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RESEARCH MEMORANDUM

FLIGHT AND ANALYTICAL STUDY OF ROLL REQUIREMENTS OF A FIGHTER AIRPLANE

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SUMMARY

Flight tests and analytical studies have been made to review the question of roll requirements for fighter airplanes where primary emphasis is placed on the requirements for pursuit tracking by an attacking airplane and evasive action by a target airplane.

The flight tests showed that simple turning maneuvers were as effective for evasion as maneuvers that included attempts at feinting.

The analytical study showed that large increases in the roll performance of the target did not greatly increase the roll requirements of the attacker attempting to follow exactly. Increasing the lift acceleration of the target did place slightly larger roll requirements on the attacker. The requirements on the attacker increased as the change in roll angle necessary to follow the target increased up to 180°.

From the calculations presented, the roll performance required of an attacking airplane on any pursuit-tracking situation may be estimated. In general, it appears that the roll performance required in practical tracking situations would be less than called for at the present time by the military flying-qualities specifications.

INTRODUCTION

The present military flying-qualities specifications (ref. 1) require that fighter airplanes be able to roll through a bank angle of 100° in one second up to an altitude of 20,000 feet in the high-speed level-flight condition. Recently, these requirements have been questioned because of new problems that have appeared. Roll divergence problems, caused and aggravated by the high rolling velocity required in the present specifications in combination with inertia factors, have become prevalent. Also, fighter airplanes are being built larger in size and, as a result, have

an increased amount of difficulty in meeting the present requirements. These problems call for a review of the roll requirements for fighter airplanes.

This paper presents the results of flight and analytical studies of required roll performance. Primary emphasis is placed on the roll requirements for pursuit tracking by an attacking airplane and evasive action by a target airplane. Preliminary studies indicated that these tasks would be among the most critical ones from the standpoint of rolling performance in high-speed flight. The flight tests were examined to determine the quality of the tracking and to determine what type of roll maneuver in combination with limited lift acceleration, airspeed, and range variations resulted in the best evasion. The analytical study was made to study systematically and in detail several aspects of roll-performance requirements. No considerations of low-speed roll requirements, such as would be used in landing, are made in this paper.

SYMBOLS

g	acceleration of gravity, ft/sec^2
t	time, sec
τ	time constant of rolling motion, sec
e	base of natural logarithms
ϕ	roll angle, deg
n	load factor or lift acceleration
a	acceleration, ft/sec^2
r	radius, ft
V	velocity, ft/sec
R	range, ft
$\dot{\phi}$	rolling velocity, deg/sec
$\ddot{\phi}$	rolling acceleration, radians/sec/sec
s	differential operator, d/dt
Δ	increment

Subscripts:

1,2	constants
m	maximum design value
xy,xz	horizontal and vertical planes in space
A	attacker
T	target
H	horizontal

DESCRIPTION OF TESTS AND CALCULATIONS

In the flight tests, when two jet airplanes with approximately the same performance were used, motion pictures were taken of the fixed gun-sight presentation in the attacking airplane as it attempted to track a target. Some limitations were imposed on the tests to isolate roll performance. The runs were started in a steady tail chase, and the target attempted to evade the attacker by rolling at the pilot's discretion and performing turning maneuvers with the lift acceleration limited to 3g. During these runs the target normally changed the direction of the turns every few seconds. Runs were started with ranges of approximately 3,000 and 1,500 feet. Most of the tests were performed at an altitude of 30,000 feet, and a few were performed at an altitude of 10,000 feet. A limited number of the tests at low altitude were made with a 4g limit on the lift acceleration in an attempt to determine the effect of lift acceleration on the roll requirements of the attacker. All runs were made at a Mach number of 0.6. Every effort was made to keep the closing rate low during the runs, but invariably the range decreased. The shortest range that appeared in the tests was approximately 1,000 feet. Each run lasted approximately 1 minute.

The rolling-velocity and rolling-acceleration envelope presented in figure 1 was covered by varying the total aileron deflection allowed the target, by varying the altitude, and by making tests with the tip tanks of the target airplane both full and empty. Runs were made with the target restricted in roll performance so that the maximum rolling velocity and rolling acceleration corresponded to several different points within this envelope, and with the attacking airplane unrestricted. Next, the target was left unrestricted, and the total aileron deflection allowed the attacker was limited.

The object of imposing these conditions on the airplanes was to determine the effect of varying roll performance on the ability of the target to improve the evasion by significantly increasing the errors shown on the films.

The flight tests were paralleled by an analytical study. Calculations were made to determine the roll performance required to follow exactly a target that rolls and increases lift acceleration. The attacker can be assumed to be keeping the gunsight cross hairs centered on the target. The general type of maneuvers that were found to be effective in the flight tests were simulated as target maneuvers in the analytical study. In different cases the target was assumed to roll 90° and 180° and to increase lift acceleration to 3g and 5g (increments of 2g and 4g). Various 90° and 180° cases are related in that the same maximum target rolling acceleration was used, whereas the rolling velocity was higher in the 180° roll maneuvers. The required performance of the attacker is expressed as the maximum rolling acceleration and maximum rolling velocity required to follow a variety of target maneuvers for all reasonable values of range and airspeed.

In the tracking phase of the analytical study, the most severe target maneuvers within the realm of probability were used, and the resulting performance required of the attacker was assumed to represent the maximum performance needed.

A brief analytical study of the acquisition phase of the attack was made, in which the roll performance of an airplane was arbitrarily restricted and the effect of such restriction on the end result of the path in space of the airplane was determined. Acquisition maneuvers are thought of in this paper as those maneuvers which are performed to bring the attacker to a position behind the target within reasonable range and a position where the tracking error is relatively small.

The general term "roll performance" may refer to maximum rolling acceleration, rolling velocity, or time required to change bank angle a certain amount. However, in order to be able to express roll performance in a satisfactory manner, the relation between these three quantities should be clearly understood. Therefore, calculations to determine the combination of rolling acceleration and rolling velocity that will result in a given change in bank angle in a given time were made, and the results are presented in this paper. This information also will be useful in relating the results of the analytical study, which present roll requirements in terms of rolling velocity and rolling acceleration, to the present requirements which express roll requirements in terms of time to change bank angle a certain amount.

METHOD OF ANALYSIS

Tracking Requirements

The equations establishing the relation between target and attacker are presented in reference 2. The equations for perfect pursuit tracking, presented in the appendix of reference 2, are used in this paper. Also presented in reference 2 is a discussion on the limits of range, airspeed, and time for which the equations can be considered to give correct answers. The results presented in this paper will be correct for all values of range and airspeed assumed to be representative of practical tracking situations. The equations also neglect to account for a lead angle, but this factor should have small effect on the calculated rolling performance. These equations relate the space acceleration in the xz-plane and the space acceleration in the xy-plane of the two airplanes. The expressions for the components of the space acceleration of the target are:

$$a_{xz_T} = g\left(n_T \cos \phi_T - 1\right)$$

$$a_{xy_T} = g n_T \sin \phi_T$$

The accelerations of the attacker are related to the accelerations of the target by the expressions:

$$a_{xz_A} = \frac{\left(V_A/V_T\right) a_{xz_T}}{s\left(R/V_T\right) + 1}$$

$$a_{xy_A} = \frac{\left(V_A/V_T\right) a_{xy_T}}{s\left(R/V_T\right) + 1}$$

The lift acceleration and bank angle of the attacker are determined from the space accelerations by the expressions:

$$n_A = \frac{1}{g}\sqrt{\left(a_{xz_A} + g\right)^2 + a_{xy_A}^2}$$

$$\phi_A = \tan^{-1} \frac{a_{xy_A}}{a_{xz_A} + g}$$

The method of analysis was to assume particular target motions and then to determine the motions of the attacker required to follow the target.

In order to describe the motion of the target in a simple but realistic manner, the transient part of the lift acceleration and roll-angle time histories of the target were assumed to vary as the trigonometric function

$$\frac{1}{2}\left(\cos \frac{180^{\circ}}{t_1} t - 1\right)$$

The times required for the target to complete the transient changes in lift acceleration and roll angle t_1 were varied, with the extreme cases surpassing the performance that could be expected of present-day airplanes. These target variables were used in combination with a wide range of the variable R/V_T. It should be seen from the equations that for a given target maneuver the motion of the attacker is a function only of R/V_T when the velocity of the target and attacker are equal. In addition, some calculations were made for the situation in which a closing rate between the target and attacker was assumed.

Time histories of the roll angle and lift acceleration of the attacker were obtained with an electronic analog computer. The maximum rolling velocity and rolling acceleration were obtained from the time histories of the roll angle. The rolling velocity was obtained by electronically differentiating the roll-angle time variation and the maximum rolling acceleration by graphically differentiating the rolling velocity time variation.

Rolling Velocity and Rolling Acceleration Required to Achieve a Given Bank Angle

The variation of the combination of rolling velocity and rolling acceleration necessary to bring an airplane to, and stop at, a given bank angle in a given time was determined in the following manner.

It was assumed that the ailerons were moved in a step to full deflection, then at the appropriate time t_1, were moved to full deflection in the opposite direction, and finally returned to zero deflection at time t_2. The resulting rolling velocity was assumed to vary as an exponential function, so that the expressions for the first and second parts of the motion are, respectively,

$$\dot{\phi}_1 = \dot{\phi}_m\left(1 - e^{-t/\tau}\right)$$

$$\dot{\phi}_2 = -\dot{\phi}_m - \left[\left(-\dot{\phi}_m - \dot{\phi}_{t_1}\right)e^{-\left(t-t_1\right)/\tau}\right]$$

When the maneuver is completed, $\dot{\phi}_2$ will equal 0, so that the following relations can be used:

$$\dot{\phi}_{t_1} = \dot{\phi}_m\left(1 - e^{-t_1/\tau}\right)$$

$$\dot{\phi}_{t_2} = 0 = -\dot{\phi}_m - \left\{\left[-\dot{\phi}_m - \dot{\phi}_m\left(1 - e^{-t_1/\tau}\right)\right] e^{-\left(t_2-t_1\right)/\tau}\right\}$$

By simplifying this expression, the following relation is obtained:

$$1 = 2e^{-(t_2-t_1)/\tau} - e^{-t_2/\tau}$$

By assuming a value for t_2, and varying τ from 0 to ∞, all possible values of t_1 can be determined. With t_2 assumed and t_1 determined, the maximum rolling velocity required to reach a given bank angle can be determined. The expression for the specified final bank angle ϕ_{t_2} is:

$$\phi_{t_2} = \phi_1 + \phi_2$$

$$= \int_0^{t_1} \dot{\phi}_1 dt + \int_{t_1}^{t_2} \dot{\phi}_2 dt$$

$$= \dot{\phi}_m\left[t_1 - \tau\left(1 - e^{-t_1/\tau}\right)\right] + \dot{\phi}_m\left[-\left(t_2 - t_1\right) + 2\tau - 2\tau e^{-\left(t_2-t_1\right)/\tau} + \tau e^{-t_2/\tau} - \tau e^{-t_1/\tau}\right]$$

Once again by varying τ from 0 to ∞, all possible values of maximum design rolling velocity $\dot{\phi}_m$ required under the specified conditions to change bank angle by the given amount ϕ_{t_2} can be determined. The corresponding rolling acceleration required for that part of the maneuver when rolling velocity is increasing is determined by the expression

$$\ddot{\phi}_m = \dot{\phi}_m/\tau$$

The exponential variation of rolling velocity was chosen because that is the characteristic of the rolling velocity of an airplane when it is assumed to have a single degree of freedom in roll. If a finite aileron-deflection rate were assumed in place of the step motion used in the analysis, the result would be a decrease in maximum rolling acceleration that could be obtained. The effect of this decrease on the time history of rolling velocity would be very similar to that obtained with a step motion of the ailerons in conjunction with an increased value of τ. The results of this analysis are therefore applicable when the maximum rolling acceleration is limited as a result of a finite rate of aileron deflection.

Path of the Airplane

The path of the airplane in a horizontal plane was determined in the following manner. It was assumed that the airplane had to roll 90°. The radius of curvature of the horizontal projection of the flight path is

$$r = \frac{V^2}{n_H g}$$

where

$$n_H = n \sin \phi$$

The velocity was assumed to be 600 feet per second, and the lift acceleration was assumed to increase to 3g. The transient time history of the lift acceleration and bank angle were assumed to vary as a trigonometric function, so that

$$\phi = \frac{90}{2}\left(\cos \frac{180^{\circ}}{t_1} t - 1\right)$$

$$n = \frac{2}{2}\left(\cos \frac{180^{\circ}}{t_1} t - 1\right) + 1$$

where t_1 is the time assumed to complete the transient change. The path was plotted in a step-by-step manner, with the steps equal to the distance traveled in 0.1 second.

RESULTS AND DISCUSSION

Flight Tests

The motion pictures obtained in the flight tests in which the roll performance of the target was varied and the attacker left unrestricted were closely examined, and the general quality of the evasion in each run was given a relative score. To make an objective check on the relative score, a number was given to the score by making a frame-by-frame study to determine the percent of time that the tail pipe of the target was outside a 10-mil-diameter circle. No change in the quality of the evasion could be determined by either method as the roll performance of the target was varied throughout the test envelope. The errors that did occur were larger than the tracking errors normally expected in tracking

a nonmaneuvering target but were small compared to those needed for effective evasion. At times during these tests the target airplane went outside the field of view of the camera, which was 7°, but usually returned within a short time. It is possible that more effective evasion maneuvers could have been made if the target airplane had information on the motion of the attacker. However, in these tests the pilot of the target airplane was usually unable to see the attacker. In many cases, the errors due to disturbances such as those caused by the wake of the target or by gusts appeared larger than those caused by the maneuvering of the target.

Several points of interest were brought out by the films. Rolling more than 180° was not useful as an evasion maneuver because the attacker merely waited for the target to start to displace, at which time he would roll through the smaller angle to follow (angle less than 180°). For the same reason, feinting by rolling in one direction and then reversing the roll before increasing lift acceleration was ineffective. Increasing the roll performance of the target was no help to its evasion capabilities, and this fact was made particularly evident in those runs in which the target was allowed full aileron deflection at low altitude. It was apparent that the target could roll 90° or more before the attacker would start to roll. It was concluded that, even if the target had the physically impossible ability to roll instantly from one bank angle to another before increasing its lift acceleration, the evasion score would not have been appreciably changed. The lag of the attacker in following the roll angle of the target was not important. In fact, as was stated before, the attacker would not even attempt to maneuver until it became apparent that the target was pulling "g's." The attacker was able to follow the resulting displacement of the target at all times. Evidently, the lag resulting from human reaction time was not an important factor in the results because of the relatively long time required for the target to create a flight-path displacement.

In all of the runs mentioned previously, the attacking airplane was unrestricted. However, the attacker never used more than one-half of its available aileron. In an attempt to establish a condition in which the quality of the tracking would be noticeably changed from the level noted on the previous runs, the attacker was restricted to 1/4 aileron and the target was allowed full aileron. The maximum rolling velocity of the airplane in this condition was approximately 45° per second. For runs started at a range of 3,000 feet, the tracking performance was the same as noted in the previous unrestricted runs. The attacking pilot noted that he was frequently against the aileron stops, and he felt that the situation represented a borderline case. When the runs were started at a range of approximately 1,500 feet, the quality of the tracking noticeably deteriorated. Errors of the order of 50 to 100 mils appeared and were maintained for longer periods of time than noted previously. The pilot of the attacking airplane felt that the target was able to break away. These remarks apply to runs in which the target performed horizontal

turning maneuvers. When the target performed a split S type of maneuver (rolled 180° and accelerated downward), the tracking errors increased further and the target was able to break away more quickly.

Analytical Study of Tracking Requirements

The flight tests led to the general conclusions mentioned in the previous paragraphs but did not allow any quantitative results. Therefore, an analytical study was made to determine the maximum rolling performance needed to perfectly follow a target. The target maneuvers selected in this study represent the maneuvers that were noted to be successful in the flight tests, that is, maneuvers combining simple roll and increase of lift acceleration.

Some typical time histories obtained in this study of the motions of the attacker which were required to follow exactly a target are shown in figure 2. These illustrations were obtained from the cases in which R/V was constant, that is, there was no closing rate between the target and attacker. Because of the assumptions made in the tracking equations, the steady-state lift acceleration of the attacker is equal to the steady-state lift acceleration of the target. In general, for large values of R/V, the attacker takes an appreciable length of time to reach steady-state lift acceleration and roll angle.

The maximum rolling velocity and rolling acceleration required to follow a variety of target maneuvers have been plotted against the variable R/V in figures 3 to 7. The problem assumes that the performance of the attacker must duplicate the performance of the target at $R/V = 0$ (zero range). In general, the requirements on the attacker fall off rapidly as R/V is increased. Figure 3 shows that increasing the roll performance of the target to an infinite amount does not greatly increase the requirements made on the attacker at R/V values larger than 1. This is in agreement with what was noted in the flight tests. Increasing the lift acceleration of the target results in a slight increase in the required roll performance of the attacker at large values of R/V. This increment decreases to zero at zero R/V. The increase calculated is in agreement with what was experienced in the flight tests. When the length of time required for the target to reach steady-state lift acceleration is decreased, larger rolling acceleration and less rolling velocity are required of the attacker. The most important single factor in increasing the roll requirements on the attacker was the angle that the attacker rolled through. Since neither increasing the roll performance nor increasing the lift acceleration of the target caused very large increase in roll performance required of the attacker in the 90-degree-of-roll maneuvers, these factors cannot explain the increase in roll performance required of the attacker in the 180-degree-of-roll maneuvers. It is concluded that the amount of bank angle which the attacker must change is the primary factor which causes the increase in the required performance.

Speaking in a relative manner, it can be seen that an increase in airspeed at a given range will result in an increase in rolling requirements, whereas an increase in range at a given airspeed will result in a decrease in rolling requirements. The data are given in a general form, by plotting the roll-performance requirements against R/V, so that requirements corresponding to any particular set of conditions can be determined. In order to illustrated the variation in roll requirements with change in airspeed, figure 8 has been derived from figure 3. Shown are the rolling-velocity and rolling-acceleration variation with true airspeed required to follow a target that rolls 90° in 1 second and increases lift acceleration an increment of 2g in 1 second, at a range of 3,000 feet.

Also shown in figure 8 are results obtained when a closing rate between the target and attacker was assumed. In these cases the attacker was assumed to have a velocity of 1,400 feet per second and the target to have a velocity of 1,200 and 1,000 feet per second. The initial range was 3,000 feet. Small increases in the rolling-velocity and rolling-acceleration requirements over the case for no closing rate are indicated. Including a closing rate brings about two changes in the tracking equations - a change in the ratio V_A/V_T in the numerator and a change in range in the denominator. The examples show that the change in range is the most important factor, since most of the increase in the requirements noted in these cases can be accounted for by considering the change in range that occurs while the attacker is rolling. During a prolonged series of maneuvers the effect of a change in range will be far greater than the effect of the ratio of the airspeeds of the two airplanes so far as roll requirements on the attacker are concerned.

The highest value of rolling velocity and rolling acceleration for the attacker occurred in following a target that rolled 180° in 1.4 seconds and increased lift acceleration to 5g. It is felt that these assumptions for the target represent the most severe set of conditions that are likely to be encountered in actual tracking. The values obtained in this case were 128° per second for the required rolling velocity and 5 radians per second per second for the required rolling acceleration at a value of R/V of 3. The requirements gradually increase as R/V is reduced to 1. Since these rolling-performance requirements were calculated for perfect tracking, it is believed that they represent an upper limit of practical requirements for roll performance.

A number of the flight tests were made in conditions that were similar to those assumed in calculating the results shown in figure 3. In these flight tests the target had a maximum rolling velocity of 150° per second and a maximum rolling acceleration of 7 radians per second per second. The maneuvers consisted of turns of 3g. The comparison between the flight tests and the calculations are not exact for two reasons. First, in the flight maneuvers, rolls of more than 90° were used, which would raise the

requirements higher than those presented in figure 3. Second, the tracking was not exact, which would be expected to lower the requirements. When the attacker was restricted to 1/4 aileron, which allowed a maximum rolling velocity of approximately 45° per second and a maximum rolling acceleration of 2 radians per second per second, the pilot felt that he had only marginal performance for R/V conditions of from 5 to 3 (runs started at a range of 3,000 feet). Figure 3 shows that the attacker meets the calculated required performance for these conditions. For R/V conditions of from 3 to 1 the motion pictures from the flight test showed that the tracking deteriorated. The calculations show that the attacker does not meet the requirements at these conditions. Therefore, it seems that, although the tracking in the flight tests was not perfect, the requirements for satisfactory performance in the flight conditions tested correspond closely with the calculated requirements for perfect tracking.

Rolling Velocity and Rolling Acceleration Required to Achieve a Given Bank Angle

A requirement that an airplane be able to reach a certain bank angle in a certain length of time presupposes a certain combination of maximum rolling velocity and rolling acceleration. The variations of the combination of rolling velocity and rolling acceleration needed to roll to and stop at 90° in 1.75 and 1.2 seconds are plotted in figure 9. The figure shows the boundaries of rolling velocity and rolling acceleration needed to meet the arbitrary conditions specified. Also shown in the figure is the boundary corresponding to the present requirements, that is, to be able to pass 100° bank angle in one second. The two sketches on the figure illustrate the time histories represented by points near the extreme sections of the curve for 90° in 1.2 seconds.

In general, the roll requirements established in the calculated tracking study are lower than those called for by the present military flying-qualities specifications. Even if the requirements for the case in which the most severe target maneuver was assumed are considered at a relatively low value for R/V (180° in 1.4 sec, $\Delta n = 4g$ in 1 sec, $R/V = 1$), the values of rolling velocity and rolling acceleration, $\dot{\phi} = 150^{\circ}$ per second, and $\ddot{\phi} = 5$ radians per second per second, are less than those needed to meet the present requirements.

Figure 9 can be used to relate the results obtained from the analytical tracking study with requirements stated in the form specifying time required to roll a certain bank angle. In the typical time histories, shown in figure 2, it can be seen in one instance that the attacker is required to roll 90° in approximately 3.5 seconds. However, it is clear that this statement is not sufficient to specify the roll requirements needed for perfect tracking. By using the values of maximum rolling

velocity and rolling acceleration required in this case ($\dot{\phi}$ = 85 deg/sec, $\ddot{\phi}$ = 2.75 radians/sec/sec) and figure 9, it can be seen that an airplane which could meet these requirements could roll 90° in 1.75 seconds. In general, this relation may not be exactly correct, since the values of rolling velocity and rolling acceleration referred to in figure 9 represent maximum design values, whereas the values obtained from the tracking study are simply maximum values occurring at certain times during a particular set of rolling maneuvers. These maneuvers are such that an airplane with a time constant in roll between 0.5 to 0.7 second could duplicate the tracking time histories with a maximum rolling velocity nearly equal to the maximum required rolling velocity. An airplane with a roll time constant less than 0.5 second would have to have a maximum design rolling velocity at least as great as that specified by the tracking requirements. Then the maximum rolling acceleration would inherently be larger than that required. In this case the tracking time history could be duplicated by applying aileron control at a rate less than maximum. An airplane with a roll time constant that was large compared to 0.7 second which could meet the maximum rolling acceleration requirements would inherently reach a larger steady rolling velocity than that required. The tracking time history could be duplicated by applying full aileron deflection and then reversing before full rolling velocity was reached.

The requirements for banking 90° and stopping can be compared with flight tests reported in reference 3. In these tests the total aileron deflection of the airplane was reduced in steps as the pilot attempted to change bank angle 90° and stop. It was found that the optimum time required was 1.75 seconds. When enough aileron deflection was allowed so that the airplane could theoretically attain 90° in less time, it was not possible to do so because of overshoot. The time required to reach a steady-state change of 90° increased as the maximum roll performance exceeded the optimum values of rolling velocity and rolling acceleration associated with the optimum time. However, the pilots felt that reduction of the roll performance below the optimum values of rolling velocity and rolling acceleration would be undesirable for satisfactory general flying of the airplane. These results point to the fact that an airplane which can meet roll-performance requirements for satisfactory general flying may very likely exceed the roll performance which is needed or which can be used for satisfactory tracking. In cases in which the roll-performance requirements for general flying exceed foreseeable tactical requirements, the designer must weigh the desire to provide optimum airplane handling qualities against possible performance or structural advantages resulting from limiting the rolling capabilities to those needed solely for tactical requirements.

The question remains as to what is the best manner of stating roll-performance requirements. Time to roll to and stop at 90° was considered because it was felt that this requirement more closely correlates with what is needed for satisfactory tracking. However, a requirement of this

form is difficult to check in flight tests because a pilot cannot consistently stop a roll at a given angle. The present military requirements are stated in a form that is somewhat easier to check in flight tests. Whereas it may be desirable to be able to state roll requirements in terms of time required to bank a certain amount, it is apparent that when the requirements are stated in this manner they might, in some cases, be met with either a maximum rolling velocity or rolling acceleration that is too low to meet tracking requirements. To avoid this difficulty it may be necessary to supplement the roll requirements with specifications for maximum rolling velocity or rolling acceleration or both.

The form of the present requirements, that is, to be able to roll through 100° in 1 second, was originally arrived at with the idea that the measurements would be easy to make in flight without the aid of recording instruments. In practice, however, accuracy limitations restrict the usefulness of this method. In reference 3 an example is presented in which the aileron power would have to be doubled to reduce the time required by about 0.1 second, which is within the accuracy of measurement by a pilot with a stopwatch. It is apparent that recording instrumentation would be necessary to measure both bank angle and time accurately enough for quantitative analysis when a condition of 100° in 1 second is approached. The use of recording instruments to determine rolling velocity and rolling acceleration directly would not, therefore, cause much greater difficulty. In any event, it is desirable that the relation between these quantities and time required to change bank angle a certain amount be clearly understood.

Path of the Airplane

In an analytical study of the effects of gross changes in roll performance on the acquisition phase of tracking, a comparison has been made of the horizontal projections of the path in space of an airplane which can roll 90° in both 1 and 2 seconds, respectively. It was assumed that the airplane rolled 90° and increased lift acceleration to 3g. The transient of the lift acceleration change was assumed to require 1 second. It is felt that the lateral displacement represented by the results is typical of the maneuver necessary for target acquisition. The results are shown in figure 10.

The transient parts of the two curves differ only slightly, and the steady-state part in each case is a circle of the same radius with the centers displaced 240 feet from each other. In other words, the airplane which required 2 seconds to roll 90° could follow the same path as the airplane which required 1 second to roll 90° by starting the maneuver 0.4 second earlier.

It is assumed that a typical acquisition maneuver would consist of one or two changes in flight path and would require at least 30 seconds. In view of these considerations, it does not seem that the cause of a difference of 0.4 second in time required could be considered as significant. It would seem that only in very rare cases should the roll performance of an airplane dictate the difference between success or failure of target acquisition. Further flight tests of acquisition should be made to check these conclusions.

CONCLUSIONS

Some conclusions drawn from flight tests and an analytical study of the roll requirements of a fighter airplane are presented below. Calculations are presented which allow determination of the roll requirements of an attacking airplane in a pursuit-tracking situation for reasonable values of airspeed and range and for a variety of target maneuvers. Within the limits of the flight tests, the results agreed with the calculated results.

1. Flight tests showed that simple turning maneuvers are as effective for evasion as maneuvers that include attempts at feinting. The lag in response of the pilot of the attacking airplane was not an important factor in following the target.

2. Large increases in roll performance of the target did not greatly increase the roll requirements of the attacker attempting to follow exactly. Increasing the lift acceleration of the target did place slightly larger roll requirements on the attacker. The requirements on the attacker increased as the change in roll angle necessary to follow the target increased up to 180°.

3. In general, it appears that the roll performance required of the attacker in practical pursuit-tracking situations would be less than called for at the present time by the military flying-qualities specifications.

4. A brief analytical study indicated that target acquisition would require less rolling performance than the pursuit-tracking tasks.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 25, 1956.

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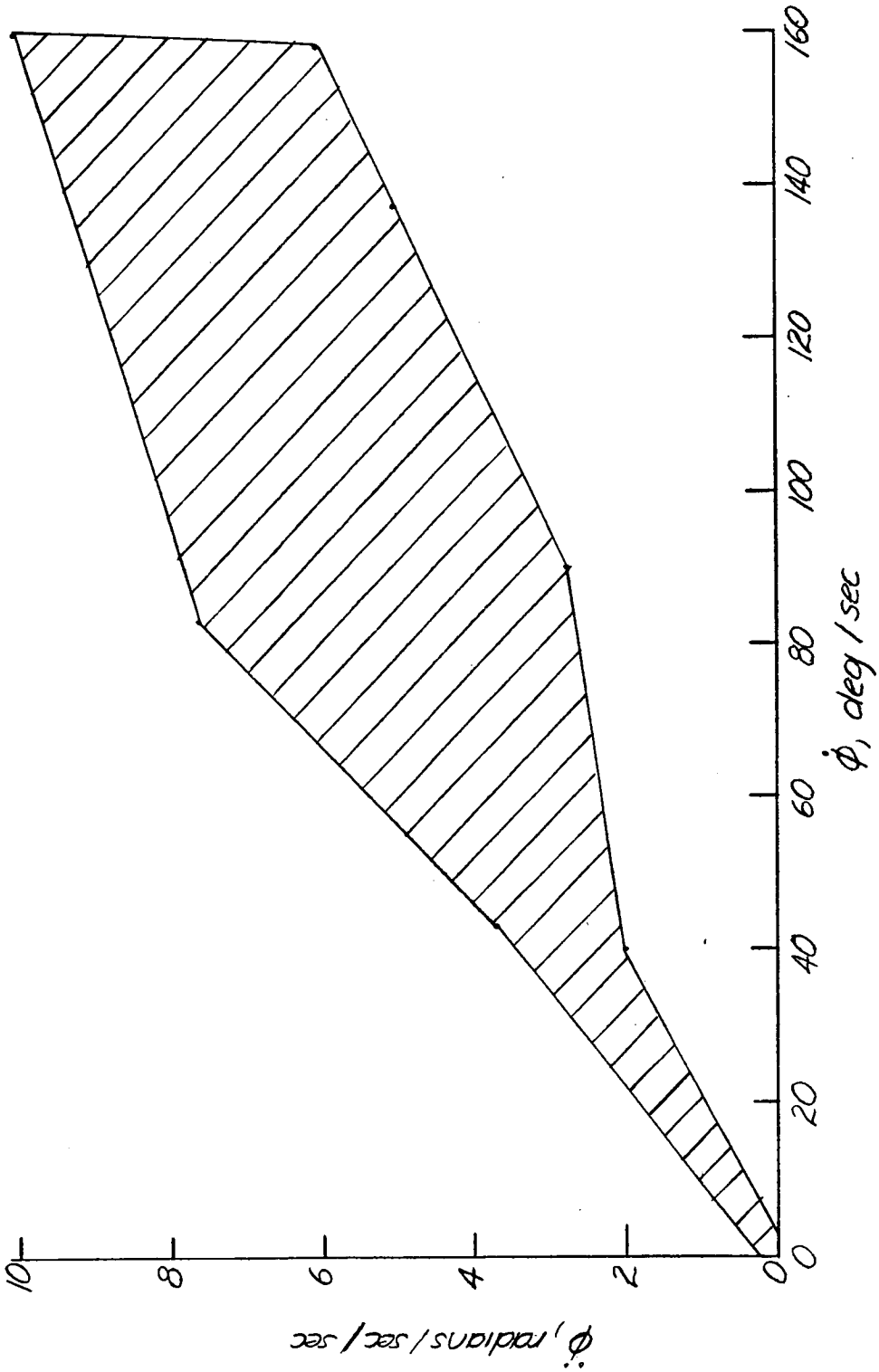

Figure 1.- Test envelope of maximum rolling velocity and maximum rolling acceleration of target airplane covered in flight tests.

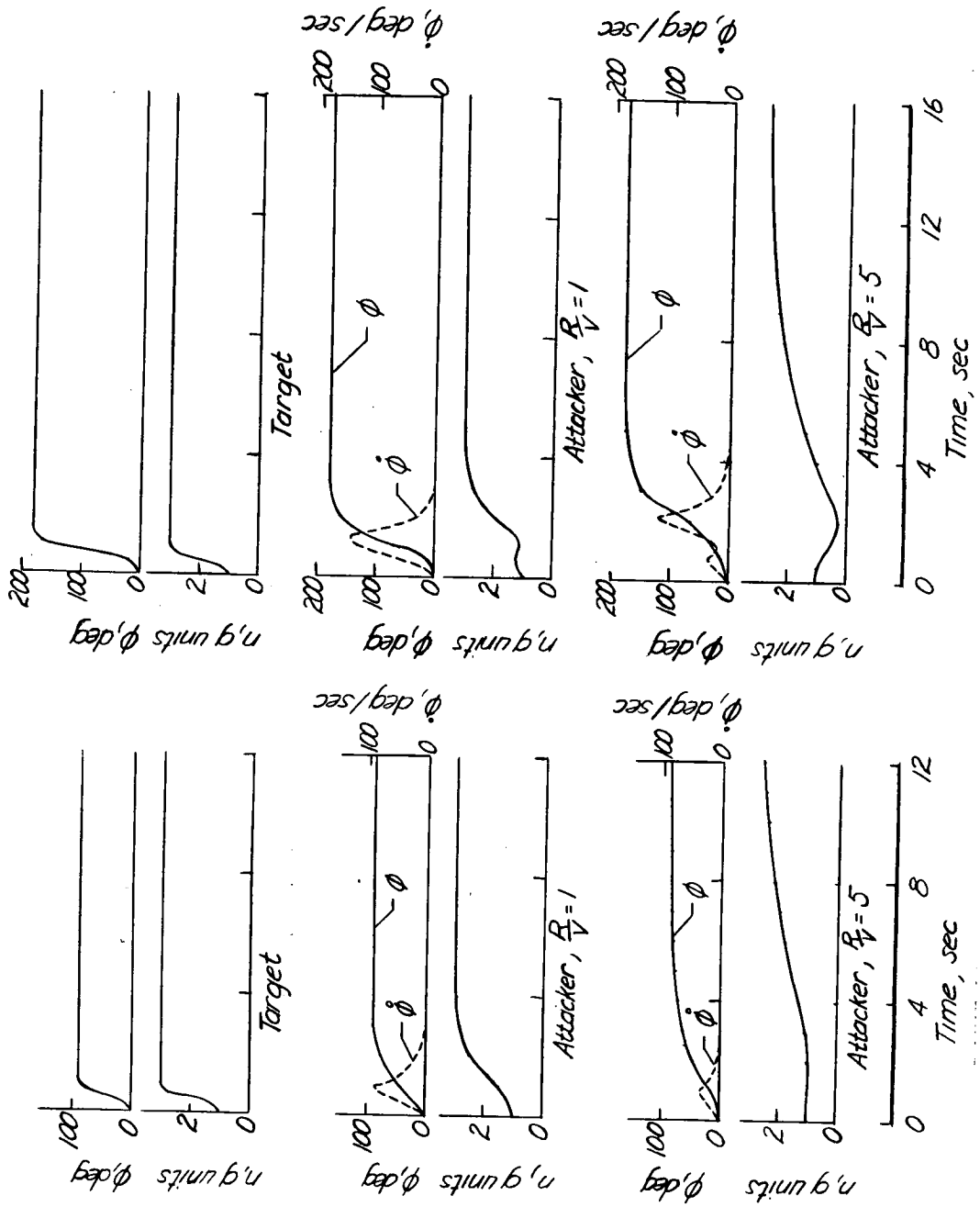

Figure 2.- Sample time histories of the assumed target maneuver and the calculated attacker maneuver required to follow exactly the target.

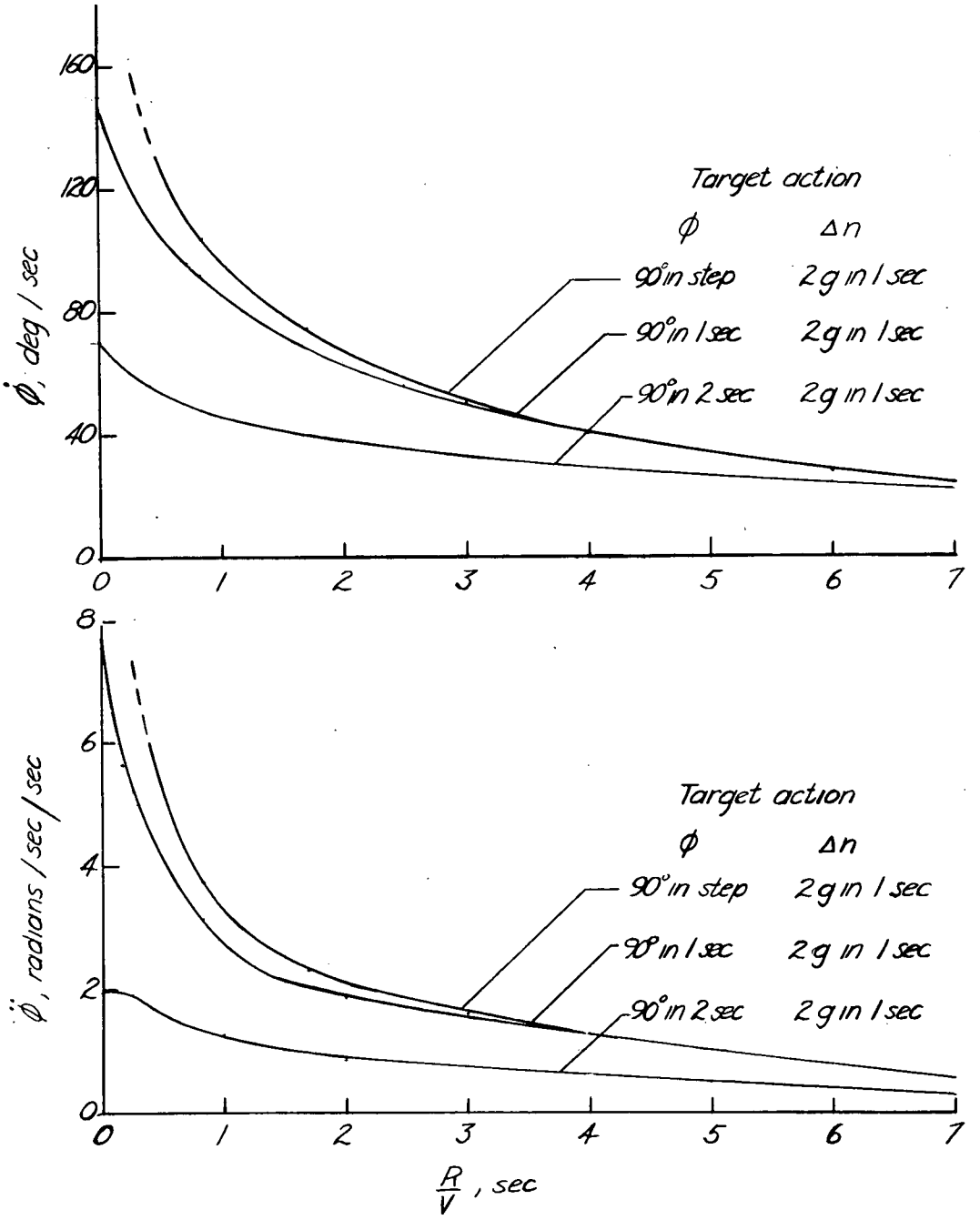

Figure 3.- Variation with R/V (range divided by true airspeed) of the maximum rolling velocity and maximum rolling acceleration required of the attacking airplane to follow exactly the target maneuver noted in the figure.

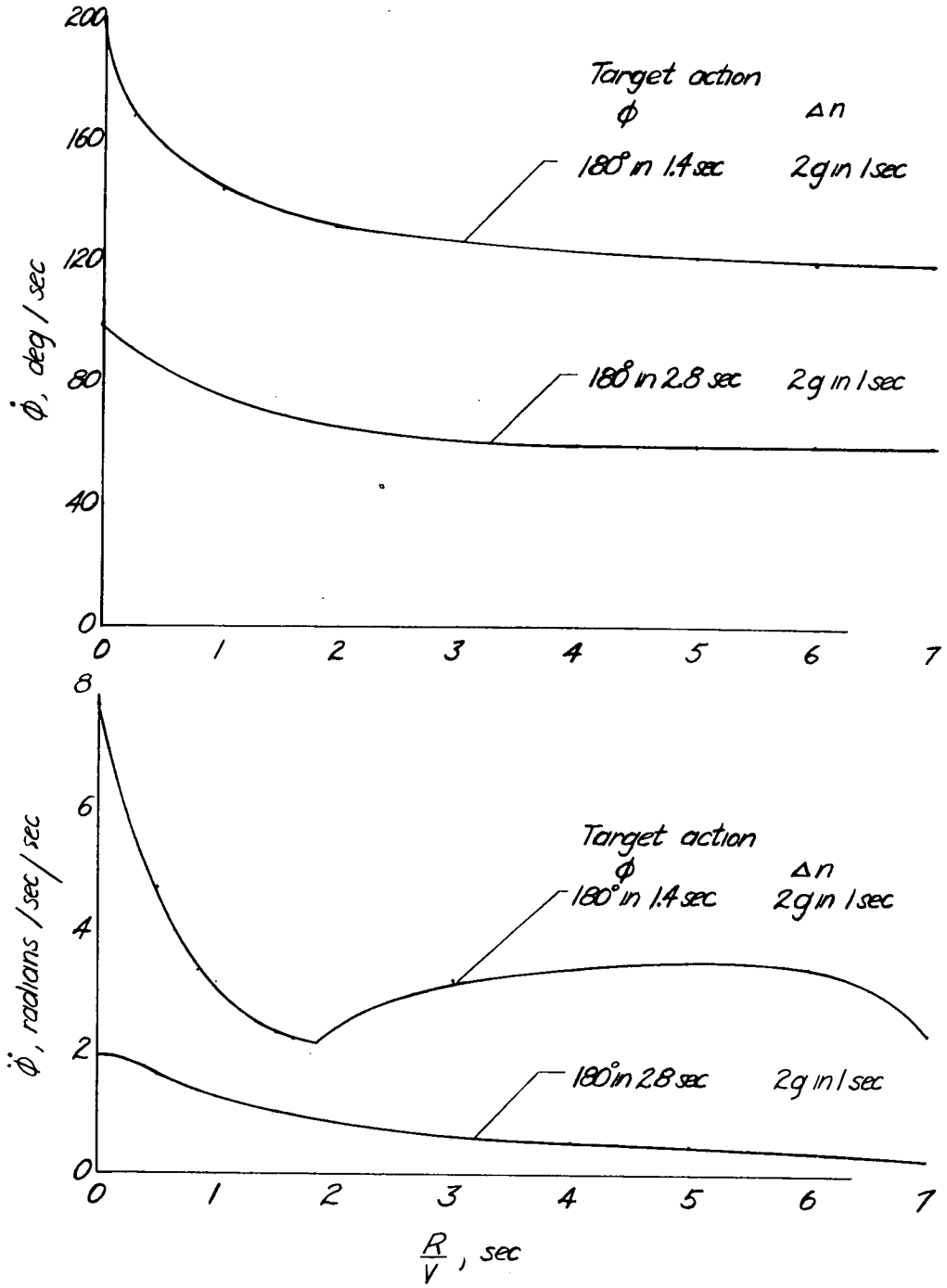

Figure 4.- Variation with R/V (range divided by true airspeed) of the maximum rolling velocity and maximum rolling acceleration required of the attacking airplane to follow exactly the target maneuver noted in the figure.

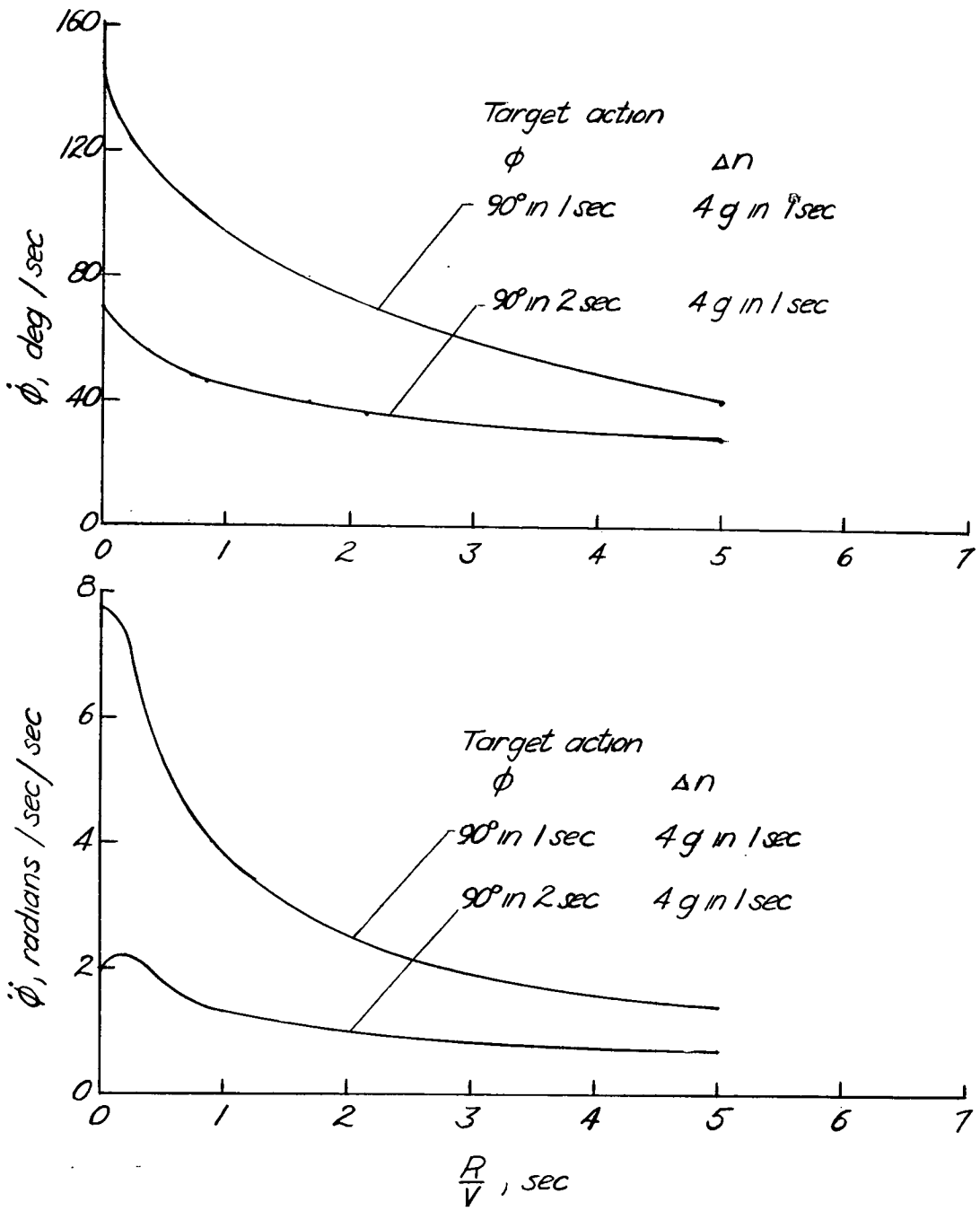

Figure 5.- Variation with R/V (range divided by true airspeed) of the maximum rolling velocity and maximum rolling acceleration required of the attacking airplane to follow exactly the target maneuver noted in the figure.

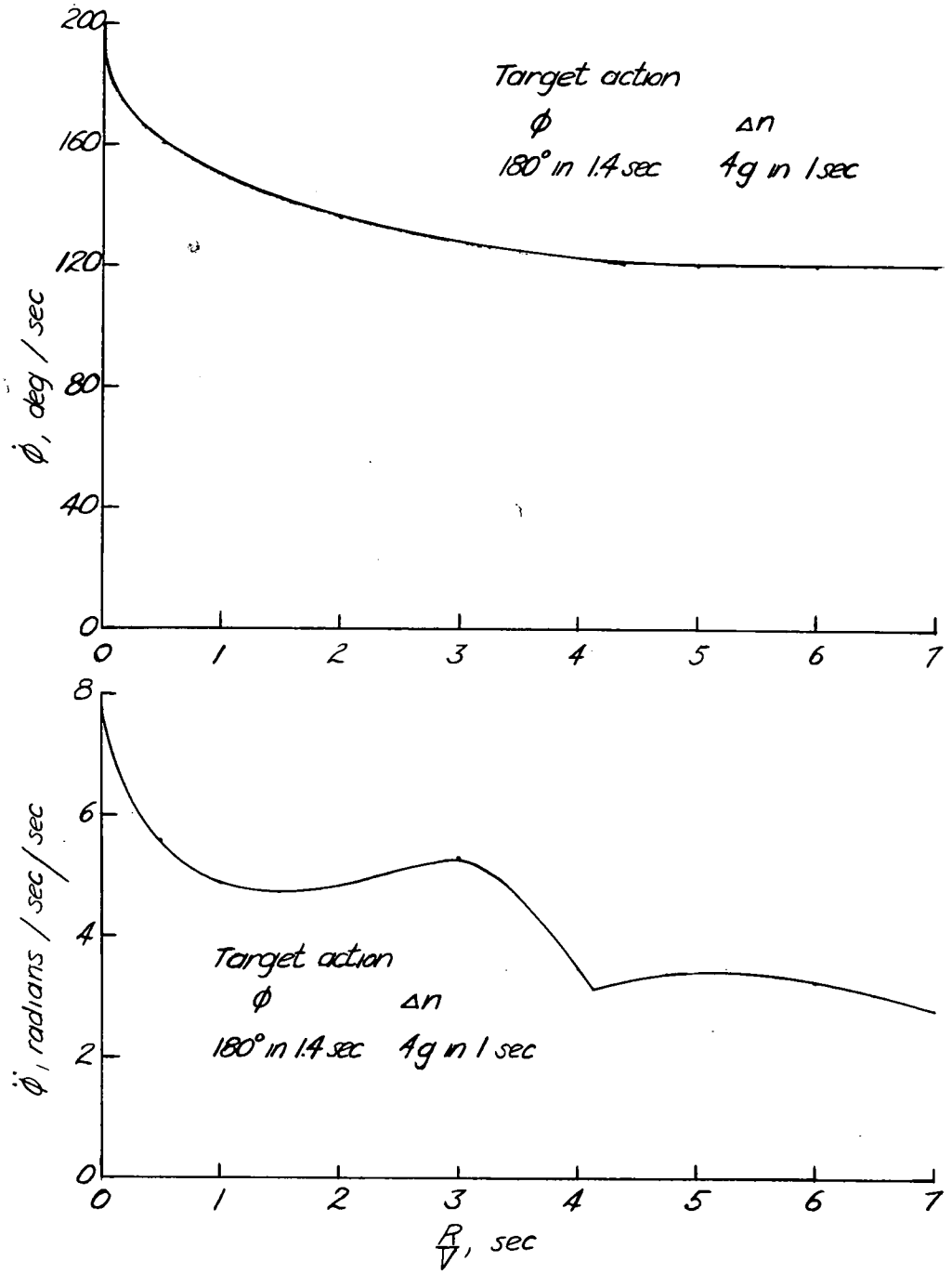

Figure 6.- Variation with R/V (range divided by true airspeed) of the maximum rolling velocity and maximum rolling acceleration required of the attacking airplane to follow exactly the target maneuver noted in the figure.

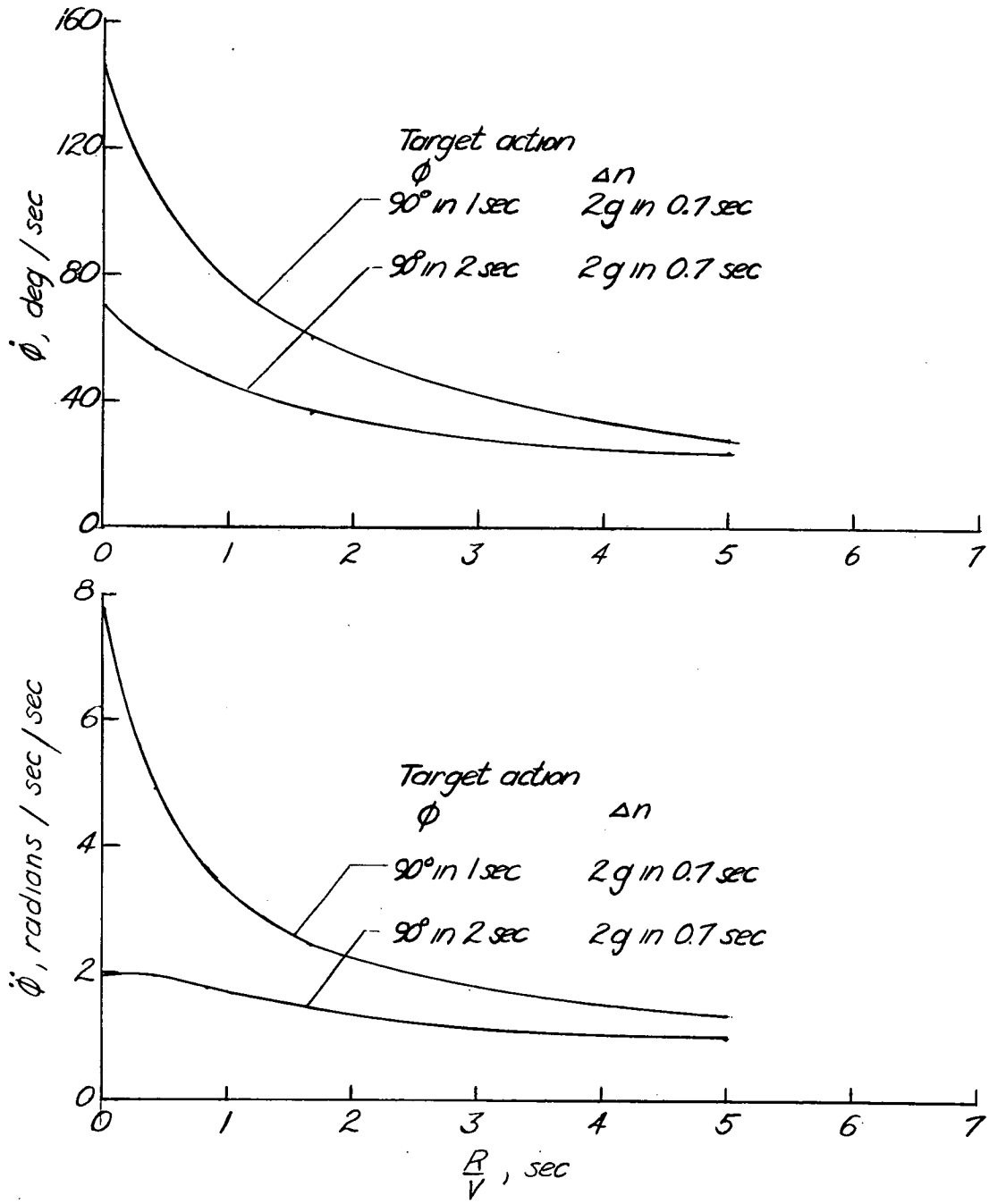

Figure 7.- Variation with R/V (range divided by true airspeed) of the maximum rolling velocity and maximum rolling acceleration required of the attacking airplane to follow exactly the target maneuver noted in the figure.

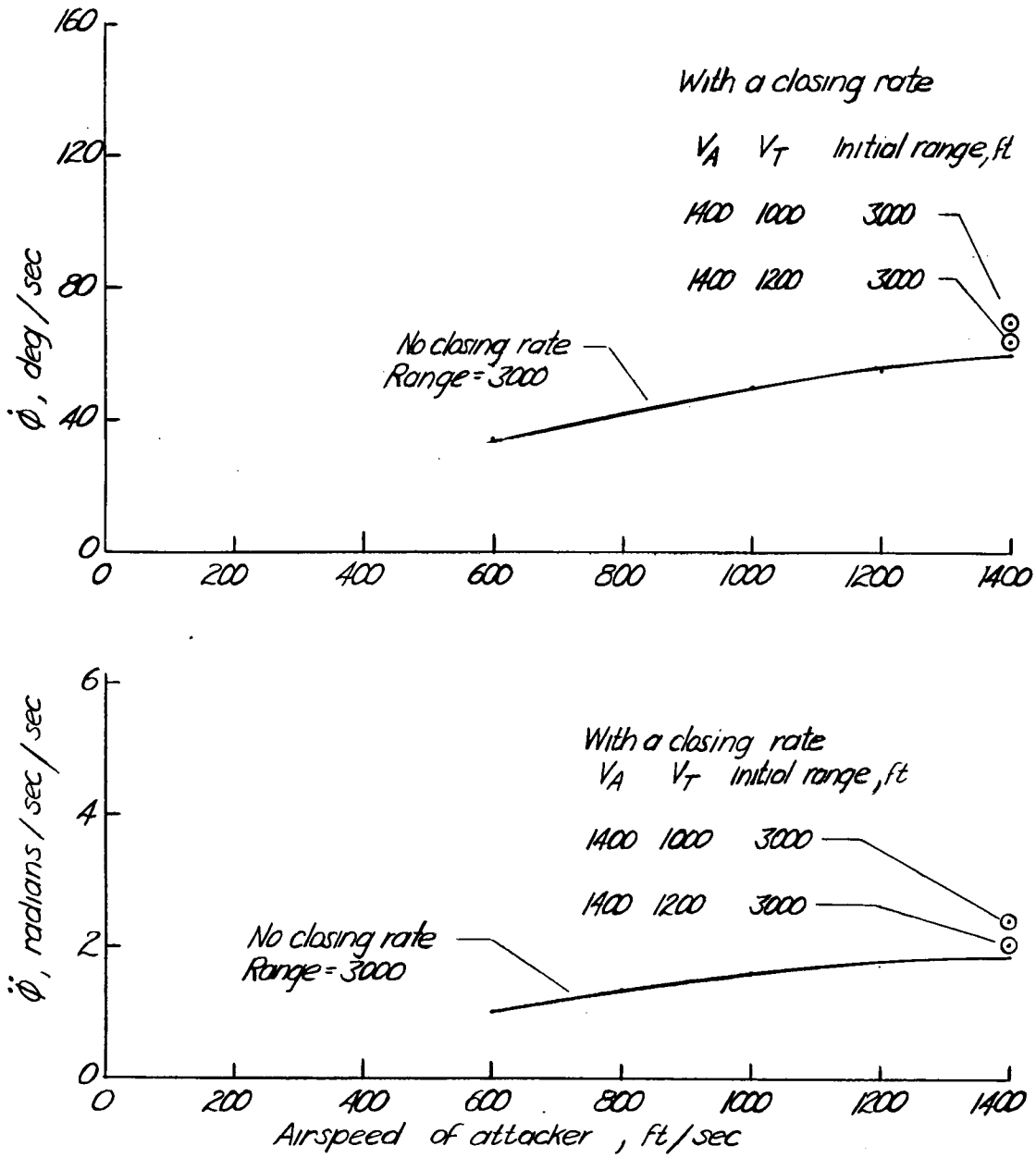

Figure 8.- Variation with airspeed of the roll requirements to follow exactly a target that rolls 90° in 1 second and increases lift acceleration an increment of 2g in 1 second.

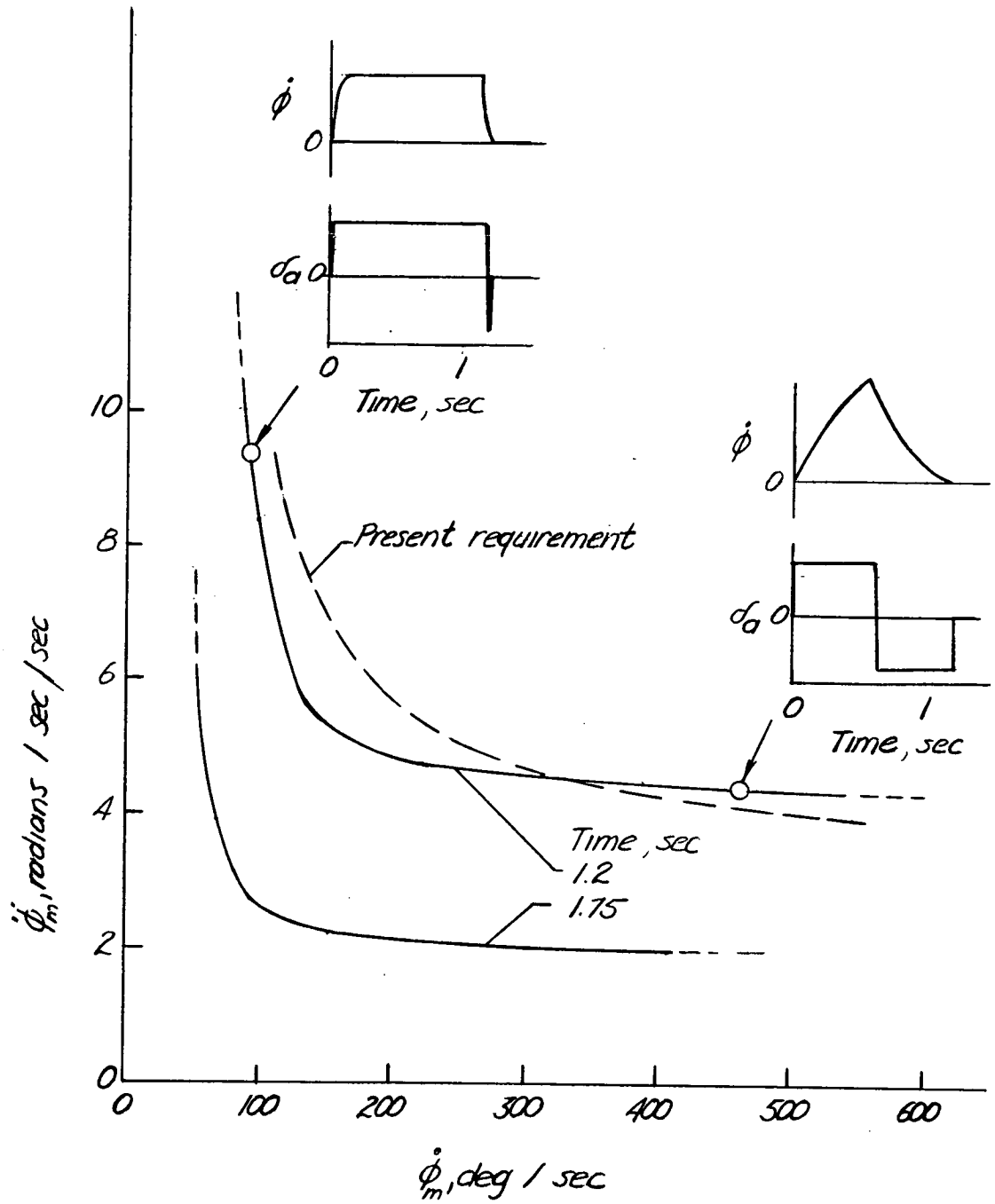

Figure 9.- Boundaries of maximum design rolling velocity and rolling acceleration needed to achieve the roll-angle history noted in the figure. Shown are the requirements to roll to and stop at 90° in 1.2 and 1.75 seconds and the requirements necessary to achieve the present requirement of passing through 100° in 1 second.

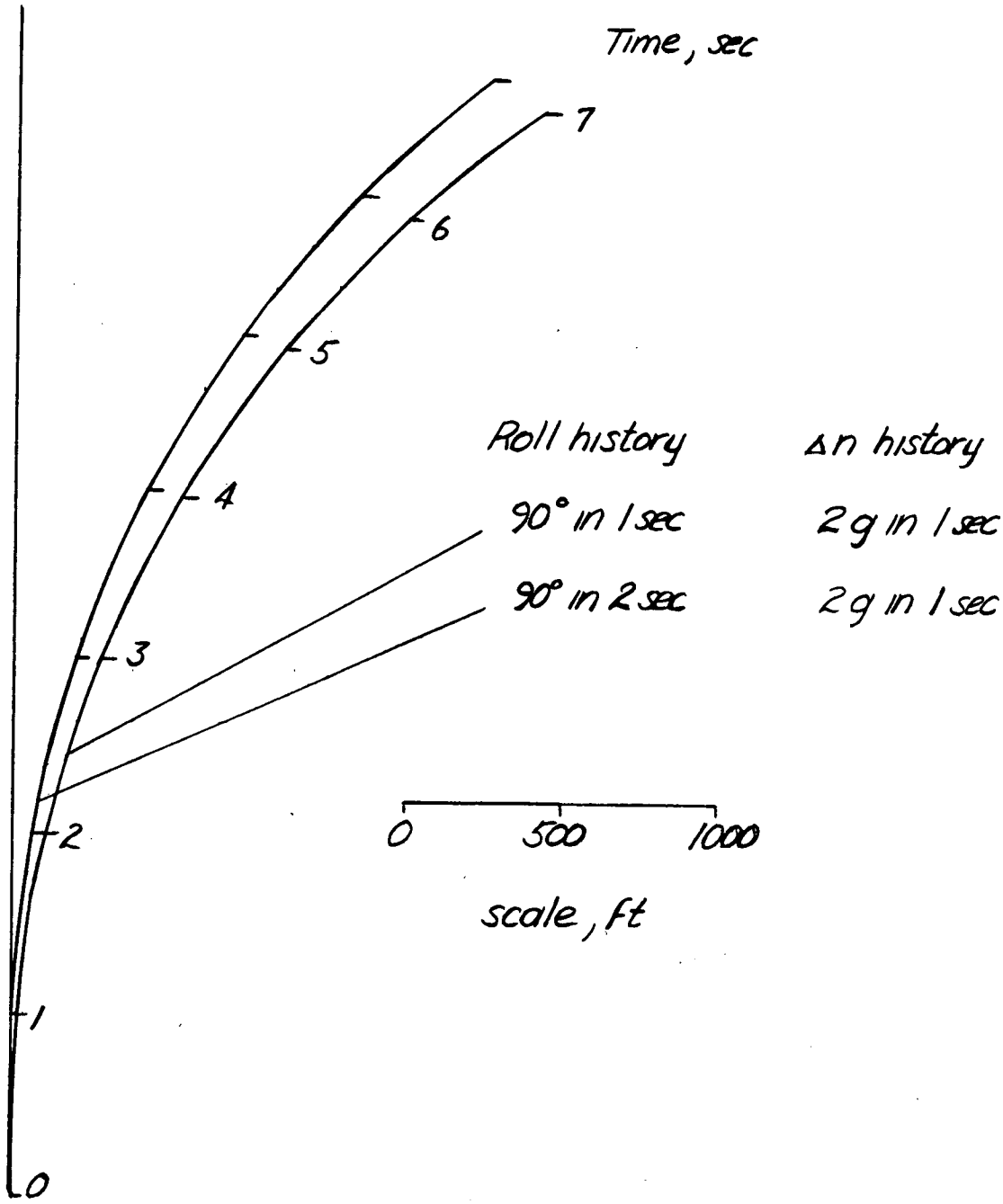

Figure 10.- The horizontal projection of the path of an airplane that performs the maneuver noted in the figure when at a true airspeed of 600 feet per second.