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# RESEARCH MEMORANDUM

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## THEORETICAL INVESTIGATION OF SOME DISCONTINUOUS YAW DAMPERS

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Classified ... Unclassified
By ... Naca Tech Pub Announcement #97 ... CHANGE)
24 Feb 56
By .....
GRADE OF OFFICER MAKING CHANGE)
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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
WASHINGTON
April 5, 1954

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RESEARCH MEMORANDUM

# THEORETICAL INVESTIGATION OF SOME DISCONTINUOUS YAW DAMPERS

By William H. Phillips and Helmut A. Kuehnel

## SUMMARY

A theoretical investigation of some discontinuous yaw dampers has been made with a modified phase-plane method to investigate the effectiveness of these devices in providing damping and to study the residual hunting often expected of discontinuous controls. In the cases of yaw-damper operation considered, the rudder runs at a constant rate and is abruptly returned to neutral before starting to run at a constant rate in the direction necessary for the next signal reversal. The points at which the rudder starts to run at a constant rate and snaps back to zero are governed by a system of contacts actuated by a sideslip vane. Some possible mechanisms for providing the types of rudder motion analyzed are discussed. The four methods of auxiliary rudder operation are as follows: to oppose the build-up of yaw, the return of yaw, buildup and return of yaw, and to oppose the yawing velocity with a limited rudder deflection.

Comparison of the damping of the four cases indicates that opposing the buildup of yaw results in poor damping, opposing the return of yaw results in good damping, but the airplane is held at some finite sideslip angle when a time lag is present. Such a situation would probably be very undesirable. Operating the auxiliary rudder to oppose both the buildup and return of yaw results in good overall damping and opposing the yawing velocity with limited rudder deflection results in better damping at high amplitudes of oscillation with somewhat reduced damping at smaller amplitudes for the one value of maximum rudder deflection considered.

The theoretical results indicate that a discontinuous control similar to those investigated may be adjusted to hunt at sufficiently small amplitudes so as not to hamper the pilot during gunnery runs and still remain effective in producing damping at larger amplitudes. The device inherently provides adequate damping over a large range of airspeed and does not oppose the pilot in steady maneuvers.

## INTRODUCTION

Present design trends toward low aspect ratio and high wing loading have in many cases had serious adverse effects upon the damping of lateral oscillations. As a result, auxiliary devices to improve the damping of lateral oscillations are coming into widespread use on high-performance airplanes. However, the yaw dampers are, in general, complex systems which usually employ a rate gyro or other sensing element to detect the motion of the airplane and to supply signals to an electronic amplifier. The resulting amplified signal is then fed to the rudder servo to produce the corrective rudder motion.

It would be desirable from a reliability and maintenance standpoint to arrive at a simpler type of yaw damper. Reference 1 presents one approach to the problem of simplification where a combination of a viscous damper in the rudder system and adjusted hinge-moment parameters cause the rudder to float with the relative wind so that it lags the sideslip angle. This system was found to improve the damping of the control-free lateral oscillation but rather accurate adjustment of the hinge-moment parameters was required. This system may not be satisfactory in the transonic speed range because of the large erratic variation of hinge-moment parameters which usually occurs in this range.

The present analysis is concerned with some discontinuous yaw dampers in which an auxiliary rudder is run at a constant rate in a direction dependent upon the direction of sideslip. The mechanical system consists only of a sideslip sensing vane fitted with a system of contacts to operate a relay which in turn controls the direction of rotation of an electric actuator on an auxiliary rudder. In the systems investigated, the auxiliary rudder actuator is assumed to allow the auxiliary rudder to snap back to zero deflection before starting to run at a constant rate in the direction necessary for the next signal reversal. Among the arrangements considered are systems in which the auxiliary rudder remains at zero or some finite deflection during part of the oscillation cycle.

Discontinuous-type yaw dampers such as those considered in this analysis would be expected to derive their advantages over present yaw dampers mainly because of their simplicity. Therefore, greater reliability, decreased weight, cost, and maintenance time would be expected of the systems. Also, the discontinuous dampers would probably remain effective through the transonic speed range. Discontinuous mechanisms, however, often produce steady hunting oscillations of small magnitude which might be objectionable in this application. The present analysis is intended to study the degree of damping produced by these devices and the amplitude of hunting oscillations associated with them. In addition, the effect of changes in airspeed on the operation of the devices is considered.

## SYMBOLS

| | |
|---|---|
| $I_z$ | aircraft moment of inertia in yaw |
| $N$ | yawing moment or ratio, $\frac{N_{\delta_r}}{N_\psi}$ |
| $R$ | constant rate of rudder movement in terms of $s$, $\frac{\dot{\delta}_r}{\omega_n}$ |
| $s$ | nondimensional measure of time, $\omega_n t$ |
| $t$ | time, sec |
| $\delta_r$ | rudder angle, deg |
| $\theta$ | angle in phase plane, deg |
| $\zeta$ | damping ratio |
| $\psi$ | angle of yaw, radians |
| $\omega$ | damped natural frequency in terms of time unit $s$, $\sqrt{1 - \zeta^2}$ |
| $\omega_n$ | undamped natural frequency of uncontrolled airplane, radians/sec |
| $P$ | period of the uncontrolled airplane, sec |
| $T_{1/2}$ | time for oscillation to damp to half amplitude |
| $C_{1/2}$ | cycles for oscillation to damp to half amplitude |
| $D$ | differential operator, $d/ds$ |
| $N_{\dot{\psi}}$ | variation of yawing moment with yawing velocity, $\frac{\partial N}{\partial \dot{\psi}}$ |
| $N_\psi$ | variation of yawing moment with yaw angle, $\frac{\partial N}{\partial \psi}$ |
| $N_{\delta_r}$ | variation of yawing moment with rudder angle, $\frac{\partial N}{\partial \delta_r}$ |
| $V_i$ | indicated airspeed, knots |

Subscript:

o initial value or value at the start of an interval

A dot over a quantity denotes differentiation with respect to actual time.

## ANALYSIS

Types of yaw-damper operation considered.- The four cases of auxiliary rudder operation considered in this report are shown graphically in figure 1 and are summarized in the following table:

| Case | Control operation to oppose - | Signal to start control moving | Signal to return control to neutral |
|---|---|---|---|
| I | Buildup of $\psi$ | Sign of $D\psi$ when $\psi$ goes through zero | $D\psi = 0$ |
| II | Return of $\psi$ | Sign of $D\psi$ after $D\psi$ changes sign | $\psi = 0$ |
| III | Buildup and return of $\psi$ | Combination of cases I and II | Combination of cases I and II |
| IV | $\psi$ with maximum $\delta_r$ limited | Sign of $D\psi$ | $D\psi = 0$ |

Equation of motion.- The present analysis utilizes the modified phase-plane method described in reference 2. In order to explain the method of expressing the results in nondimensional form, the nondimensional equation of motion of the system is first derived.

The equation is derived for a single-degree-of-freedom system oscillating in yaw and controlled by an auxiliary rudder. In this form, the equation readily lends itself to phase-plane analysis and period and damping of the oscillating system may be predicted. It will be noted that, in a single-degree-of-freedom system, the yaw angle $\psi$ is equal in magnitude to the sideslip angle $\beta$; therefore, the two notations may be used interchangeably.

In the graphical solutions of the four cases, a constant time lag is introduced to simulate the time that would actually be required for the auxiliary rudder to decelerate and return to zero deflection and to accelerate to constant velocity. The method of handling the time lag will be discussed later.

The equation of motion is as follows:

$$I_z\ddot{\psi} - \dot{\psi}\frac{\partial N}{\partial \dot{\psi}} - \psi\frac{\partial N}{\partial \psi} = \delta_r\frac{\partial N}{\partial \delta_r} \tag{1}$$

The equation is usually written in nondimensional notation in order to improve the generality of the solution.

Nondimensionalizing of equation.- First, equation (1) is divided through by $I_z$. The equation is then

$$\ddot{\psi} - \dot{\psi}\frac{\partial N/\partial \dot{\psi}}{I_z} - \psi\frac{\partial N/\partial \psi}{I_z} = \delta_r\frac{\partial N/\partial \delta_r}{I_z} \tag{2}$$

By definition then

$$\omega_n{}^2 = -\frac{\partial N/\partial \psi}{I_z}$$

$$2\zeta\omega_n = -\frac{\partial N/\partial \dot{\psi}}{I_z}$$

Making the above substitutions in equation (2) yields

$$\ddot{\psi} + \dot{\psi}(2\zeta\omega_n) + \psi(\omega_n{}^2) = -\delta_r\left(\frac{\partial N/\partial \delta_r}{\partial N/\partial \psi}\right)\omega_n{}^2 \tag{3}$$

Let

$$\frac{\partial N/\partial \delta_r}{\partial N/\partial \psi} = N$$

then,

$$\ddot{\psi} + \dot{\psi}(2\zeta\omega_n) + \psi(\omega_n{}^2) = -\delta_r N\omega_n{}^2 \tag{4}$$

Introduce nondimensional time

$$s = \omega_n t$$

and let

$$D = \frac{d}{ds} = \frac{1}{\omega_n}\frac{d}{dt}$$

Equation (4) may then be written

$$D^2\psi + D\psi(2\zeta) + \psi = -\delta_r N \tag{5}$$

Consider the right-hand side of equation (5). When the rudder is deflected at a constant rate,

$$\delta_r = \dot{\delta}_r t = \frac{\dot{\delta}_r}{\omega_n} s$$

Let

$$\frac{\dot{\delta}_r}{\omega_n} = R$$

then,

$$\delta_r = Rs$$

The dimensionless form of the equation then becomes

$$D^2\psi + 2\zeta\, D\psi + \psi = -RNs \tag{6}$$

In order to make the solution more readily applicable to a range of airspeeds and flight conditions, equations (6) is divided through by RN. Then,

$$\frac{D^2\psi}{RN} + \frac{2\zeta\, D\psi}{RN} + \frac{\psi}{RN} = -s \tag{7}$$

It is useful to plot the results of the phase-plane analysis in terms of this new variable $\psi/RN$. The following relations are readily determined from equations (4) and (7):

$$\ddot{\psi} = \frac{D^2\psi}{RN} RN\omega_n^2 \tag{8}$$

$$\dot{\psi} = \frac{D\psi}{RN} RN\omega_n \tag{9}$$

$$\psi = \frac{\psi}{RN} RN \tag{10}$$

Obtaining a graphical solution of a particular problem involves drawing a logarithmic spiral for the desired value of damping ratio and a suitable grid of lines for reading values of $D^2\psi/RN$ and $D\psi/RN$. The grid is then superimposed on the spiral with the origin located in accordance with the mode of operation (constant rudder rate or constant rudder deflection). The trajectory representing a solution may now be traced in accordance with the method described in detail in reference 2. Graphical solutions for the four cases of auxiliary rudder operation considered in this analysis are presented in figures 2 to 5. Solutions 2(a) and 3(a) are plotted with zero time lag and all other solutions are plotted with a constant time lag of $s = 0.349$. The value of $s$ is related to an angle $\theta$ in the phase plane by the equation $s = \frac{\theta}{\omega}$. Time lag $s = 0.349$ corresponds to an angle $\theta = 20^{\circ}$. The quantity $\omega$ is the damped natural frequency of the uncontrolled airplane in terms of the time unit $s$ and is related to the damping ratio $\zeta$ by the equation $\omega = \sqrt{1 - \zeta^2}$ (ref. 2).

Illustrative example.- In order to illustrate the method of obtaining a solution of a problem utilizing the modified phase-plane method, consider case I with zero time lag. The graphical solution is presented in figure 2(a). The assumed parameters and initial conditions apply to all the examples considered.

The following parameters are assumed:

$$\zeta = 0.05 (\omega = 0.9987)$$

The initial conditions are:

$$\frac{D\psi_o}{RN} = 5.0$$

$$\frac{\psi_o}{RN} = 0$$

from which may be derived from equation (7)

$$\frac{D^2\psi_o}{RN} = -0.5$$

Initially, the yaw angle is building up in a positive direction; therefore, the rudder receives a signal to run at a constant rate in the positive direction. The origin of the spiral for the condition of constant rate of rudder deflection is located at the intersection of $\frac{D^2\psi}{RN} = 0$ and $\frac{D\psi}{RN} = -1$ (ref. 2). The spiral is now rotated to pass through the initial point $\left(\frac{D\psi_o}{RN} = 5,\ \frac{D^2\psi}{RN} = -0.5\right)$ and the first interval may be traced as shown in figure 2(a). When the yawing velocity reaches zero, the rudder receives a signal to snap back to neutral; thus, the end of the first interval, designated by point 1 in figure 2(a), is fixed. Whenever the rudder snaps to neutral, the yawing acceleration undergoes a corresponding sudden change along a line of constant $\frac{D\psi}{RN}$. The magnitude of the change in $\frac{D^2\psi}{RN}$ is seen from equation (7) to be $-s$, where $s$ is the time interval during which the rudder has been running at a constant rate. The terms involving $D\psi$ and $\psi$ do not influence this jump because they do not change during the instantaneous motion of the rudder. Values of $\frac{D^2\psi}{RN}$ and $\frac{D\psi}{RN}$ are read from the grid at the end of the interval and the angle $\theta$ between the radial lines from the origin of the spiral through the initial point and the end point of the interval is read.

Thus,

$$\frac{D^2\psi}{RN} = -5.6$$

$$\frac{D\psi}{RN} = 0$$

$$\theta = 76.9^\circ$$

from which $\frac{\psi}{RN}$ may be computed from equation (7) where

$$s = \frac{\theta}{\omega} = \frac{76.9}{(57.3)(0.9987)} = 1.34$$

Thus,

$$\frac{\psi}{RN} = 5.6 - 1.34 = 4.26$$

The start of the second interval is now fixed at $\frac{D\psi}{RN} = 0$, $\frac{\psi}{RN} = 4.26$. During the second interval, the yaw angle is decreasing during which time $R = 0$ and the rudder remains neutral. The origin of the spiral is therefore located at the origin of the grids. The spiral is now rotated to pass through the initial point of the second interval and the second interval is traced. Since the auxiliary rudder remains neutral only as long as the yaw angle is decreasing, the end point of the second interval is at $\frac{\psi}{RN} = 0$, designated as point 2 in figure 2(a). The location of point 2 is determined from the fact (shown in ref. 2) that, whenever the rudder is in neutral, the value of $\frac{\psi}{RN}$ may be read from a set of vertical grid lines, with the line $\frac{D\psi}{RN} = 0$ passing through the origin of the grids for $\frac{D\psi}{RN}$ and $\frac{D^2\psi}{RN}$. This point is also the initial point for the third interval. During the third interval, the rudder is moving at a constant rate in the negative direction and the origin of the spiral is at $\frac{D^2\psi}{RN} = 0$, $\frac{D\psi}{RN} = 1$. The interval is traced in the same manner as interval 1. The above procedure is carried out until the oscillation damps or reaches a steady hunting oscillation. Time lag due to a dead space between vane contacts and time for the rudder to respond is introduced in subsequent solutions by allowing the system to operate in its present mode for a constant time interval after it receives a signal to change its mode of operation.

It should be noted that the solutions presented in figures 2 to 5 are only single trajectories. A complete solution would consist of a family of trajectories passing through an infinite number of initial points. The lines representing the trajectory in this analysis are, however, sufficiently close together to allow intermediate solutions to be interpolated in a qualitative manner. For the cases analyzed in this report, a family of trajectories will terminate in the same hunting cycle.

## RESULTS

### Theoretical Results

Time histories of $D^2\psi/RN$, $D\psi/RN$, $\psi/RN$ and $\delta_r/R$ are presented in figures 6 to 9 for the four cases of auxiliary rudder operation considered in this analysis. The time histories are obtained from the phase-plane analysis presented in figures 2 to 5 which are all plotted for the same initial conditions and parameters as presented in the previous illustration of the method of obtaining a graphical solution.

Comparison of the damping of the four cases is made for certain amplitude ranges expressed in terms of hunting amplitude. A comparison on this basis is justified in that it is the hunting amplitude that will limit the value of R or N in a practical application of a discontinuous device of the type considered. The hunting amplitude may be readily adjusted to any desired value by changing the values of R and N. The results of such a comparison are presented in the following table as time to damp to half the initial amplitude over the indicated amplitude ranges. In case 2, where the airplane approaches a steady oscillation about some sideslip angle other than zero, a value of twice the maximum sideslip occurring during the steady oscillation rather than the hunting amplitude was used in determining the amplitude ranges at which the comparison of damping is made. This method was used because the system might settle down to either right or left sideslip depending upon the initial conditions, and because the maximum sideslip would probably be the characteristic most objectionable to the pilot. The values of time to damp to half amplitude and cycles to damp to half amplitude were measured by drawing an envelope curve of the oscillations (as shown in fig. 6(a)), and measuring the time required for the specified change in amplitude and the approximate period in the corresponding range. All the cases considered in the following table are for a time lag of $s = 0.349$.

| Case | Damping over the indicated amplitude range of multiples of the hunting amplitude | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 20 to 10 | | 10 to 5 | | 5 to 2.5 | | 2.5 to 1.25 | |
| | $T_{1/2}$ | $C_{1/2}$ | $T_{1/2}$ | $C_{1/2}$ | $T_{1/2}$ | $C_{1/2}$ | $T_{1/2}$ | $C_{1/2}$ |
| I | --- | ---- | 9.3 | 1.6 | 9.2 | 1.7 | 9 | 1.9 |
| II | 2.6 | 0.4 | 2.5 | .38 | 2.3 | .74 | 2 | .74 |
| III | 4.2 | .68 | 2.5 | .49 | 1.9 | .47 | 2.1 | .52 |
| IV | 1.7 | .34 | 1.7 | .34 | 1.9 | .47 | 3 | 1.07 |

Inasmuch as the uncontrolled airplane with $\zeta = 0.05$ requires 2.2 cycles to damp to half amplitude, the large improvement in damping in cases II, III, and IV is apparent.

Figures 6(a) and 6(b) show the motion of the system when the auxiliary rudder behaves in accordance with case I. Figure 6(a) is for zero time lag and figure 6(b) is for a constant time lag. Comparison of figures 6(a) and 6(b) indicates that the effect of time lag is to reduce the damping.

Case II offers considerably better damping than case I over the amplitude range investigated. Reference to figure 7 indicates that this case tends to hold the hunting down to relatively small amplitudes; however, the feature of opposing the return of yaw also tends to hold the system at some finite sideslip angle when a time lag is present.

The damping of case III seems to be best at low amplitudes around 5 to 2.5 times the hunting amplitude with a decrease in damping toward higher amplitudes. Time histories of case III are presented in figure 8. The irregularities of the oscillation in figure 8 from around $s = 13$ to $s = 21$ seem to occur during the transition from positive damping to steady hunting. During this transition period, the oscillation may reach a value of $\psi/RN$ lower than the hunting amplitude where the system is unstable. Therefore, the oscillation tends to build up again to a value greater than the hunting amplitude. This procedure may repeat for several cycles before the system settles down to a steady hunting condition.

Case IV differs somewhat from the previous three cases in that the rudder deflection is limited. Therefore, the equation of motion of the system as presented in the analysis section for constant rate of rudder motion does not apply exactly to this case. The theory of reference 2, however, may be applied to this case. Time histories for a particular case in which $\frac{\delta_{r_{max}}}{R} = 1.57$ are shown in figure 9. This solution is less general than those presented previously inasmuch as the value of $\frac{\delta_{r_{max}}}{R}$ ordinarily would not remain constant under various flight conditions. A constant value of $\frac{\delta_{r_{max}}}{R}$ would require the limiting rudder deflection to increase directly with the period of the oscillation. Additional solutions for various values of $\frac{\delta_{r_{max}}}{R}$ would therefore be required to determine the behavior of this system at various values of airspeed if the maximum rudder deflection remained constant.

For the example shown, best damping occurs during large-amplitude oscillations when the auxiliary rudder remains on its stop during part of the oscillation cycle. Since the auxiliary rudder runs at a constant rate, the period of oscillation determines whether the auxiliary rudder reaches its stop and how long it remains on the stop. Although there is a reduction in damping at the lower amplitudes for this case, the damping at amplitudes around 5 to 2.5 times the hunting amplitude remains the same as for case III over the same range. However, at even smaller amplitudes the damping decreased considerably from the damping of case III.

## Application of Results to a Given Set of Conditions

Application of the results for given values of airspeed, rudder rate, and so forth, may best be illustrated by an example. In this example, three values of airspeed are assumed along with the period of oscillation and natural frequency of the uncontrolled airplane at each airspeed. A value for the quantity N of the particular airplane being considered must be determined and the rate of auxiliary rudder movement $\dot{\delta}_r$ assumed. For this example

$$N = 0.53$$

$$\dot{\delta}_r = 5^{\circ}/\text{sec}$$

when N, $\dot{\delta}_r$, and $\omega_n$ are known, the quantity RN is determined for each airspeed. The following table summarizes the above conditions.

| $V_i$, knots | P, sec | $\omega_n$, radians/sec | RN |
|---|---|---|---|
| 100 | 4 | 1.57 | 0.0294 |
| 200 | 2.5 | 2.51 | .0184 |
| 330 | 1.6 | 3.91 | .0118 |

Since the values of $(\zeta)$ and $(N)$ are essentially independent of airspeed, it is necessary to determine only the natural frequency of the uncontrolled airplane $\omega_n$ and the quantity RN for each airspeed and apply them to the results of the phase-plane analysis in accordance with equations 8 to 10 to obtain time histories of the airplane motion at the assumed airspeed. The present example is worked out with the

auxiliary rudder behaving in accordance with case III by reading values of $\frac{D\psi}{RN}$ and $\frac{\psi}{RN}$ from figure 8 at regular intervals of nondimensional time s. These quantities, along with $\omega_n$ and RN for a particular airspeed, are substituted into equations (9) and (10) to determine $\dot{\psi}$ and $\psi$; also, s is converted to real time where $t = \frac{s}{\omega_n}$. The resulting time histories are presented in figures 10 to 12 for speeds of 100, 200, and 300 knots, respectively. In general, only the yawing velocity $\dot{\psi}$ and the yaw angle $\psi$ are of practical interest and therefore are the only quantities plotted in figures 10 to 12.

In applying the results shown in figure 8 to various values of airspeed, the time lag in seconds in operation of the rudder must be assumed to vary inversely as the airspeed. In practice, this condition might not be exactly fulfilled, although the time required for the rudder to snap back to neutral from a deflected position would probably decrease with increasing airspeed because of the increased restoring moment on the rudder.

Some effects of speed on the hypothetical airplane and yaw damper combination (controlled airplane) may be derived from a comparison of the envelope curves of figures 10 to 12. A comparison of the damping at the above three airspeeds was made from a common initial yaw angle. Time to damp to half the initial amplitude and cycles to damp to half the initial amplitude were determined from each figure with $\psi = \pm 0.05$ radian (or $\pm 2.87^{\circ}$) as the initial yaw angle. The above quantities along with hunting amplitude are tabulated below to facilitate comparison.

| Speed, knots | $T_{1/2}$, sec | $C_{1/2}$ | Hunting amplitude, radians |
|---|---|---|---|
| 100 | 1.85 | 0.5 | ±0.004 |
| 200 | 1.6 | .7 | ±.0025 |
| 330 | 1.35 | .9 | ±.0015 |

From the above table it may be concluded that, over the speed and amplitude range investigated, the effect of increasing speed is to decrease the time to damp to half the assumed initial amplitude, increase cycles to damp to half the initial amplitude, and reduce the hunting amplitude.

Although the preceding comparison was made for a given initial amplitude of disturbance, there is some justification for making a comparison on the basis that the initial amplitude varies inversely as the airspeed, because disturbances due to rough air or aileron yawing moments are likely to be greater at lower values of airspeed. For this purpose, the entire time histories of figures 10 to 12 may be compared directly.

## PRACTICAL CONSIDERATIONS FOR YAW-DAMPER DESIGN

Possible methods of auxiliary rudder operation.- The preceding analysis has not been concerned with practical methods of achieving the various types of yaw-damper operation considered. Although no attempt is made in the present report to study the engineering problems involved in the design of such mechanisms, some thought has been given to possible means of achieving yaw-damper operation of the types analyzed. The reasons for selecting these particular methods of operation are based on some practical considerations which are now discussed briefly.

In designing a discontinuous control, the first type of mechanism usually considered is an on-off control which results in a square-wave motion of the control element (in this case the auxiliary rudder). Such a method appears undesirable for the present application, however, partly because of its jerky action and partly because the large power required to move the rudder rapidly would probably require the use of a pneumatic or hydraulic actuator which can withdraw short bursts of high power from a source of stored energy. These devices, although they may be practical, introduce elements of questionable reliability which it was desired to avoid. If the rudder were arranged to run back and forth at a constant rate with the reversal points determined as a function of yaw angle, a smoother type of control would be obtained and the reduced power requirements would probably allow the use of an electric actuator. The triangular-wave form of the rudder motion introduced by this type of operation, however, introduces phase lag of $90^{\circ}$ behind the control signal, whereas a phase lead of $90^{\circ}$ ahead of the yaw is required for obtaining optimum damping of the yawing oscillations. If a yaw sensitive device is used as the sensing element, some means to introduce a phase lead of $180^{\circ}$ in the control signal would be required. No mechanism capable of providing this much phase lead was found. Therefore, an effort was made to reduce the phase lag associated with the control motion. By use of the controls analyzed previously, which require the rudder to run at a constant rate and then snap back to neutral before starting on the following cycle, the phase lag of the rudder motion is reduced. No detailed consideration has been made of the power requirements for these types of control operation. Use of a preloaded

centering spring on the rudder might be required to return the rudder rapidly to neutral. The actuator which displaces the rudder would have to overcome the restoring tendency of this spring together with the aerodynamic restoring moments on the rudder. It does not appear, however, that the instantaneous power requirements would be as large as those associated with an approximately square-wave type of rudder motion.

Some possible means of achieving the yaw-damper operation of the four cases considered in this report are presented in figure 13. The sideslip sensing device for this illustration is a simple vane. It is shown later that a vane offers certain advantages as compared to other sensing devices such as a rate or displacement gyro or a lateral accelerometer. A set of light electrical contacts is fixed to the sideslip vane shaft and the mating contacts are mounted on a yoke or pair of yokes which pivots about the vane shaft. The yoke may be rotated by the sideslip vane against a light friction restraint. A circuit through a low-amperage power supply to one of the relay coils is completed through the vane and yoke contacts. The relay shown in figure 13 will, in turn, complete a circuit to the auxiliary rudder actuator.

Case I.- The contact arrangement for opposing the buildup of yaw is presented in figure 13(a). As the airplane yaws, a vane contact closes a circuit through one of the yoke contacts. The vane is represented schematically in figure 13 as a streamlined airfoil section. The vane drags one of the yokes with it while the other yoke is restrained by a mechanical stop. One relay coil is actuated depending upon the direction of yaw and, in turn, closes a circuit to the auxiliary rudder actuator. When the yawing velocity becomes zero, the yoke is restrained at its maximum deflection by friction. As the vane starts to return to neutral, the circuit is broken and the rudder is allowed to snap back to neutral. The rudder remains neutral as the yaw angle is decreased and the displaced yoke is returned to its stop by the yoke return arm. This arm incorporates a preloaded spring strong enough to overcome the friction restraint on the yoke. The purpose of the spring is to allow the vane to deflect by compressing the spring against the undisplaced yoke which is restrained by a stop.

Case II.- The contact arrangement for opposing the return of yaw is shown in figure 13(b). As the yaw angle builds up in this case, there is no complete circuit to either relay coil. The wiper arm contacts the wiper strip and the opposite vane contact drags the yoke to a deflected position depending on the yaw angle. As the yawing velocity reverses, however, the pair of contacts on the same side as the wiper arm is closed and a circuit through one relay coil is completed and the rudder actuator is thus energized. When the yaw angle again becomes zero, the wiper arm breaks the circuit and the rudder returns to neutral before the cycle repeats in the opposite direction. A variation of this

arrangement, simply a reversal of the connections to the wiper strip, may also be used to give the contact action required for case I.

Case III.- The contact arrangement for opposing the buildup and return of yaw is presented in figure 1(c). This case is a combination of cases I and II. The contact action required is obtained from a variation of case II by simply connecting the wiper strips as in figure 13(c). As the yawing velocity is increasing, a set of vane and yoke contacts close the circuit through the wiper strip. As the yawing velocity reverses, the circuit is momentarily broken and the rudder is allowed to return to neutral. The opposite set of vane and yoke contacts then completes the circuit and the rudder runs in the opposite direction.

Case IV.- The contact arrangement for opposing the yawing velocity is presented in figure 13(d). In this case the yaw damper opposes the yawing velocity and the auxiliary rudder deflection is limited. Limiting the rudder deflection may be accomplished by a pair of stops on the auxiliary rudder and does not affect the contact arrangement. Depending upon the direction of yaw, the vane contact will close a circuit through one yoke contact to the relay. The vane will drag the yoke with it and as long as the yawing velocity does not change sign the rudder actuator will receive a signal to run the auxiliary rudder in the corresponding direction. After the auxiliary rudder has reached its maximum deflection, it will remain there until the yawing velocity reverses, at which time the auxiliary rudder will first return to neutral and then start to run in the opposite direction.

A sketch of an auxiliary rudder actuator applicable to this type of control is presented in figure 14. All the gears from the motor to the auxiliary rudder cable drum are in constant mesh. Gears A and B are faced with a friction disk to mate the clutch facings C and D. The three wires from the clutch solenoids are connected through a power supply to the relay contacts shown in figure 13. When the yaw damper is in operation, the motor continually turns in one direction. The direction of rotation of the auxiliary rudder cable drum is dependent upon which pair of clutch facings are engaged (A-C or B-D). Each clutch facing may be engaged by one of the clutch solenoids depending upon the signal from yaw vane contacts. When neither clutch solenoid is engaged, the auxiliary rudder is free to float back to neutral. If desired, the return to neutral may be aided by a preloaded centering spring on the auxiliary rudder.

Discussion of sensing devices.- Within the limits of approximation of the foregoing theory, either a sideslip vane, a lateral accelerometer, or a displacement gyro might be used to operate the contact mechanism for the yaw damper. The displacement gyro, however, would sense long-period heading changes from a straight course as well as short-period oscillations. Additional rather complicated mechanisms would be

required to allow the device to function as a yaw damper during turns or other maneuvers involving a change in heading.

The use of a sideslip vane or a lateral accelerometer avoids the sensitivity to heading changes. A relatively large accelerometer mass, however, would probably be required to give operating forces for the contact mechanism equivalent to those obtainable from a relatively small vane.

A rate gyro is not equivalent to the preceding devices inasmuch as it gives a signal which leads the yawing displacement by 90°. The additional lead provided by a rate gyro would allow the use of other, perhaps simpler, contact arrangements or methods of control operation. The rate gyro, however, gives a signal in a steady turn which would introduce additional problems.

Comparison with conventional yaw damper.- A conventional linear yaw damper using a rate gyro as a sensing element tends to provide increased amounts of rudder deflection in oscillations at higher values of dynamic pressure because the yawing velocity for a given amplitude of yaw varies inversely as the period of the oscillation. For this reason, if such a device is adjusted to provide optimum damping in a high-speed condition, it may, unless special provisions are made, be relatively ineffective in the low-speed landing-approach condition. For the same reason, if the device is adjusted to provide optimum damping in the low-speed condition, the effective large increase in gain with increasing dynamic pressure, together with lag or dead spot in the mechanisms, may result in instability or hunting in the high-speed conditions. The yaw dampers investigated in the present report tend to reverse this condition and provide increased rudder deflection at lower values of airspeed. As a result, no special provisions are required to change gains as a function of dynamic pressure.

The yaw dampers considered herein have an inherent tendency to hunt at small amplitudes. As shown previously, however, the hunting amplitude may be relatively small even though the damping at larger amplitudes is adequate. A hunting amplitude of ±0.0015 radian, or ±1.5 mils, may be difficult for the pilot to detect except in conditions of very smooth air. Although conventional yaw dampers are intended to operate as linear systems, nonlinear effects such as deadspot or friction frequently cause a similar tendency to hunt at small amplitudes.

A yaw damper using a rate gyro as a sensing element gives a signal opposing the pilot in a steady turn. Therefore, additional equipment is usually provided to cause the signal to disappear in a steady turn. The use of a sideslip vane as a sensing device in the system studied in this report avoids this problem.

Effect of pilot control.- As shown in figure 7(a), the arrangement in case II, which opposed the return of the airplane to zero yaw, produced excellent damping but resulted in a small steady-state sideslip. If the pilot used his controls in an effort to reduce this sideslip, the yaw damper would apply additional rudder to oppose him, and a condition might develop in which the pilot was fighting the yaw damper. Such a situation would probably be very undesirable and the arrangement of case II is therefore considered unsatisfactory. This difficulty is avoided with the other control arrangements studied.

## CONCLUDING REMARKS

A theoretical analysis of some discontinuous yaw dampers has been made to determine the degree of damping produced by these devices and the relative magnitude of residual hunting to be expected of different discontinuous-type controls. In the four cases of yaw-damper operation considered in this report, the rudder runs at a constant rate and is abruptly returned to neutral before reversing. The points at which the rudder motion starts and reverses are governed by a system of contacts actuated by a sideslip vane. The four methods of auxiliary rudder operation are as follows: to oppose the buildup of yaw, the return of yaw, buildup and return of yaw, and to oppose the yawing velocity with a limited rudder deflection.

Comparison of the damping of the four cases indicates that opposing the buildup of yaw results in poor damping, opposing the return of yaw results in good damping, but the airplane is held at some finite sideslip angle when a time lag is present. Such a situation would probably be very undesirable and therefore this case is considered unsatisfactory. Operating the auxiliary rudder to oppose both the buildup and return of yaw results in good overall damping. Operating the auxiliary rudder to oppose the yawing velocity with a limited rudder deflection results in better damping at high amplitudes of oscillation with somewhat reduced damping at smaller amplitudes for the one value of maximum rudder deflection considered.

The effect of change in airspeed was studied for the most promising system, that of operating the auxiliary rudder to oppose both the buildup and return of yaw.

Over the speed and amplitude range investigated, the effect of increasing speed is to decrease the time to damp to half the initial amplitude, increase cycles to damp to half the initial amplitude and reduce the hunting amplitude. The hunting amplitude can be made sufficiently small (about ±1.5 mils at an airspeed of 330 knots) that it would probably not be objectionable in gunnery runs, while good damping is maintained at larger amplitudes.

Since the type of yaw damper considered in this report produces rudder deflections proportional to the period of oscillation, the control remains effective in producing damping at low speeds as well as high speeds. Also, use of a sideslip vane as a sensing device does not give a rudder control signal opposing the pilot in a steady turn as would a linear yaw damper with a rate-gyro-type sensing element.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., February 12, 1954.

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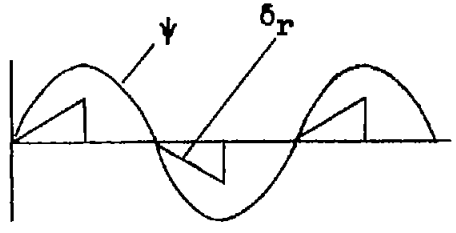
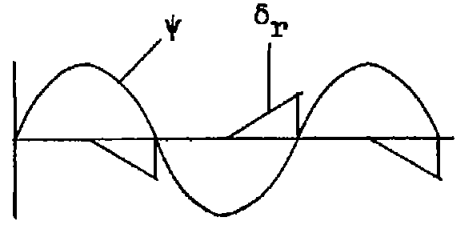
1. Curfman, Howard J., Jr., Strass, H. Kurt, and Crane, Harold L.: Investigations Toward Simplification of Missile Control Systems. NACA RM L53I21a, 1953.

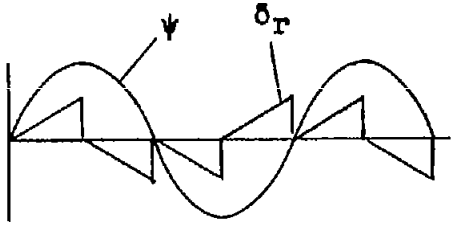
2. Phillips, William H.: Graphical Solution of Some Automatic-Control Problems Involving Saturation Effects With Application to Yaw Dampers for Aircraft. NACA TN 3034, 1953.



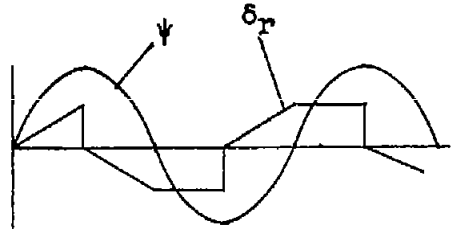

(a) Case I – oppose build-up of yaw.




(b) Case II – oppose return of yaw.

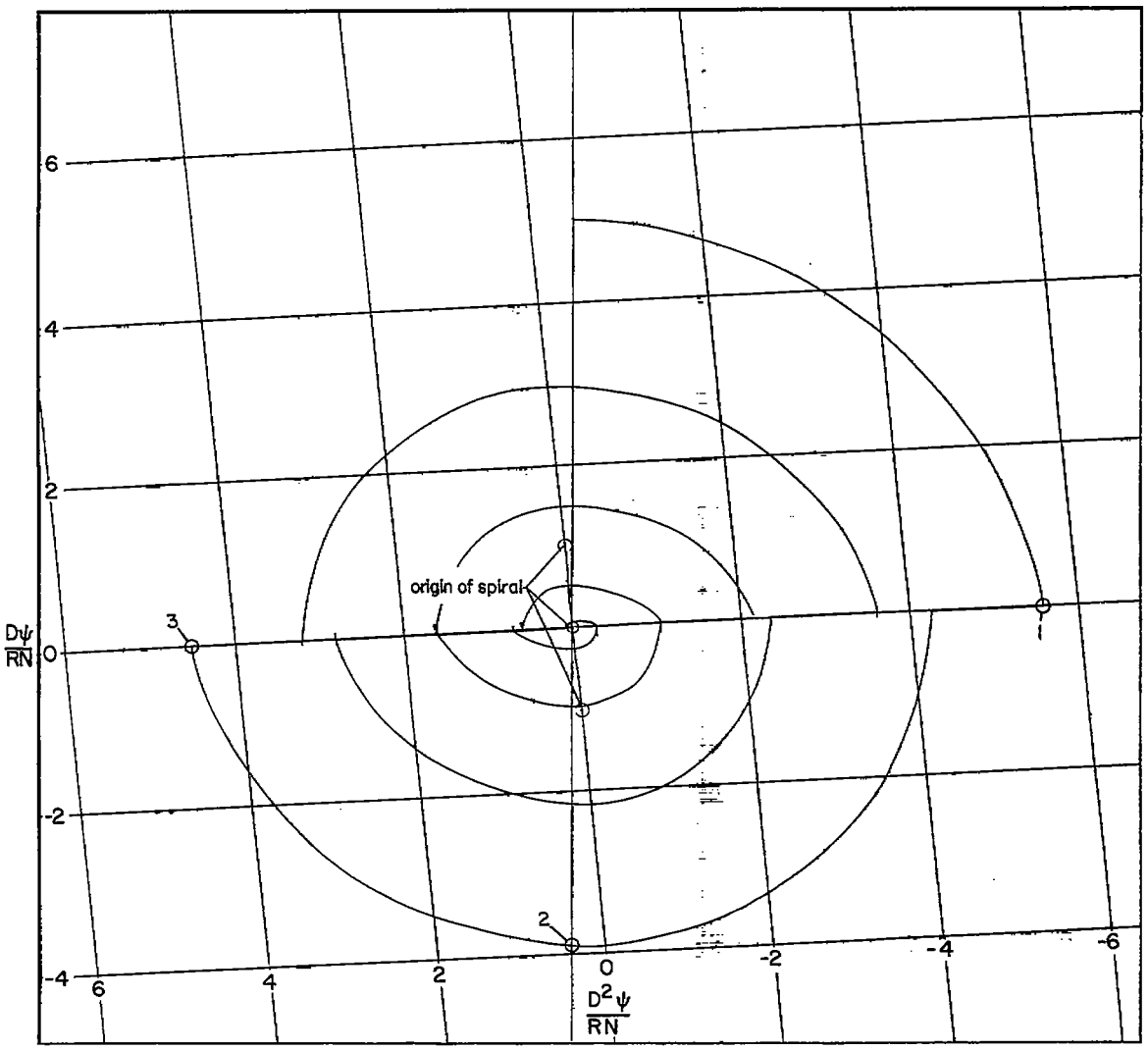



(c) Case III – oppose build-up and return of yaw.



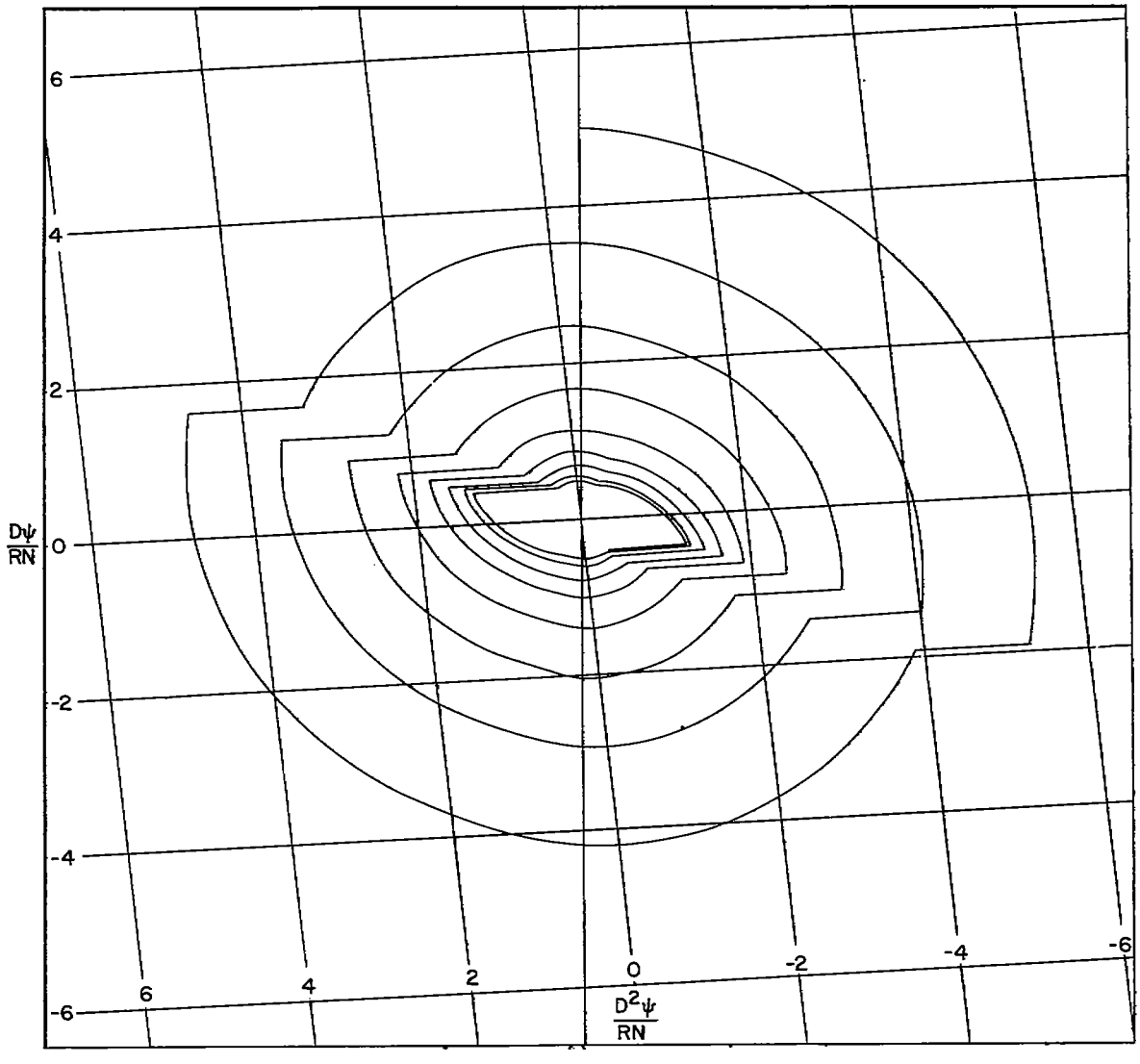

(d) Case IV – oppose yawing velocity.

Figure 1.- Rudder operation for the four discontinuous yaw-damper arrangements considered.



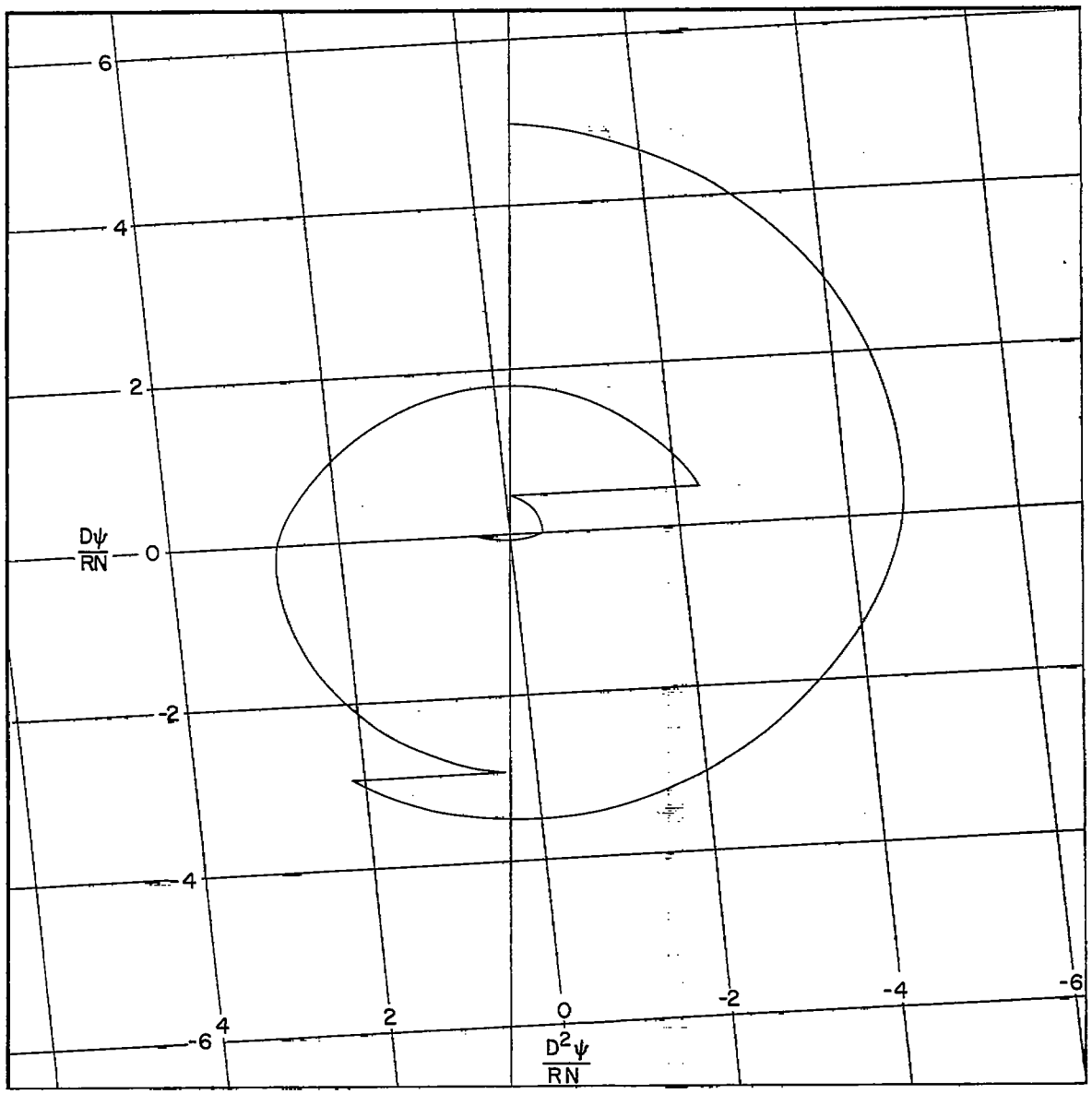

(a) Zero time lag.

Figure 2.- Graphical construction for case I (rudder operating to oppose the build-up of yaw).



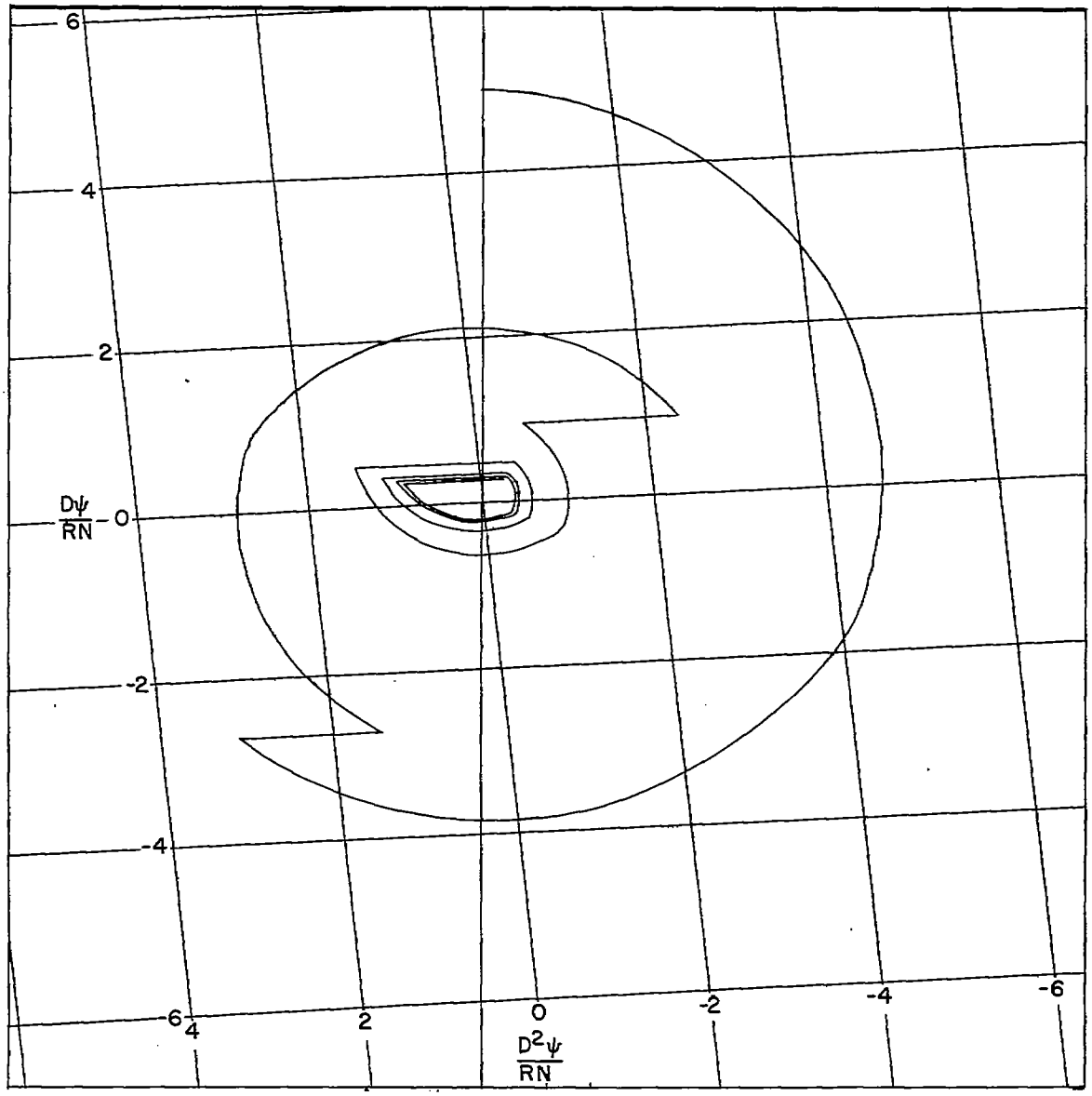

(b) Time lag s = 0.349.

Figure 2.- Concluded.




(a) Zero time lag.

Figure 3.- Graphical construction for case II (rudder operating to oppose the return of yaw).




(b) Time lag s = 0.349.

Figure 3.- Concluded.

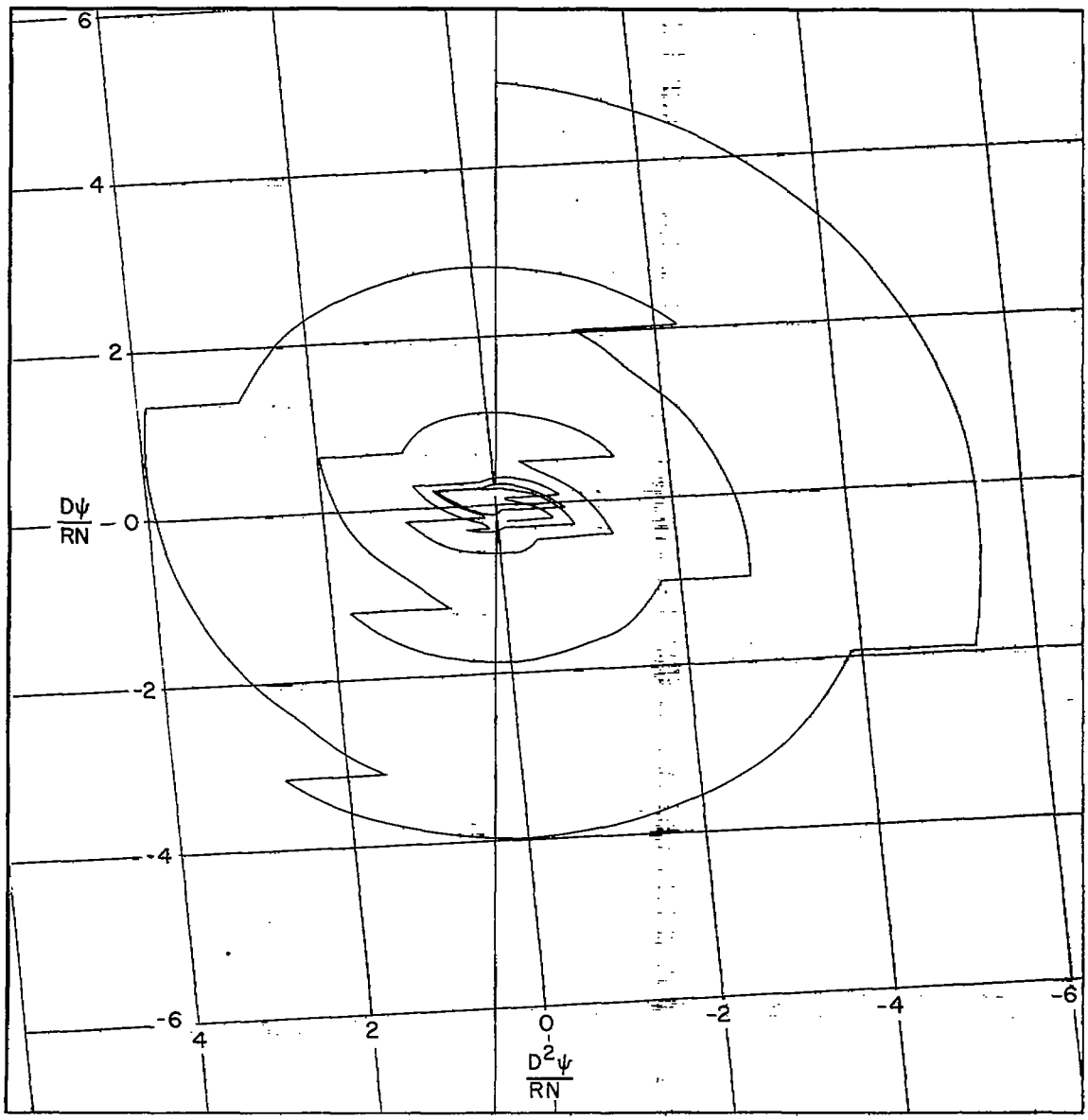



Figure 4.- Graphical construction for case III (rudder operating to oppose build-up and return of yaw). Time lag s = 0.349.

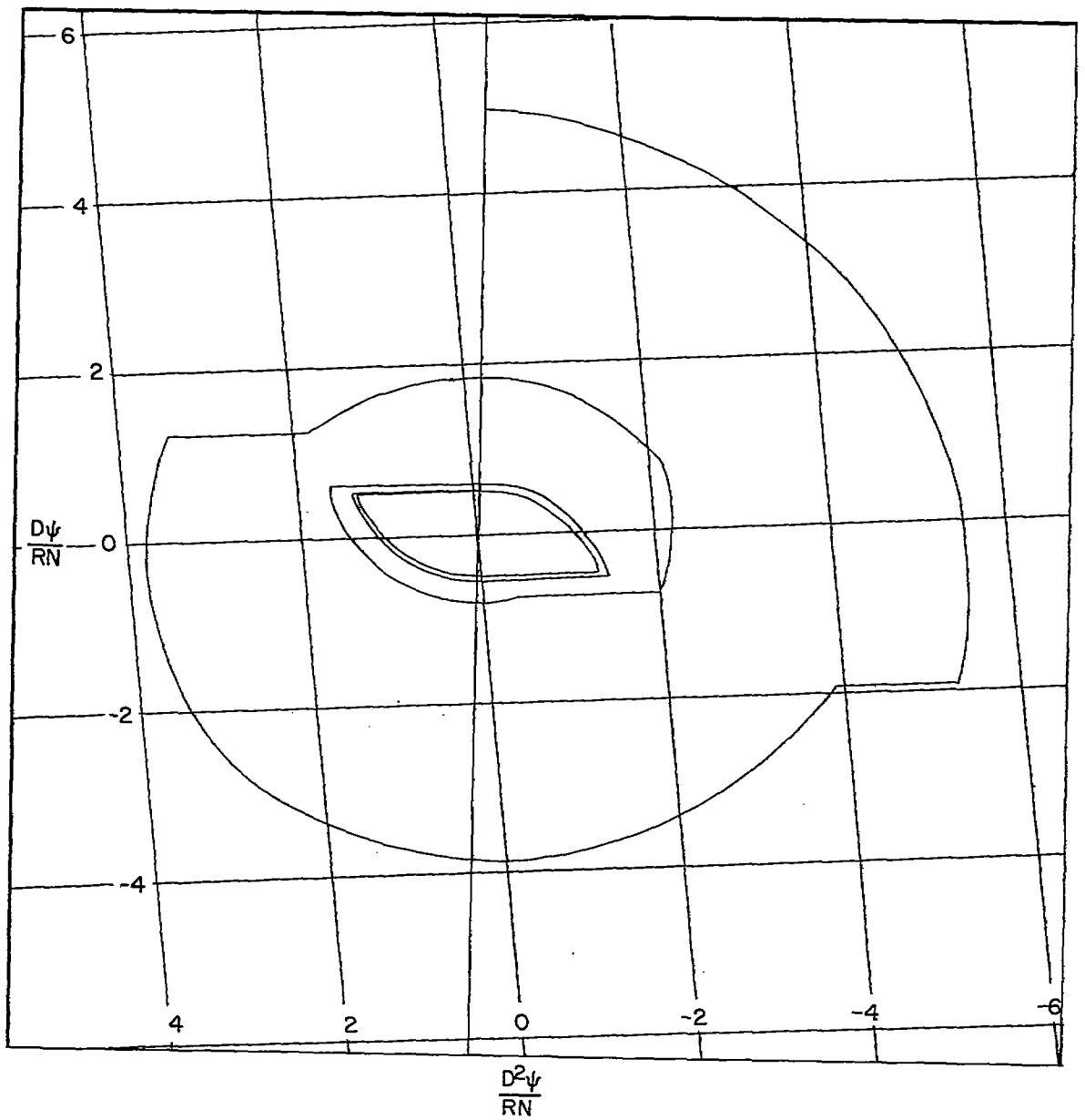
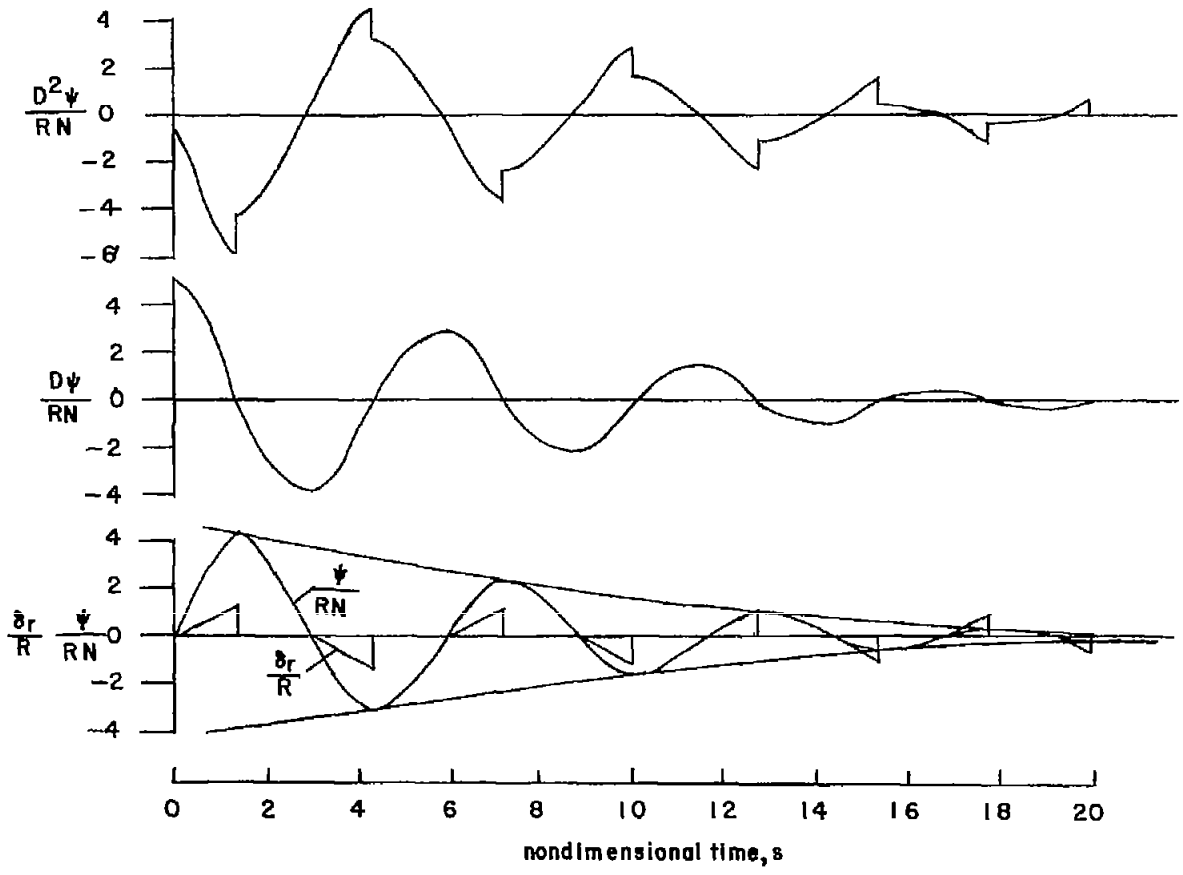
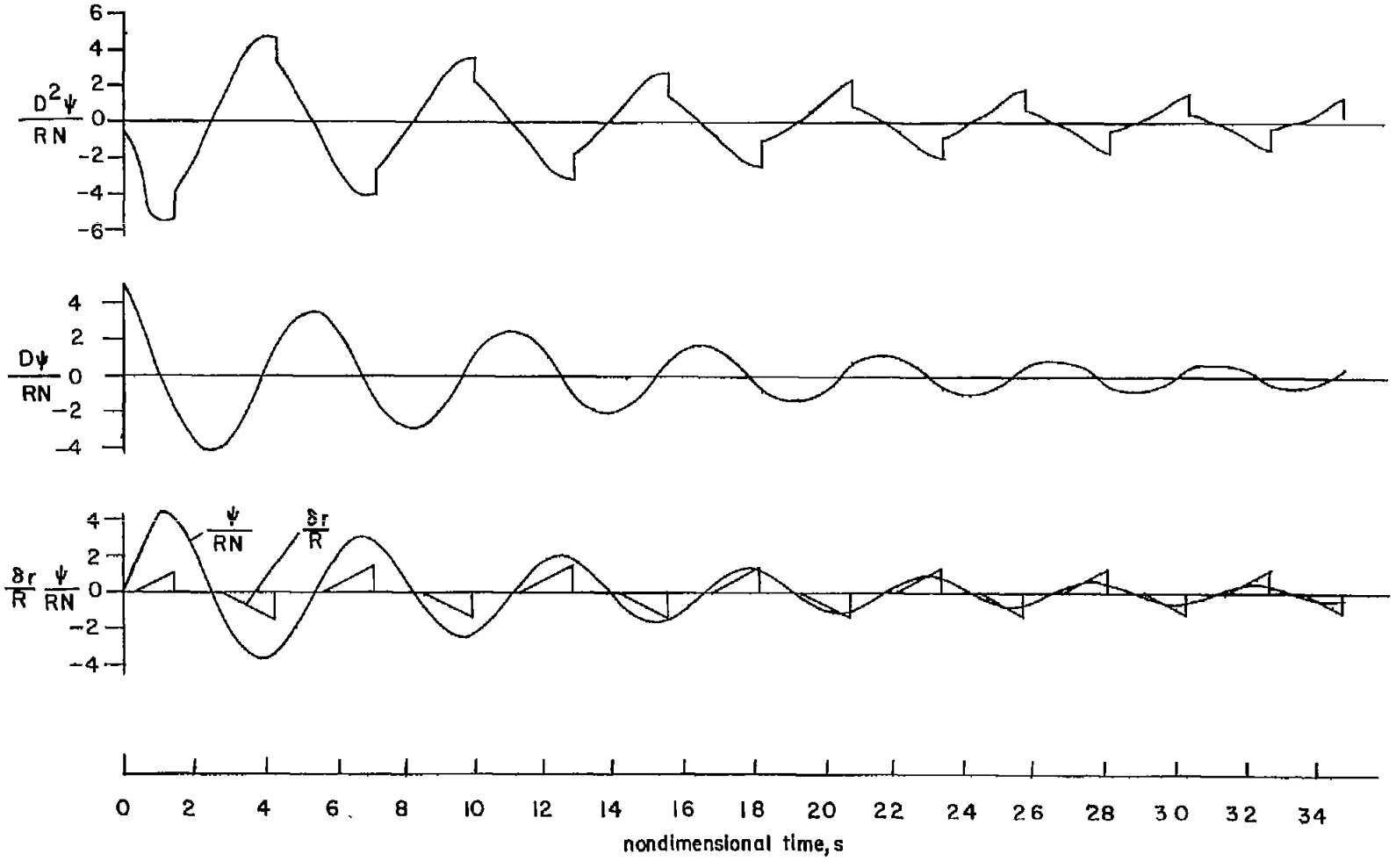



Figure 5.- Graphical construction for case IV (rudder operating to oppose yawing velocity). Time lag s = 0.349.



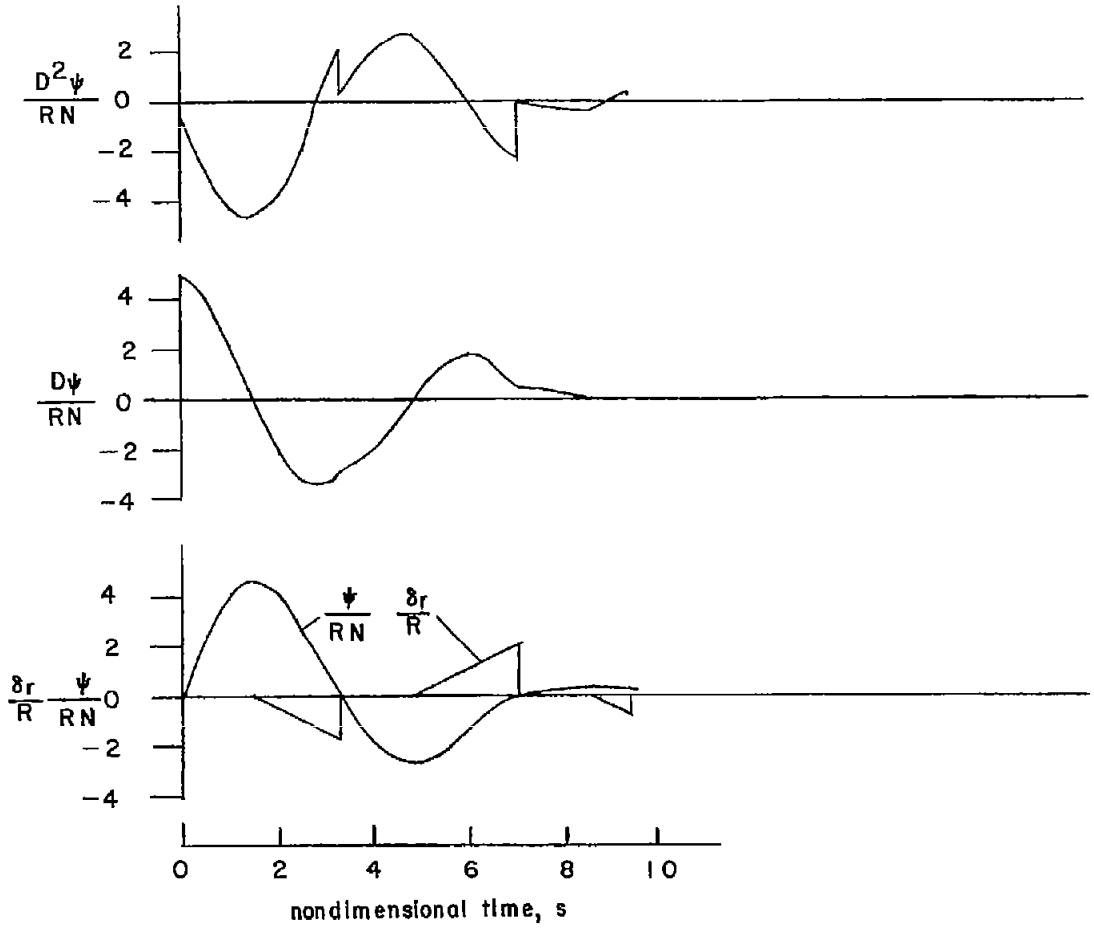

(a) Zero time lag.

Figure 6.- Time history of $\frac{D^2\psi}{RN}$, $\frac{D\psi}{RN}$, $\frac{\psi}{RN}$, and the rudder angle for case I (rudder operating to oppose the build-up of yaw). Envelope curve for reading values of damping shown for $\frac{\psi}{RN}$ curve.



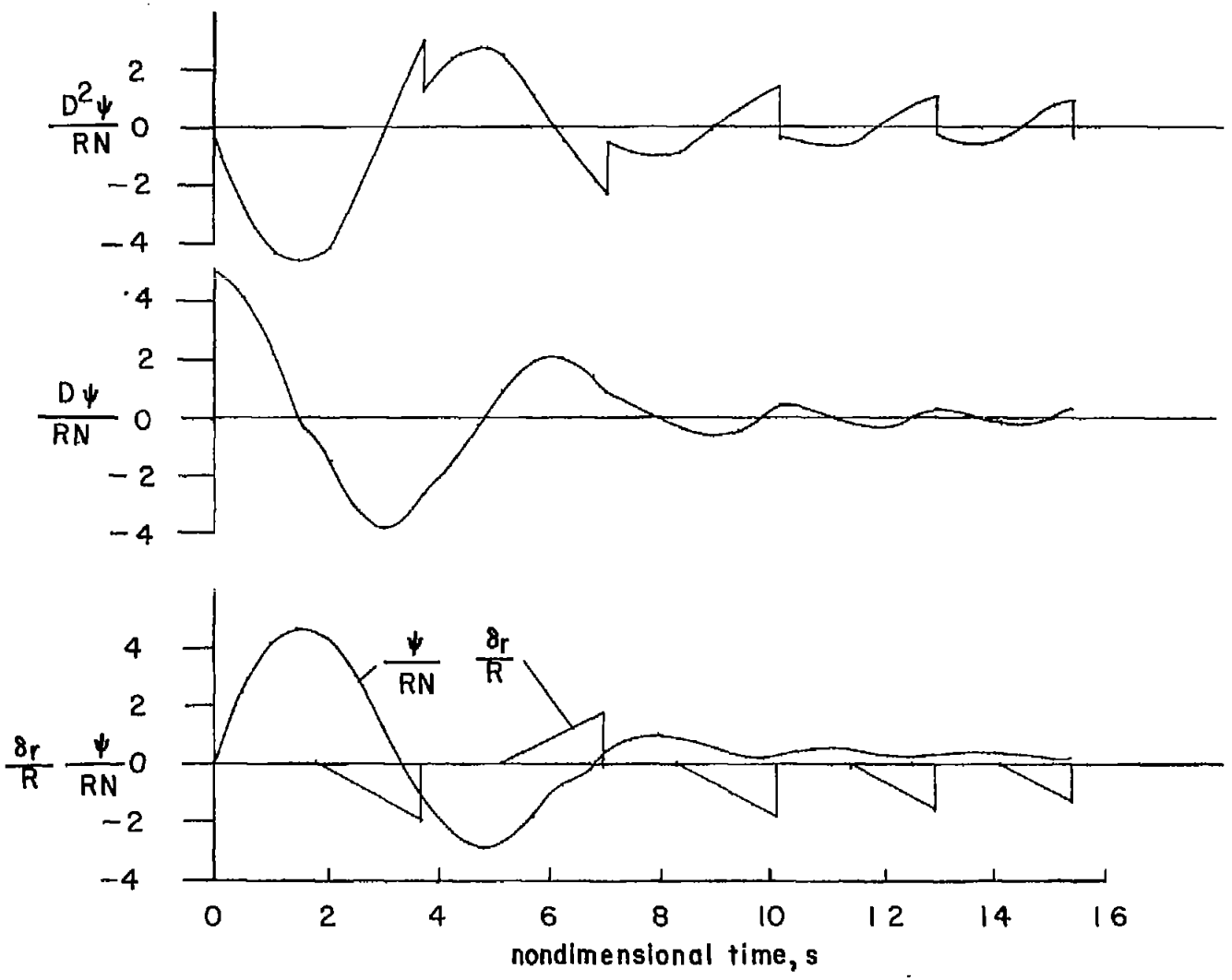

(b) Time lag s = 0.349.

Figure 6.- Concluded.




(a) Zero time lag.

Figure 7.- Time history of $\frac{D^2\psi}{RN}$, $\frac{D\psi}{RN}$, $\frac{\psi}{RN}$, and rudder angle for case II (rudder operating to oppose the return of yaw).




(b) Time lag s = 0.349.

Figure 7.- Concluded.

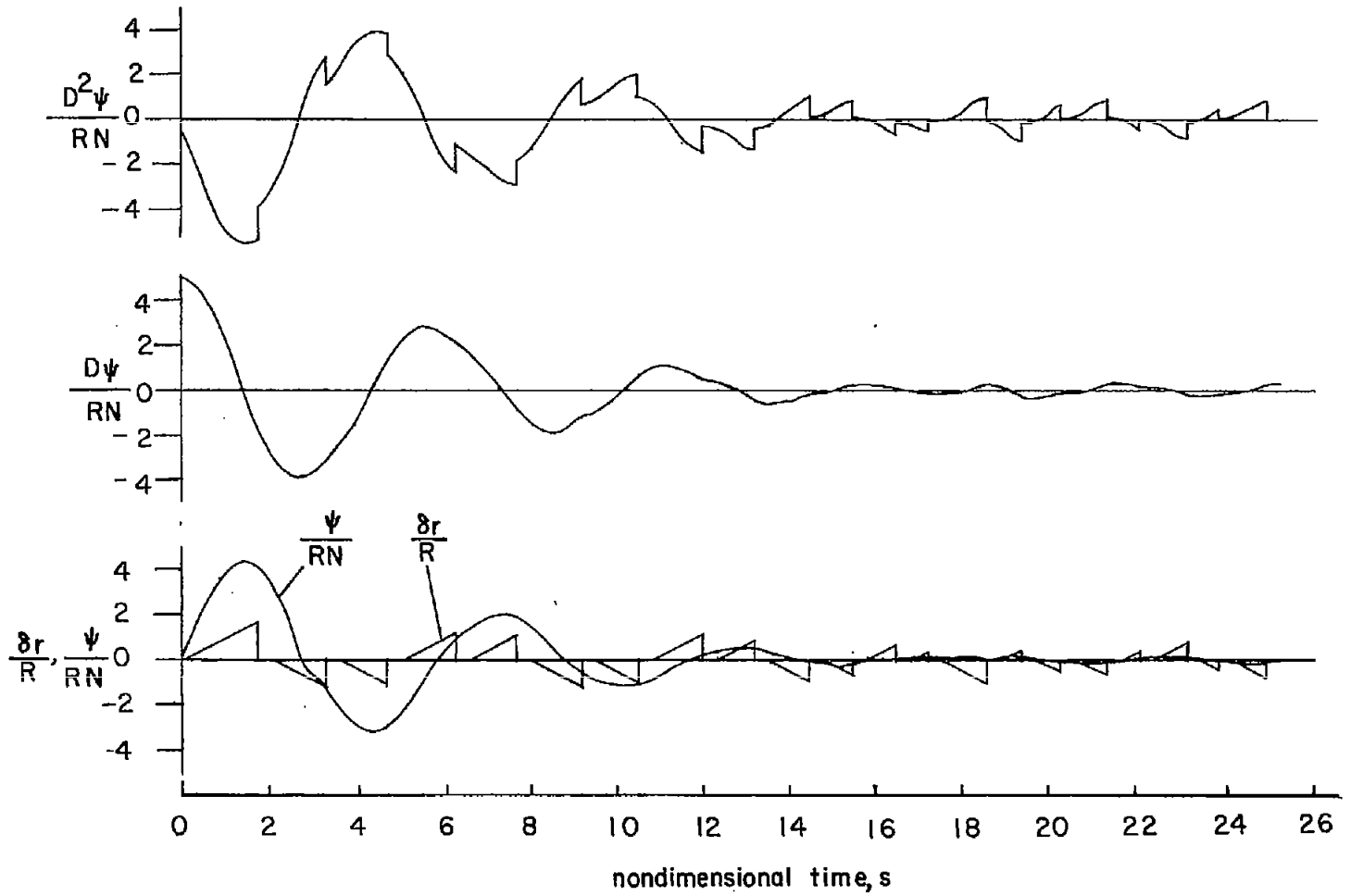



Figure 8.- Time history of $\frac{D^2\psi}{RN}$, $\frac{D\psi}{RN}$, $\frac{\psi}{RN}$, and the rudder angle for case III (rudder operating to oppose the build-up and return of yaw). Time lag $s = 0.349$.

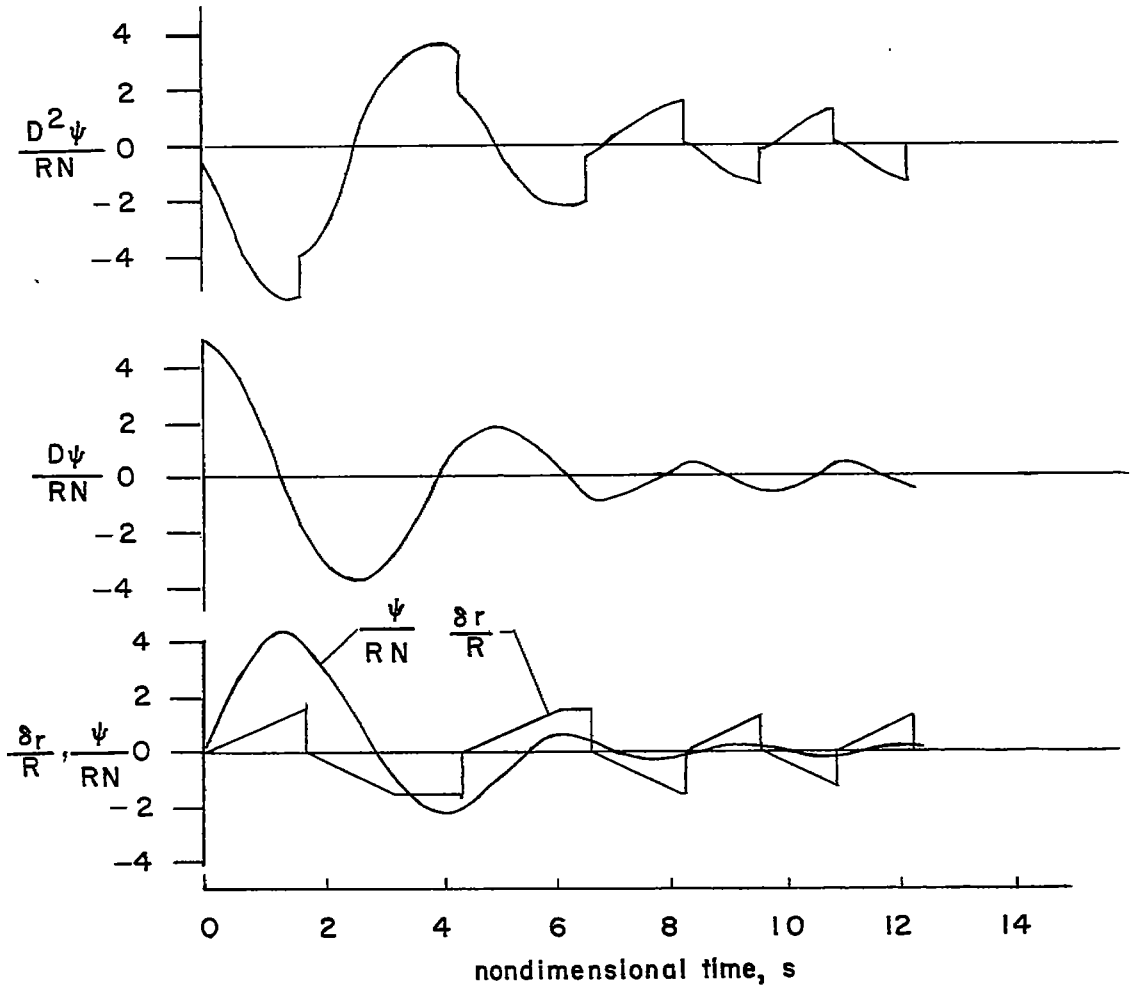



Figure 9.- Time history of $\frac{D^2\psi}{RN}$, $\frac{D\psi}{RN}$, $\frac{\psi}{RN}$, and the rudder angle for case IV (rudder operating to oppose the yawing velocity). Time lag s = 0.349.

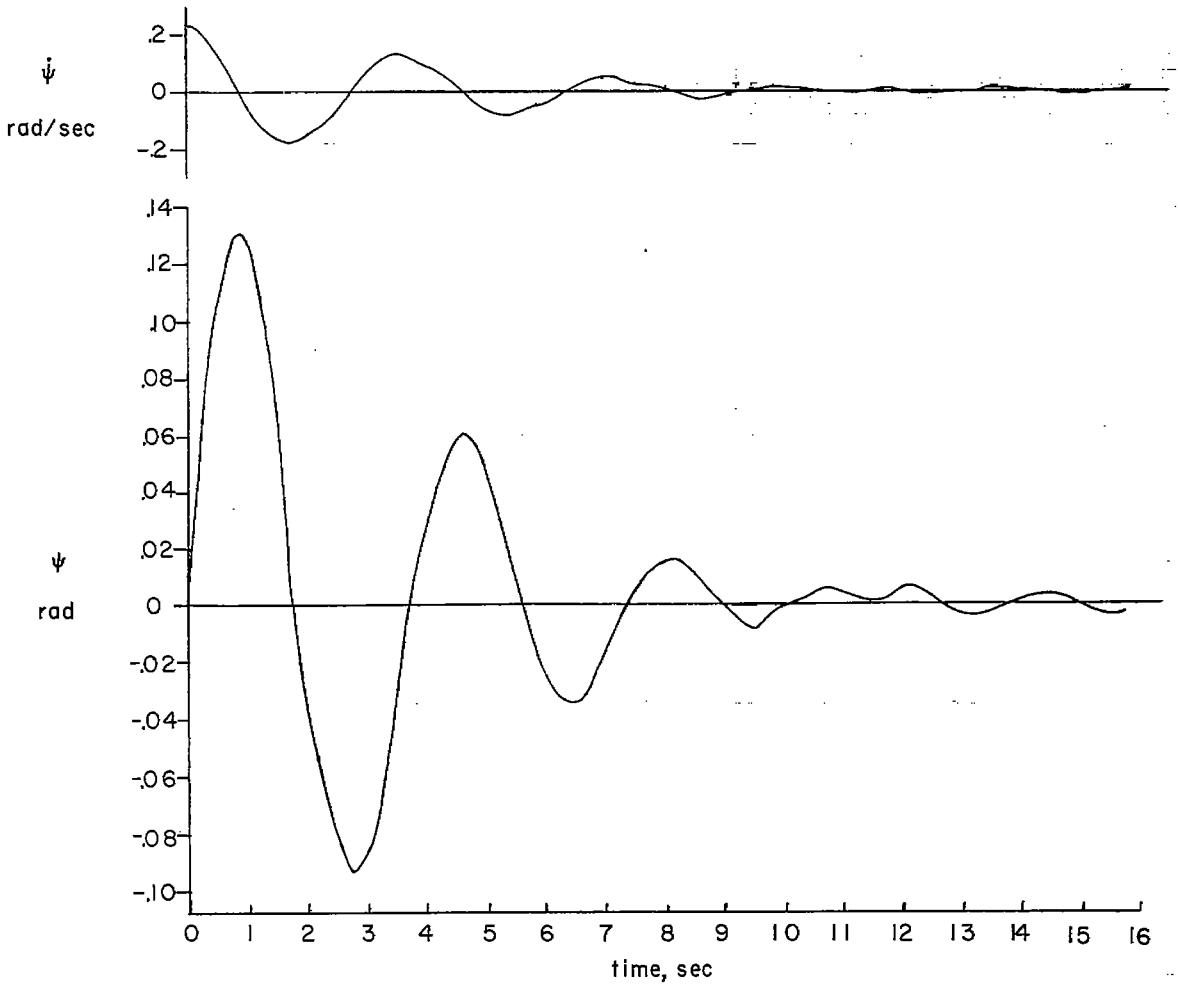



Figure 10.- Time history of yawing velocity $\dot{\psi}$ and yaw angle $\psi$ for the airplane yaw damper combination of case III (rudder operating to oppose the build-up and return of yaw) at 100 knots $V_i$.

[redacted]

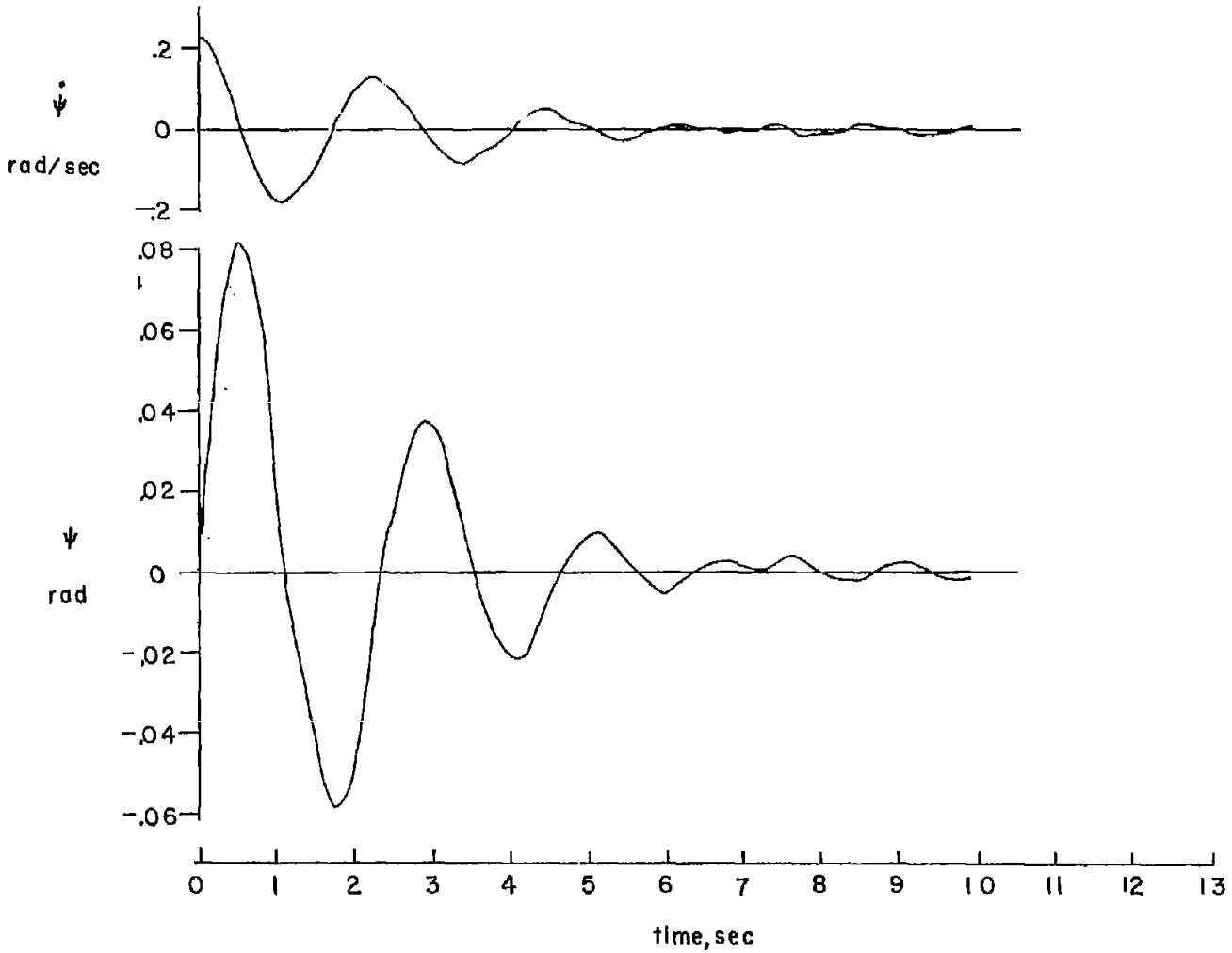



Figure 11.- Time history of yawing velocity $\dot{\psi}$ and yaw angle $\psi$ for the airplane yaw damper combination of case III (rudder operating to oppose the build-up and return of yaw) at 200 knots $V_i$.

[redacted]

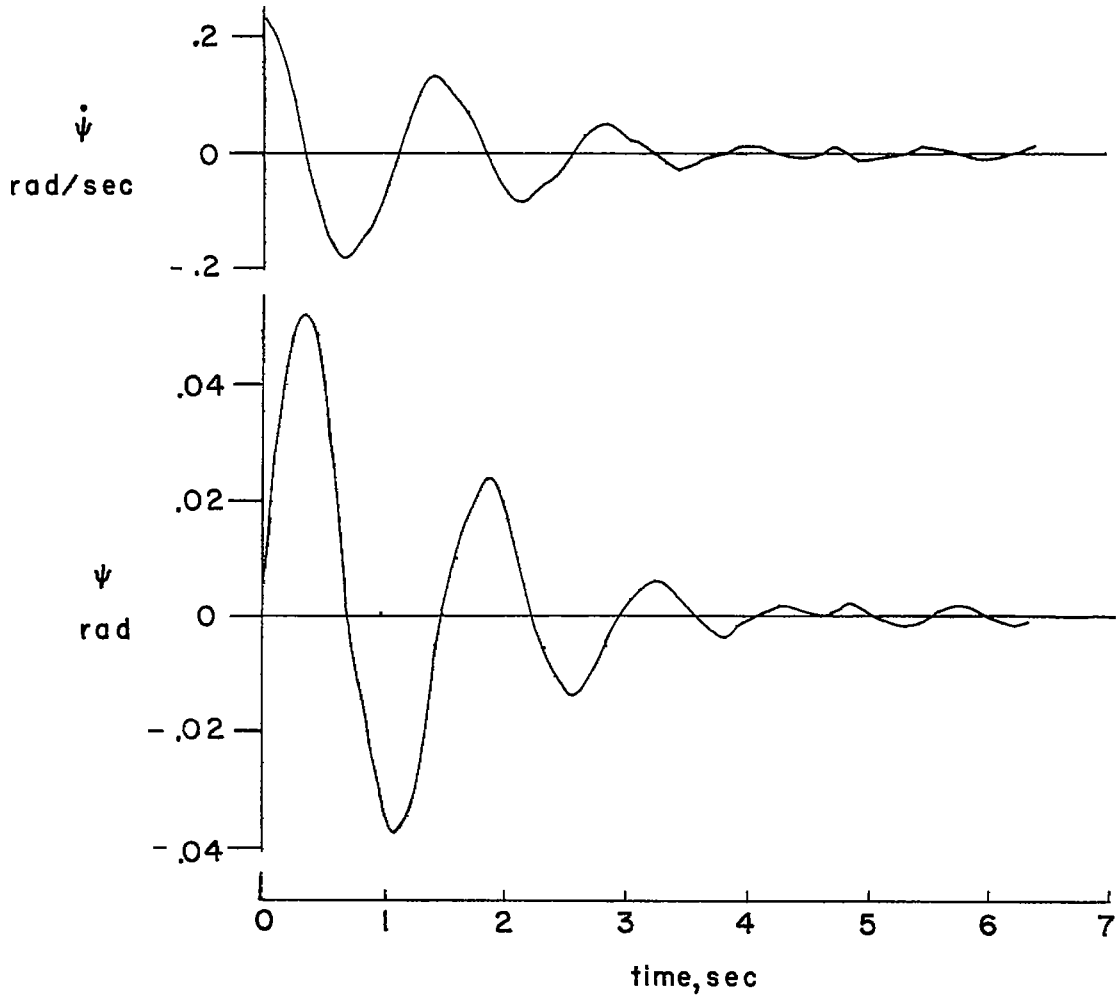
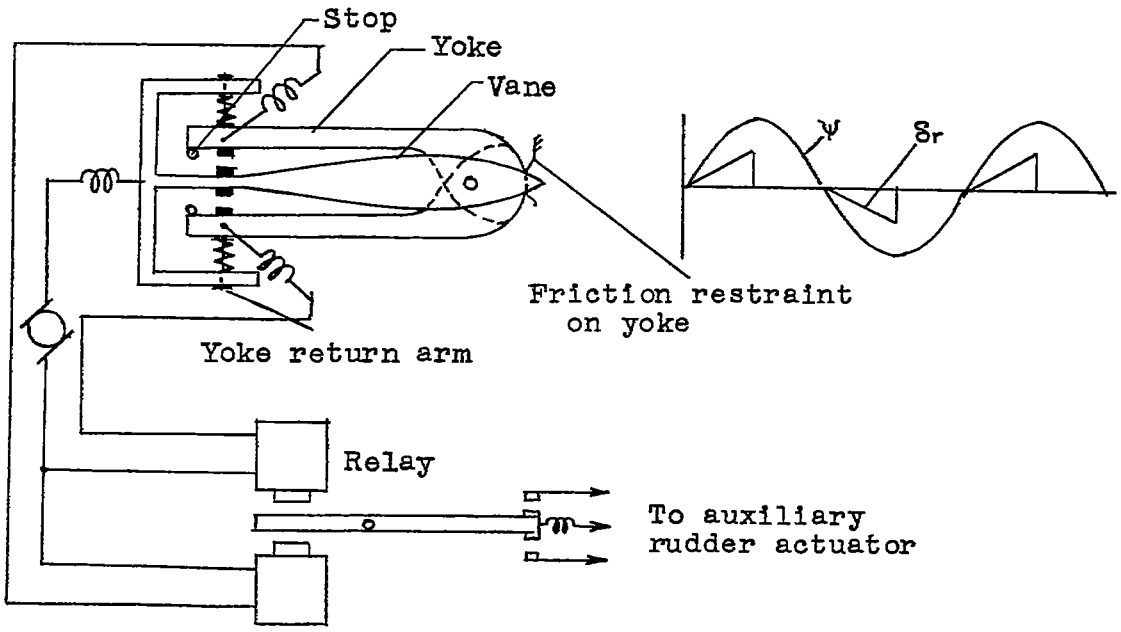
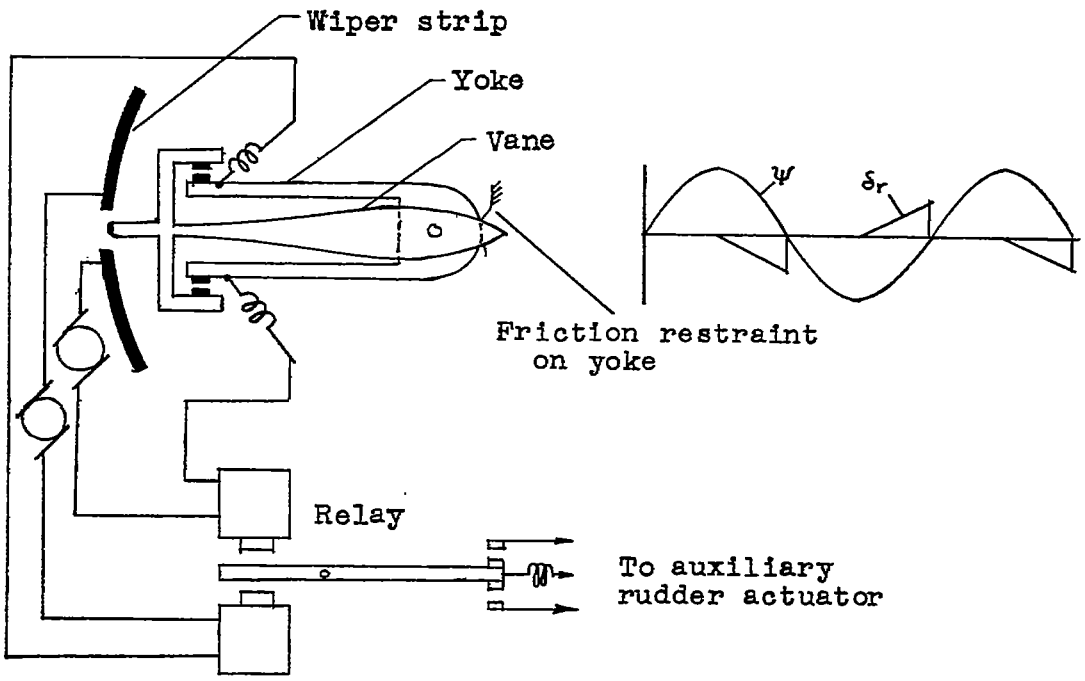



Figure 12.- Time history of the yawing velocity $\dot{\psi}$ and yaw angle $\psi$ for the airplane yaw-damper combination of case III (rudder operating to oppose the build-up and return of yaw) at 330 knots $V_1$.

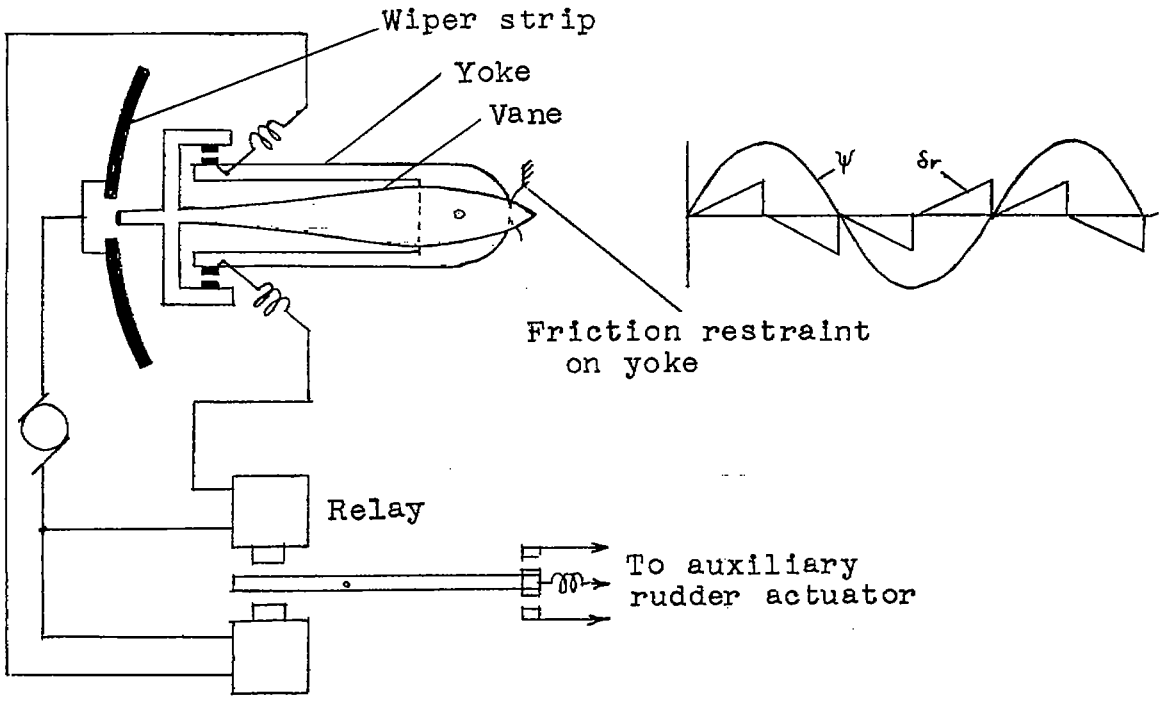



(a) Case I – oppose build-up of yaw.

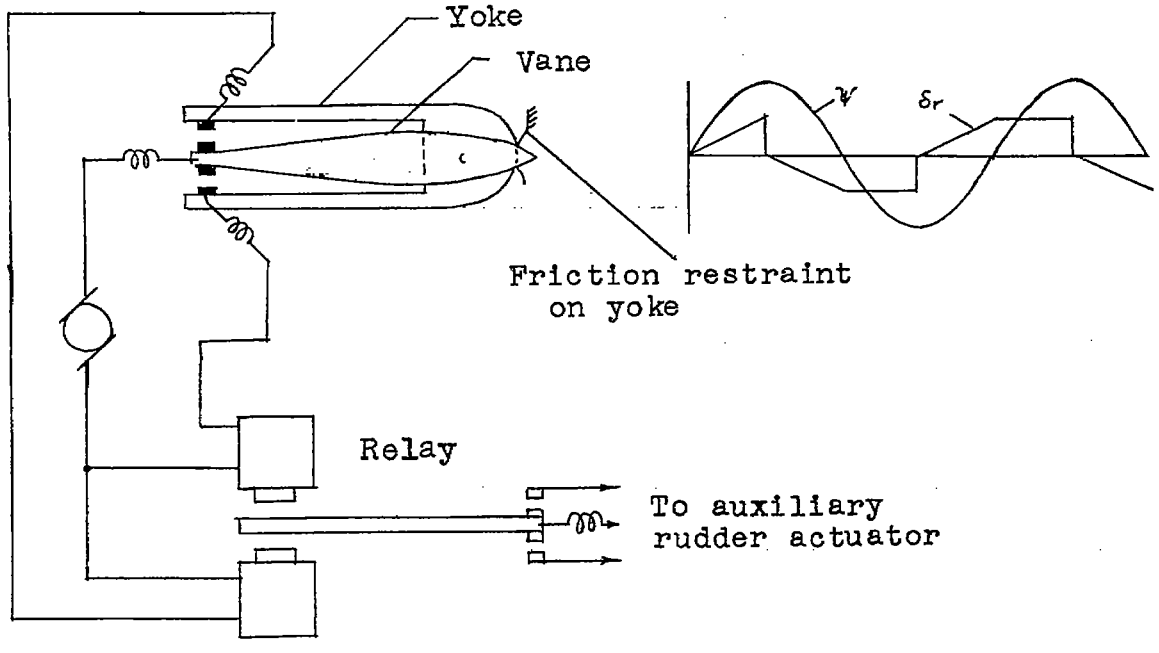



(b) Case II – oppose return of yaw.

Figure 13.- Contact arrangements for operating the auxiliary rudder in accordance with the four cases being considered.




(c) Case III – oppose build-up and return of yaw.




(d) Case IV – oppose yawing velocity.

Figure 13.- Concluded.

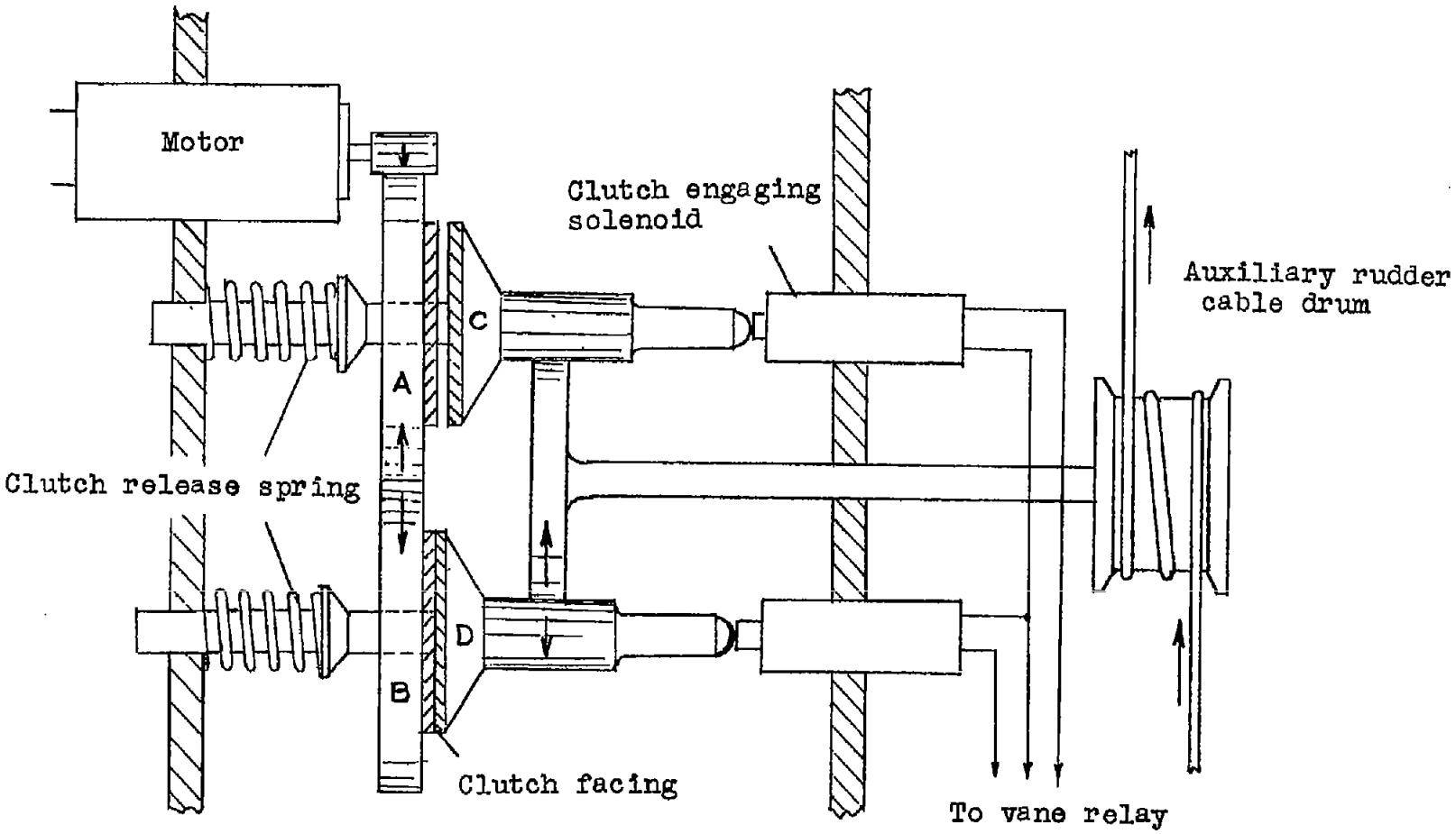



Figure 14.- Sketch of a type of auxiliary rudder actuator applicable to a discontinuous control.



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