control system were neglected. The motion of the aircraft can then be described by the equations:

$$\left(D^2 - aD\right)\phi - h\frac{V}{g}D\psi - c\delta_a = 0 \tag{A1}$$

where

$$a = \frac{1}{4}C_{l_p}\frac{V/b}{\mu K_x^2}$$

$$h = \frac{1}{2}\frac{C_{l_r}}{C_L}\frac{(g/V)^2}{K_x^2}$$

$$c = \frac{1}{2}C_{l_{\delta_a}}\frac{(V/b)^2}{\mu K_x^2}$$

For the type of motion considered (that is, no sideslip and moderate ϕ) ψ and ϕ are related by

$$D\psi = \frac{g}{V}\phi \tag{A2}$$

APPENDIX

The aileron deflection δ_a was related to the control force F by

$$\delta_a = - \frac{K_F}{\frac{\rho}{2} V^2} F \tag{A3}$$

By its nature, the simple pneumatic stabilization system provides a substantial time lag between the sensing of an angular velocity by the gyro and the application of control force. It is assumed that the effect of this lag in the action of the system can be approximated by the transfer function

$$F = \frac{K_S \omega_g}{1 + \tau D} \tag{A4}$$

It appears that some lag in the reaction of the system is probably desirable to avoid the possibility of degrading the short-period lateral motion characteristics of the airplane. The time constant τ for the present system was not determined directly but was estimated to be about 4 seconds.

The lag in the system, as represented by τ, has a destabilizing effect on the motion, which can be counteracted by tilting the gyro axis so that the gyro senses a component of rolling velocity as well as that of the turning velocity. The angular velocity sensed by the gyro ω_g is then

$$\omega_g = \cos\left(\theta_g + \alpha\right)D\psi + \sin\left(\theta_g + \alpha\right)D\phi \tag{A5}$$

Equation (A1) then becomes, upon substitution of equations (A2) to (A5),

$$\left[D^3 + \left(\frac{1}{\tau} - a\right)D^2 + \left(-h - \frac{a}{\tau} - \frac{e}{\tau}\right)D + \left(-\frac{h}{\tau} - \frac{f}{\tau}\right)\right]\phi = 0 \tag{A6}$$

where

$$e = \frac{C_{l_{\delta_a}} K_F K_S}{\rho b^2 \mu K_x^2} \sin\left(\theta_g + \alpha\right)$$

$$f = \frac{C_{l_{\delta_a}} K_F K_S}{\rho b^2 \mu K_x^2} \frac{g}{V} \cos\left(\theta_g + \alpha\right)$$

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APPENDIX

Solution of equation (A6) yields one large root λ_1, which represents a rapid subsidence and hence is of little concern, and a pair of roots λ_2 and λ_3 which describe the primary characteristics of the motion.

If

$$A = \frac{1}{\tau} - a$$

$$B = -h - \frac{a}{\tau} - \frac{e}{\tau}$$

$$C = -\frac{h}{\tau} - \frac{f}{\tau}$$

the roots of the equation can be determined closely enough for conditions of interest as

$$\left. \begin{aligned} \lambda_1 &= \frac{A}{2}\left[1 + \sqrt{1 - 4\left(\frac{B}{A^2} - \frac{C}{A^3}\right)}\right] \\ \lambda_2\lambda_3 &= \frac{C}{\lambda_1} \\ \lambda_2 + \lambda_3 &= \frac{B}{\lambda_1} - \frac{\lambda_2\lambda_3}{\lambda_1} \end{aligned} \right\} \tag{A7}$$

The damping ratio ξ is then determined from

$$\xi = \frac{1}{2}\frac{\lambda_2 + \lambda_3}{\sqrt{\lambda_2\lambda_3}} \tag{A8}$$

The gyro tilt angle θ_g required for a desired damping ratio is then determined by substituting varying tilt angles in the coefficients B and C, computing the corresponding values of ξ, and plotting these values against θ_g. These computations have been made for two airspeeds and two values of τ, by using the coefficient values given in the section "Symbols," and the results are shown in figure 3.

The lateral motions of the airplane in hands-off recovery from a turn were computed, by using equation (A6), with gyro tilt angles of 0° and 35° for comparison with flight-test measurements. These results are given in figure 6.

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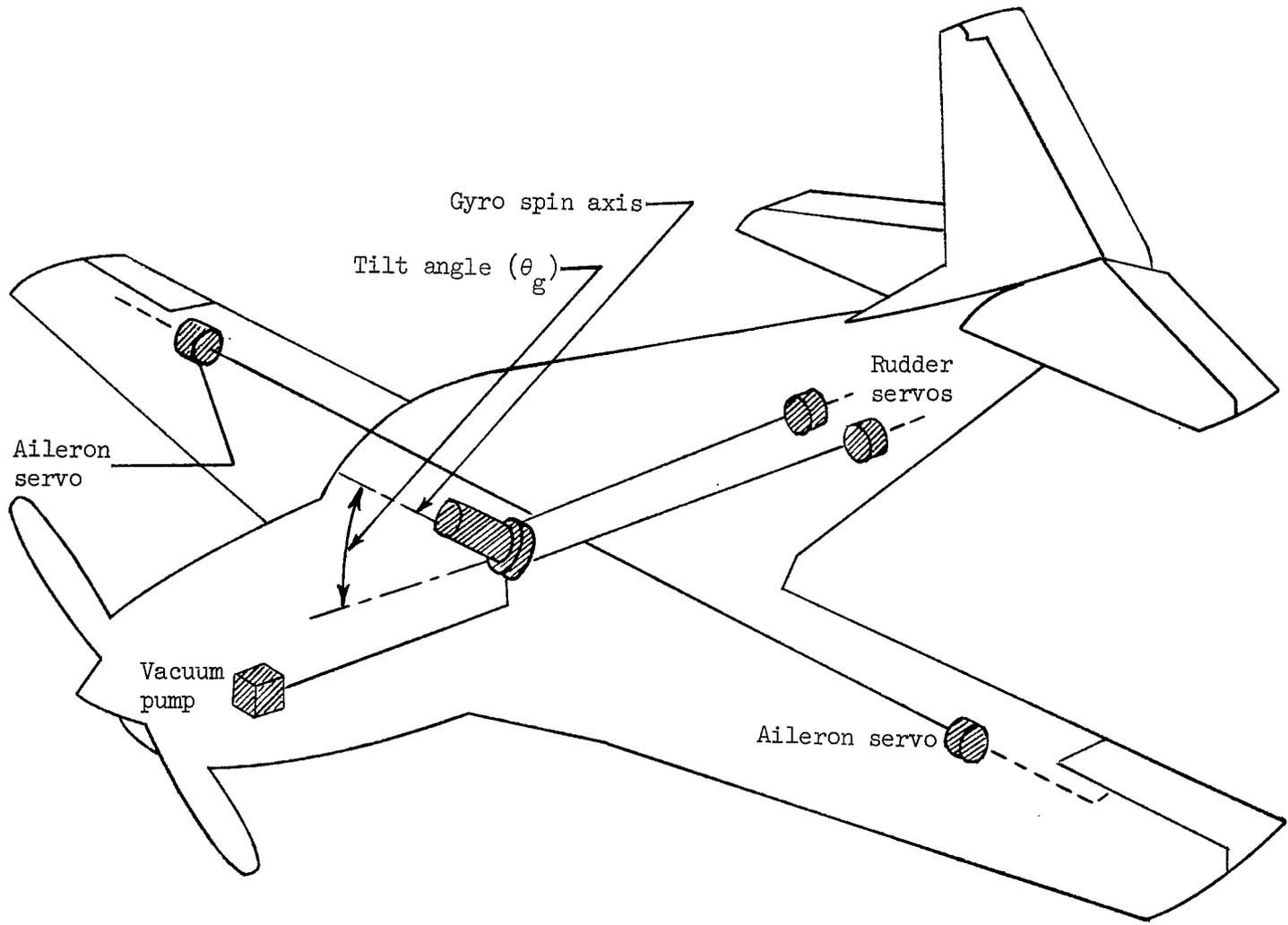
Figure 1.- Lateral stability augmentation system.
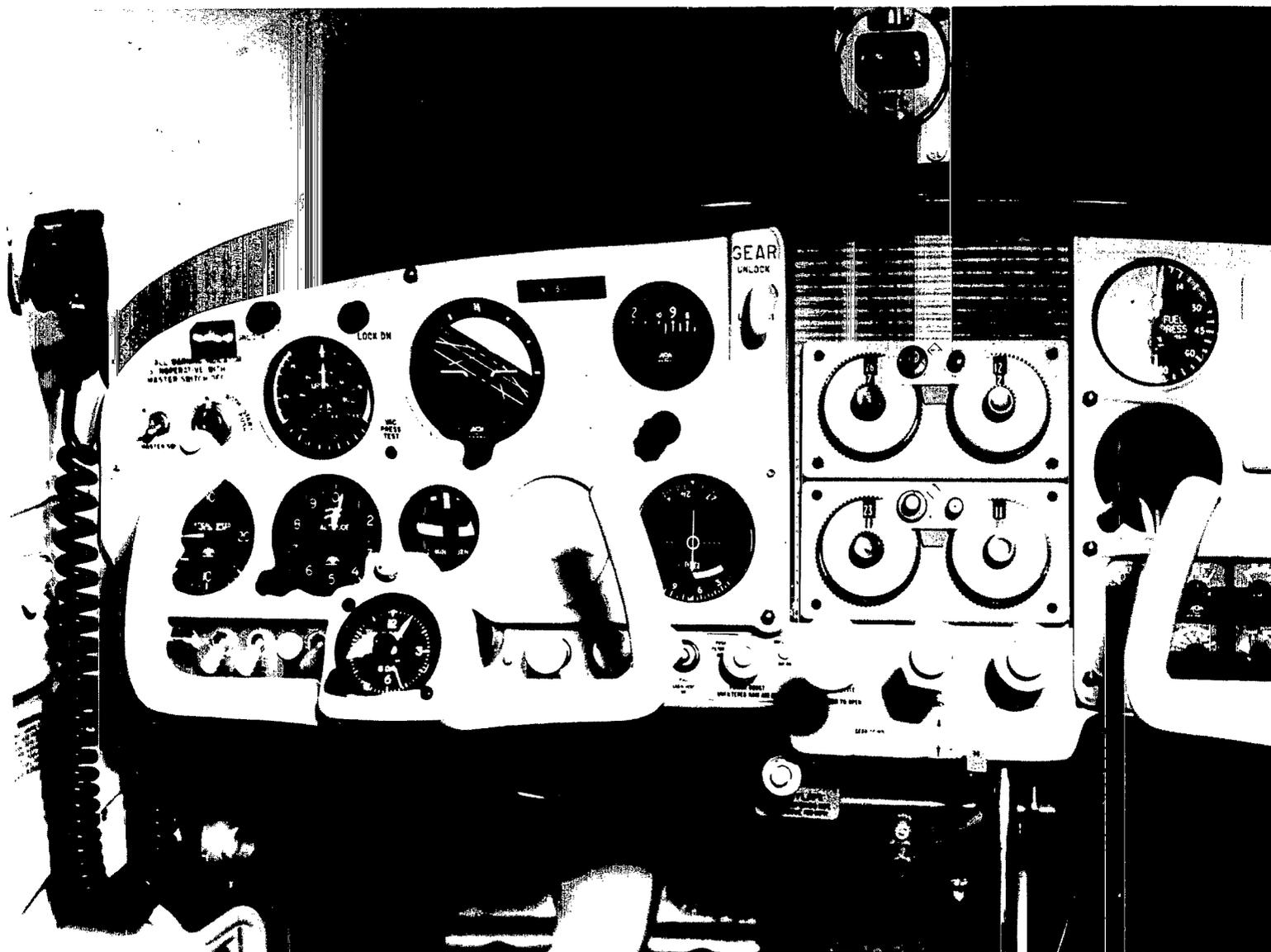
Figure 2.- Aircraft flight instruments.
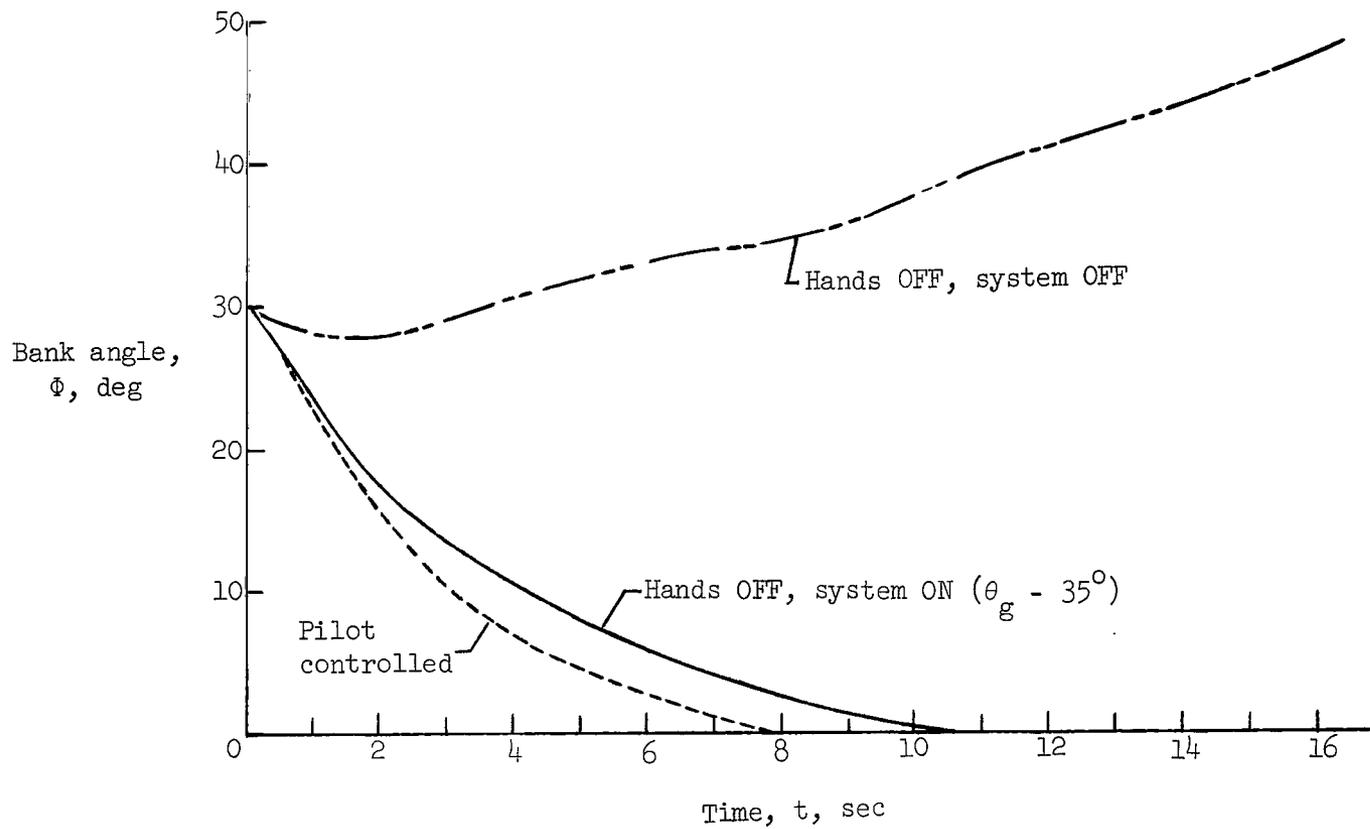
Figure 3.- Lateral response with system on and off and with pilot-controlled recovery. Indicated airspeed, 135 knots; altitude, 5000 feet.
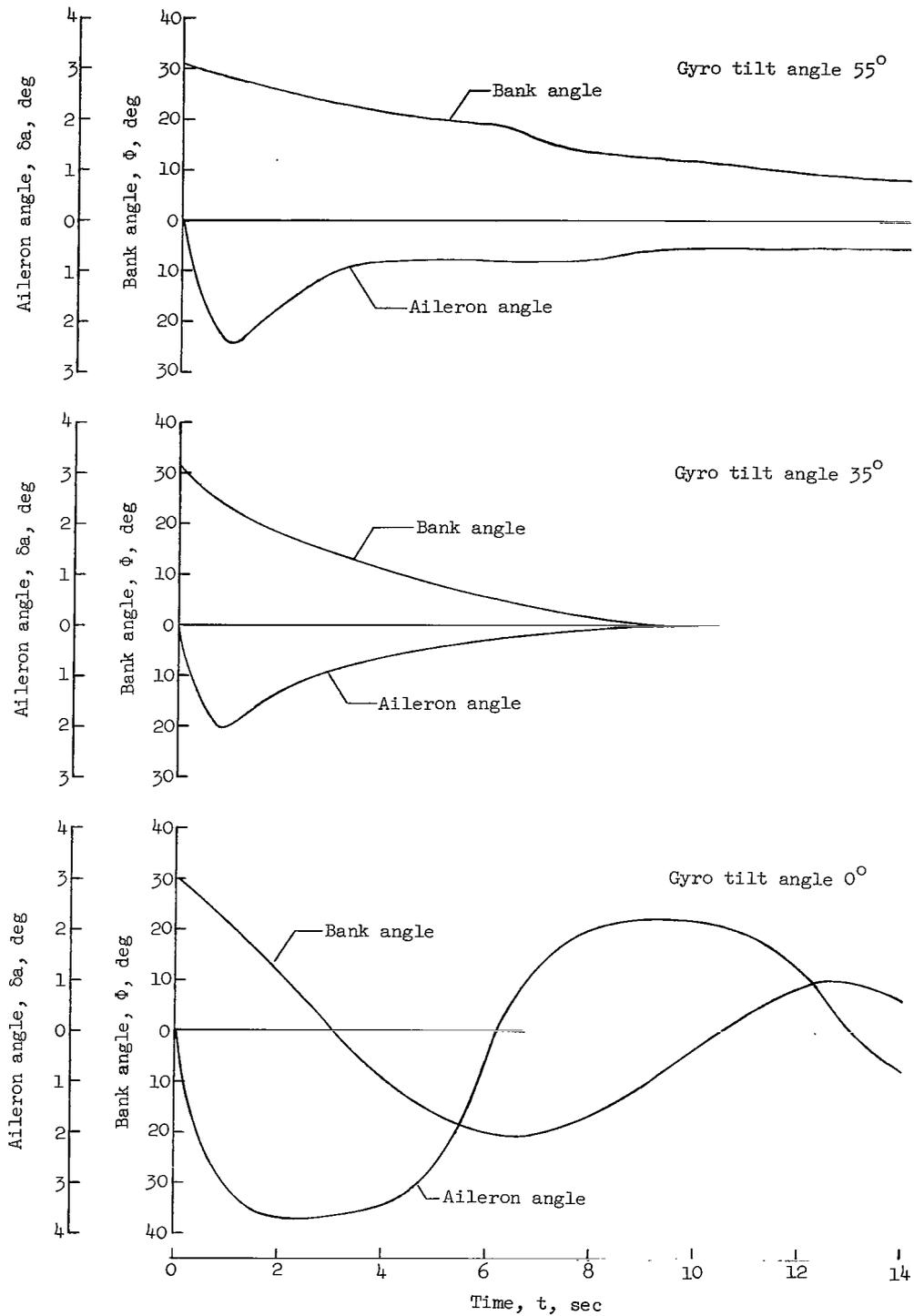
Figure 4.- Lateral motion and aileron response following control release during a turn with various gyro tilt angles θ_g as measured in flight at 135 knots indicated airspeed and 5000 feet altitude.

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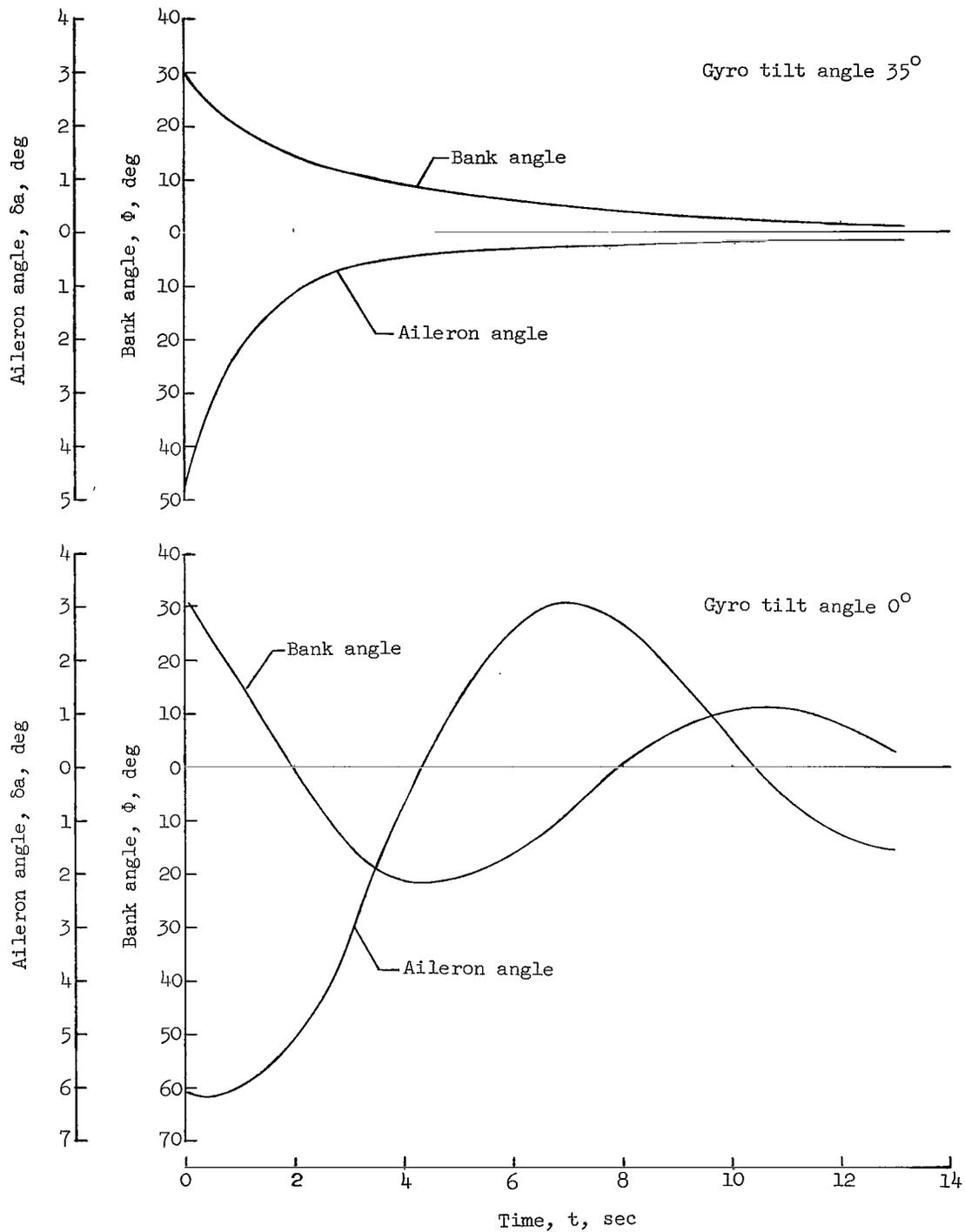
Figure 5.- Calculated lateral motion and aileron response after control release during a turn with various gyro tilt angles θ_g. Time constant, $\tau = 4$ sec; indicated airspeed 135 knots.
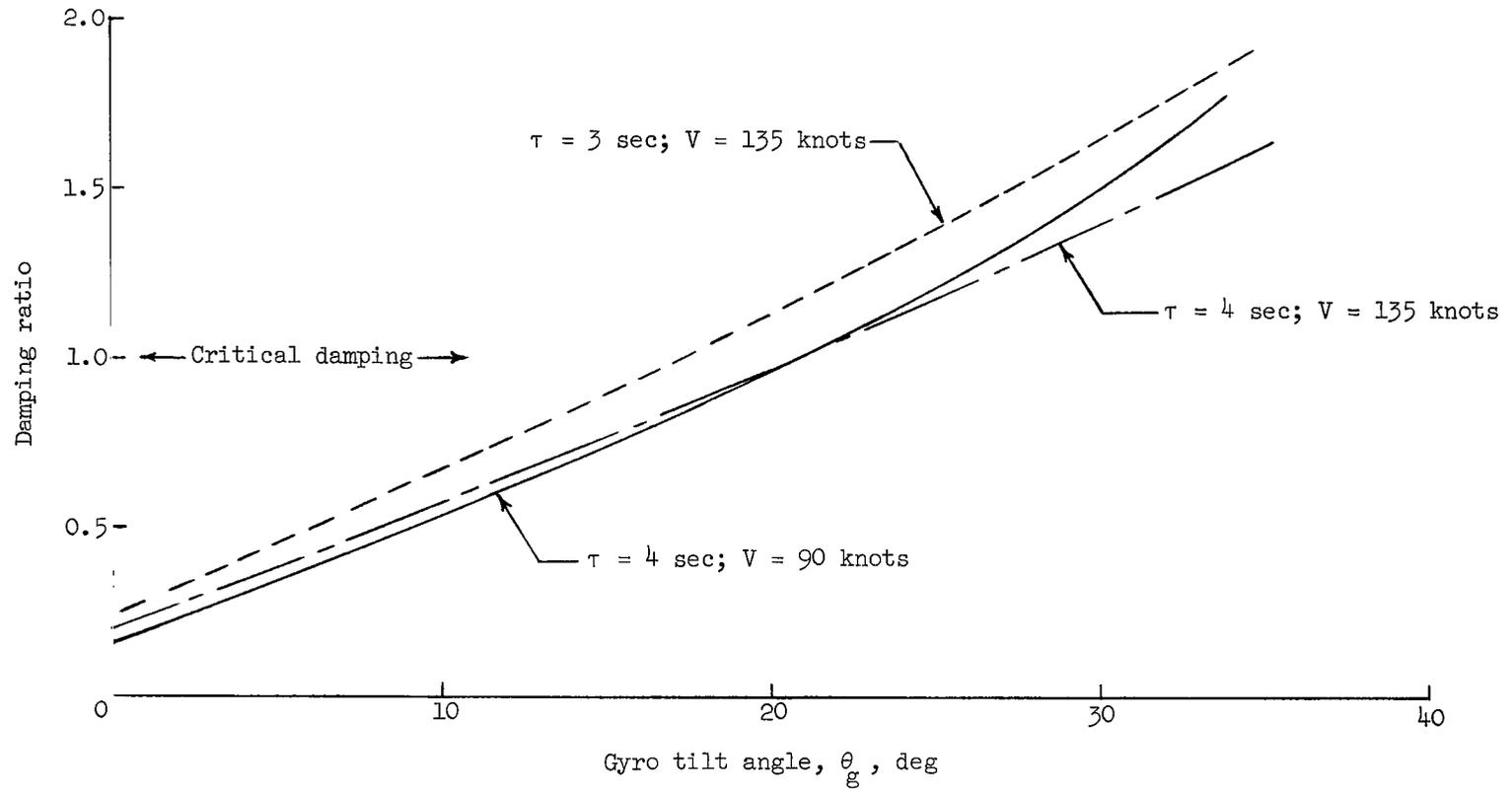
Figure 6.- Calculated effect of gyro tilt angle on damping ratio.
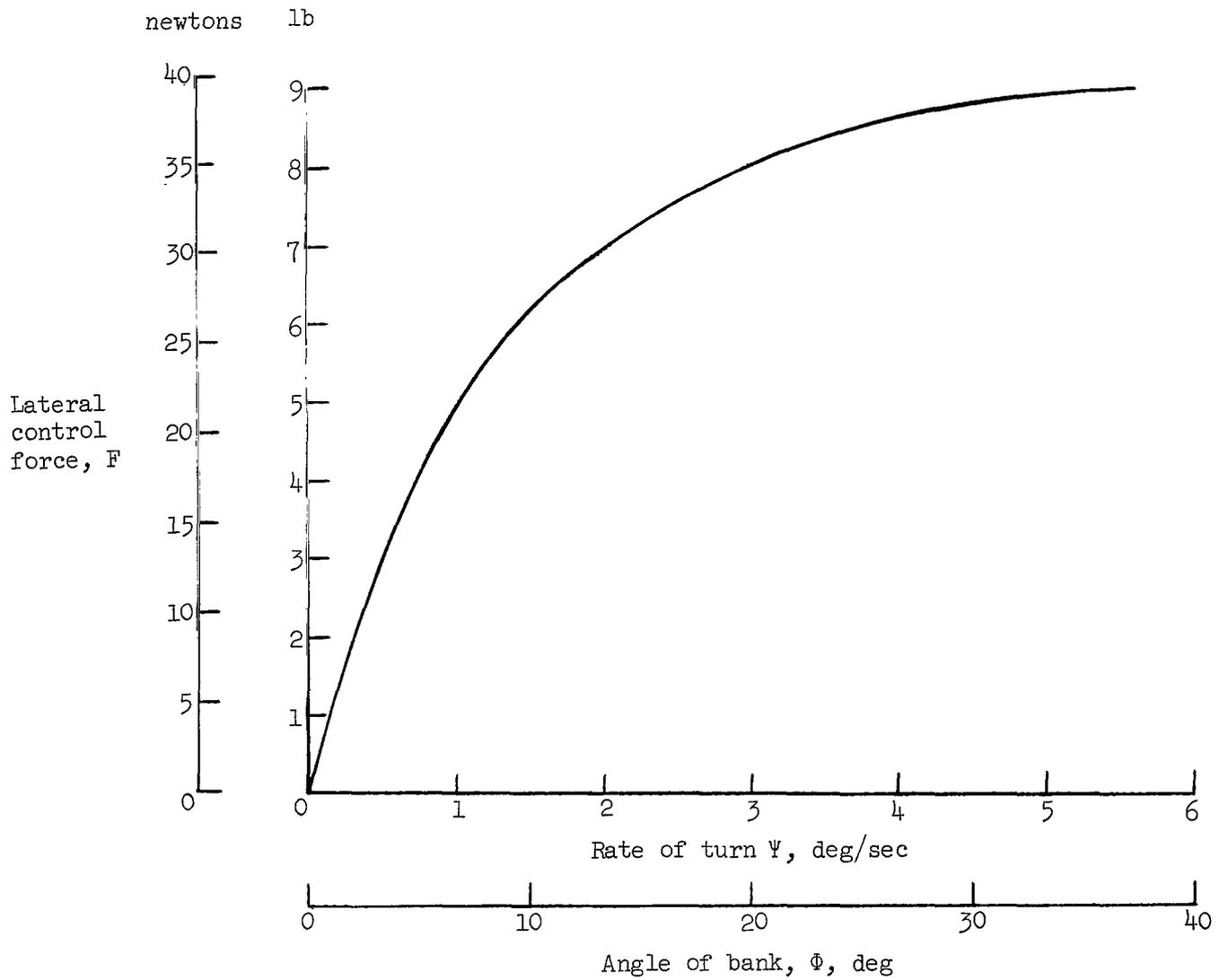
Figure 7.- Lateral-control force during a steady turn, at 135 knots indicated airspeed and 5000 feet altitude. $\theta_g = 35^0$.
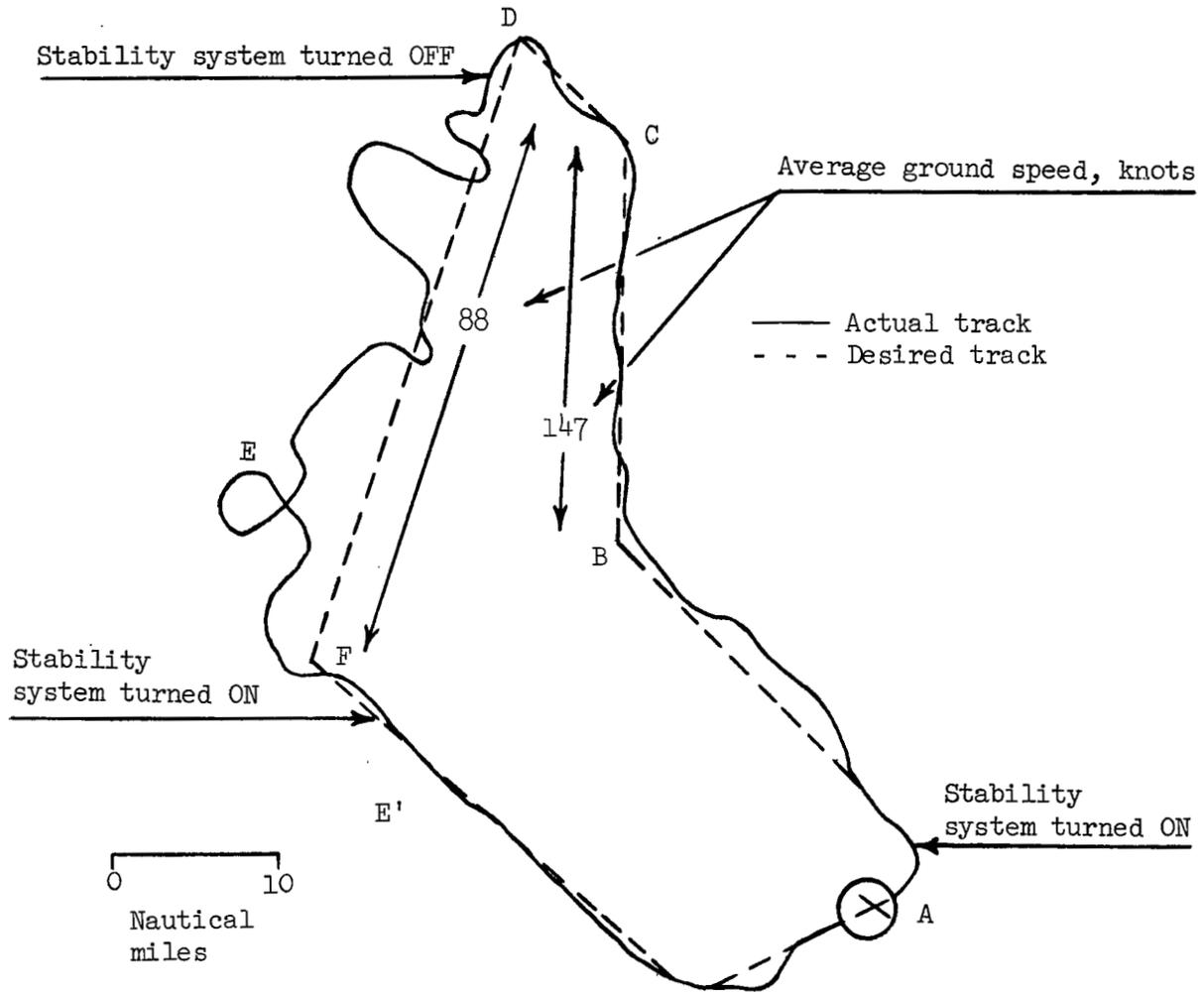
Figure 8.- Flight pattern of noninstrument-rated pilot during cross-country flight.

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