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RESEARCH MEMORANDUM

ABILITY OF PILOTS TO CONTROL SIMULATED SHORT-PERIOD YAWING OSCILLATIONS

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SUMMARY

In order to provide information concerning the ability of human pilots to control short-period yawing oscillations, an investigation has been conducted with several pilots using a yaw simulating device.

A pilot's ability to control the short-period yawing oscillations of this device has been determined as a function of period, control effectiveness, and inherent damping. This ability to control the oscillations is also a function of pilot response judged on a basis of the phase relationship between his controlling motions and the yawing oscillations. This response improved appreciably with practice. It was not feasible to set forth a precise period as the shortest to which an average pilot with practice in controlling short-period yawing oscillations can correctly respond with consistency, because of the variations found even in a given pilot's ability. The tests indicated, however, that this period was in the range slightly greater than 1 second. It was found that a pilot responded in approximately the same way to oscillations in the "yaw chair" as to similar oscillations in actual flight tests. His success in damping the oscillations was also about the same in both cases.

INTRODUCTION

Because of the trend toward higher speeds and higher operating altitudes of aircraft, the problem of short-period yawing oscillations has become more pressing. Much recent work has been directed toward design of automatic pilots with the necessary response characteristics for controlling short-period oscillations. However, even with a suitable automatic pilot, it is desirable that the human pilot be able to damp the oscillations if the necessity arises. Little is known about human-pilot ability, although the need for such information has been recognized for some time. Of particular interest is the lower limit of the period of oscillation that a human pilot could be expected to damp out. Also of interest are the effects of varying control effectiveness and inherent damping on the ability of pilots to control short-period yawing oscillations. The present paper presents results obtained from an investigation of pilots' reactions by use of a simulating device to produce the oscillations.

The present investigation was limited to yawing oscillations for three reasons:

(1) Simulating a one-degree-of-freedom oscillatory system was easy.

(2) In the case of military aircraft, yawing motions are primarily responsible for any loss of gun-firing accuracy attributed to short-period oscillations because the guns are approximately alined with the longitudinal axis.

(3) Ability to damp yawing oscillations was considered more important than the ability to damp the other components of motion that generally make up a lateral oscillation.

The last reason is brought out by the fact that an airplane may still perform short-period yawing oscillations even though restricted from any rolling motions; whereas the converse of this statement does not hold true.

SYMBOLS

N	yawing moment, foot-pounds
ψ	angle of yaw, degrees
$\dot{\psi}$	yawing velocity, degrees per second
δ_r	rudder-pedal travel, inches
δ_r'	rudder deflection, degrees
F	rudder-pedal force, pounds
I	moment of inertia in yaw (including pilot), slug-feet^2
N_{δ_r}/I	variation of yawing moment with rudder-pedal travel divided by moment of inertia
N_F/I	variation of yawing moment with rudder-pedal force divided by moment of inertia

$d\psi/d\delta_r$	variation of angle of yaw with rudder-pedal travel
$d\psi/dF$	variation of angle of yaw with rudder-pedal force
T_2	time for oscillation to reach twice amplitude, seconds
$T_{1/2}$	time for oscillation to reach one-half amplitude, seconds
V_i	indicated airspeed, miles per hour
dt	differential of time

APPARATUS

The simulating device, hereinafter referred to as the "yaw chair," is shown in figures 1(a) and 1(b). A pilot seat is mounted on a framework that is pivoted on a bearing directly beneath the seat. Oscillations are produced by springs and shock cords attached to arms extending horizontally from the framework. The period of oscillation is governed by the strength of the spring and shock-cord combination used. Rudder pedals are built into the frame, and connections by cable and pulley are made to springs on either side of the yaw chair in such a manner that a deflection of a rudder pedal will produce a yawing moment in the respective direction. The strength of these springs, referred to as "control springs," determines the yawing moment available to the pilot. Also included in the control system is a combination of shock cords which acts to restrain rudder-pedal movements and, in effect, gives the pilot a control-force feel more nearly equal to that found in actual aircraft. Because motion of the yaw chair causes deflection of the control springs, the rudder pedals have a tendency to move during a yawing oscillation in the same direction as those on an airplane with a rudder which has a tendency to float with the relative wind. The forces required to hold the rudder pedals fixed during an oscillation are of the order of 0.3, 0.6, and 0.9 pound per degree of yawing displacement for the three control springs employed. These forces are seen to be small compared to the centering effect of the shock cords. The variation of rudder-pedal force with rudder-pedal travel is shown in figure 2.

The natural motion of the yaw chair is a slightly damped yawing oscillation. In order to make these oscillations dynamically unstable, a moment that is 90° out of phase with the yawing displacement ψ must be introduced. This moment can be obtained by introducing forces proportional to the yawing velocity $\dot{\psi}$ or proportional to $\int \psi \, dt$. Both methods were tried, but, since the latter one required simpler apparatus and provided satisfactory performance, it was used. This method is accomplished through use of the hydraulic unit shown in figures 1(a) and 1(b) and is illustrated schematically in figure 3. The cable wound around the wooden drum is attached at the other end to the shock cord which provides one-half the restoring forces for the oscillations of the chair. The wooden drum is driven by a reversible hydraulic motor supplied by a variable-displacement hydraulic pump. The displacement of the pump is controlled by a control arm which operates directly from the movement of the yaw chair. A centered position results in no rotation of the drum. Thus a movement of the yaw chair away from its centered position results in a displacement of the pump, which causes the drum to be rotated at a speed proportional to the displacement. The rotation of the drum either extends or relaxes the shock cord to apply a moment to the yaw chair. This additional moment is therefore proportional to displacement and time displaced or $\int \psi \, dt$.

In order to provide a reference point for the pilot, a projector attached to the side of the chair projects an image of a gun sight on a screen in front of the pilot. A point is marked on the screen that corresponds to the position of the gun-sight-image "pipper" at zero yawing deflection. By reference to this point and the position of the gun-sight image, a pilot will undergo some of the same sensations felt in a strafing run in an actual aircraft where short-period lateral oscillations occur. It should be pointed out that this system is similar to a fixed gun-sight arrangement, whereas present-day military aircraft use predictor gun sights. However, the purpose of the gun-sight image was merely to give the pilot a reference with which to judge the oscillations; and, although it is recognized that a predictor sight might have a different reference-giving ability, this problem is considered beyond the scope of the present paper.

TESTS

Tests in which the period of oscillation, the control effectiveness, and the inherent damping of the oscillation were varied have been conducted with several pilots. Standard NACA instruments recorded the rudder-pedal position and force and the yaw angle.

In order to obtain uniformity in the tests, a sequence of events was devised and adhered to as closely as possible. The pilot was first subjected to the longest-period oscillation with the least control effectiveness available. The oscillation was then varied through the range from stable to moderately unstable in three or four steps, depending on the pilot's ability to control the oscillation. With the same control effectiveness but the next shorter period oscillation, the runs were repeated. After each series of runs, the period was decreased until the range of 2.5 seconds to 1.0 second had been traversed; then the next higher control-effectiveness control spring was installed and the entire sequence repeated. The control effectiveness was then increased again until the entire range had been traversed, and thus the sequence of the tests for one pilot was completed.

In order to correlate the data obtained with actual flight information, the control effectiveness was expressed in terms of the variation of yawing moment with rudder-pedal travel divided by the moment of inertia N_{δ_r}/I and the variation of yawing moment with rudder-pedal force divided by the moment of inertia N_F/I. These parameters are proportional to the yawing acceleration produced by a given rudder angle or pedal force. They were chosen because any linear one-degree-of-freedom oscillatory system, regardless of size, performs the same motion for a given control application provided these quantities and the natural frequency and damping ratio are equal. Values of N_{δ_r}/I and N_F/I are shown in table I, along with values for a typical fighter airplane. Also included in the table are values of $d\psi/d_{\delta_r}$ and $d\psi/dF$ for each control spring. The value of angle of yaw ψ for the yaw chair is analogous to the angle of sideslip of an airplane. The range of N_{δ_r}/I for the yaw chair is much lower than the value given for the typical airplane. As a result, more pedal travel is required on the yaw chair to obtain a given response than is required on the airplane. The range of values of N_F/I for the yaw chair, however, covered the values for the typical airplane. Although it is realized to be of possible importance, variations of force gradients with pedal travel were not investigated. The pedal-force variation with rudder-pedal travel is shown in figure 2. The use of different control springs had an almost negligible effect upon the pedal-force gradient. Stops were provided to limit the rudder-pedal travel to $\pm 4\frac{1}{2}$ inches, but maximum deflection was rarely reached in the tests.

The ranges of the other variables are as follows: period, from about 2.5 seconds to about 0.7 second; inherent damping, from slightly stable to highly unstable.

RESULTS

The ranges of the variables described in the tests were well-covered and definite trends were observed. A series of test runs made by one pilot was chosen to illustrate the individual trends, and the records were reproduced to form the figures discussed in the succeeding results. The test runs shown are chosen examples and do not cover the whole range of data obtained.

Effect of period.- The records indicate the effect of decreasing the period of oscillation upon the control ability of the pilot. Figure 4 is a reproduction of the records from a series of runs made by a pilot for which the yawing-moment variation with rudder deflection remained the same and the period varied from about 2.4 seconds to about 1.0 second. The yawing oscillations are a result of a deflection and release of the yaw chair. The column of records reproduced to the left in the figure shows the inherent damping of the system with no pilot action, and the other column of records shows the oscillations as damped by the pilot. At a period of about 2.4 seconds, the pilot was able to damp the oscillation almost dead beat. As the period was decreased, it became harder for the pilot to damp the oscillation. One reason for this condition, as observed in figure 4, is that the phase angle by which the rudder motion led the yaw angle decreased with decreasing period. Thus, in effect, as the period is decreased within the limits of the present tests, the damping efficiency of the pilot's control response decreased. There is a slight discrepancy between periods of 1.2 seconds and 1.0 second in that the oscillations were damped in almost the same number of cycles. This discrepancy can be partly explained by the fact that the pilot was holding some right rudder during the initial deflection and release in the period of 1.0 second which had some damping effect on the oscillation before the pilot began his response. It should also be emphasized that the human element present in the tests makes it difficult to make any precise analysis. The over-all impression of the figure and also the impression from the other tests was that decreasing the period of the oscillation made control of the oscillation harder for the pilot.

Present tests maintained approximately constant rudder effectiveness. This method is believed to represent closely a comparison of various airplanes with varying degrees of directional stability.

Inasmuch as the mass of the pilot formed a large part of the moment of inertia of the yaw chair, any motion of the pilot's body tended to increase the damping of the oscillation. This condition would not exist in an airplane where the mass of the pilot has a small effect upon the yawing moment of inertia. At periods above 1.0 second, the pilots could keep their bodies sufficiently rigid to prevent any but negligible effects on the results. At periods below 1.0 second, however, the pilot had difficulty in holding his body rigid. For this reason, tests in the period range below 1.0 second were not extensive. A few runs were attempted at an oscillation period as low as 0.7 second, but results were inconsistent and difficult to analyze. However, pilots' opinions were that this period of oscillation would be about the shortest they could control even with much practice.

Effect of control effectiveness.- Figure 5 shows the effect of control effectiveness upon a pilot's ability to control an oscillation. In each run shown, the yaw chair was dynamically unstable in yaw and possessed approximately the same inherent instability as shown in the records reproduced to the left in figure 5. The oscillations were started by a slight displacement of the yaw chair such as might be caused in actual flight by rough air. The pilot then attempted to control the ensuing oscillation, as shown in the records reproduced to the right in figure 5. His success apparently increased with increasing control effectiveness. In the run using the least control effectiveness, the pilot was not able to introduce enough damping to prevent this oscillation from diverging. The following run shows that with a greater effectiveness the pilot was able to control the oscillation although it required several cycles to do so. The run with the greatest control effectiveness shows that the pilot controlled the oscillation with much less trouble and with greater precision.

Even in the runs with small control effectiveness, the pilots did not ordinarily employ the full-rudder travel available. The force gradient provided apparently was large enough to limit the rudder-pedal travel used.

Effect of inherent damping.- The effect of varying the inherent damping upon the ability of a pilot to damp an oscillation of a given period with a given rudder effectiveness is shown in figure 6. The inherent damping with no pilot action is shown in the column of records reproduced to the left in the figure. Similar oscillations, but with pilot controlling action, are shown in the records reproduced to the right in the figure. The top set of records shows an oscillation of a slightly stable nature which the pilot readily controls. The next records show a slightly unstable oscillation which still presents no difficulties to the pilot although, from a comparison with the first record at a similar amplitude, it is seen that more cycles were required for damping. The third set of records shows an unstable oscillation with a higher rate of divergence and the damping of this oscillation required several cycles - obviously, the problem of controlling is becoming more difficult for the pilot. The last set of records shows oscillations having a high rate of divergence which is almost beyond the ability of the pilot. His rudder effectiveness apparently is high enough to damp the oscillation, but the small-amplitude oscillation that results from a slight overcontrol or slight undercontrol diverges so rapidly that the pilot has an almost never-ending problem. It is interesting to note that the yawing oscillation did not follow a sinusoidal pattern; hence the pilot had to be especially alert in order to make his control response correspond.

Boundary of stability.- The data, such as shown in figures 5 and 6, indicate that perhaps boundaries could be established to define the extent of inherent instability that pilots could overcome at different frequencies and with different control effectiveness. Figure 7 is the result of an analysis of tests with two pilots. Frequency is plotted against the inherent damping of the yaw chair and a curve is shown for each control effectiveness used. The pilots were able to damp oscillations described by the area to the left of the boundary curves and were unable to damp oscillations described by the area to the right. It should be noted that the curves are only approximations, especially in the frequency range above 1.0, and might vary appreciably in shape and location with different pilot ability.

The curve representing present Air Force-Navy flying-qualities requirements (references 1 and 2), shown in figure 7, shows that a large range of oscillation characteristics beyond those considered satisfactory for normal flying exists for which the pilot is still able to damp the oscillations. Apparently, in normal flight the pilot will not tolerate an oscillation which required continual attention.

DISCUSSION

Effects of accelerations and rolling motions.- It should be noted that in the yaw chair the pilot sits directly over the pivot point. At this location the linear-acceleration effects felt by the pilot are at a minimum. Even at this location, however, when the pilot was subjected to the oscillations of periods less than 1.0 second he had difficulty in keeping his legs sufficiently rigid to prevent them from flopping from side to side. The location of the pilot of an actual airplane does not necessarily correspond to this location at the pivot point, and the acceleration effects are stronger as the distance from the pivot point is increased. The pilot of an airplane also feels the accelerations due to sideslip, whereas the yaw chair does not simulate this condition. It is believed that such acceleration effects, in addition to being annoying and uncomfortable to the pilot, might affect his ability to respond to short-period oscillations. Rolling motions of the airplane would also be felt by the pilot and, if the ratio of rolling amplitude to yawing amplitude were large, the pilot's reactions to the oscillation might be appreciably different from those in the yaw chair.

Effect of the method of producing dynamic instability.- It might be expected that the boundaries of figure 7 would show that the pilot could control an increased rate of divergence at the longer periods of oscillation. However, the boundaries show that the pilot could only control decreased rates of divergence at the longer periods of oscillation. As previously discussed in the section entitled "Apparatus," two methods were considered for making the yawing oscillations unstable: One by introducing forces proportional to $\dot{\psi}$ and the other by introducing forces proportional to $\int \psi \, dt$. The two methods were originally believed to produce similar results, but the tests indicate that there may be a large difference, and the method used $\left(\text{introducing forces proportional to } \int \psi \, dt\right)$ presents a more difficult oscillation for the pilot to control. This method allows forces to be introduced when any displacement exists even though the yawing velocity is small or even zero. Consequently, the pilot had to control the oscillation exactly to 0° of yaw. The method for which the forces introduced would be proportional to yawing velocity would allow the pilot to stop the oscillation at any displacement of yaw. It is believed that if boundary curves could be drawn for the condition for which forces are introduced proportional to yawing velocity, the curves would show that the pilot could control increasing rate of divergence at the longer period of oscillations. Tests employing the method of making the yawing oscillation unstable by introducing forces proportional to $\dot{\psi}$ are planned to investigate this condition.

Pilot response.- In the discussion of the response of human pilots it is recognized that exact measurements are not possible and, therefore, no specific limits were set up to define a good or poor response. Good response was considered as an oscillation of the rudder pedals having the same average period as the yawing oscillation to be damped and leading by a phase angle of about 90°. In the present tests the pilot response is judged by observation of the phase relationship and the damping effect on the yawing oscillation.

As would be expected, the ability of different pilots varied; however, the variations were not as apparent after the pilots had some practice in the yaw chair. With no practice, most of the pilots had difficulty responding to an oscillation having a period of about 1.0 second, and a few had difficulty with oscillations of longer periods. After practice, all the pilots were able to respond correctly to oscillations having a period of about 1.0 second, although it was not unusual for a pilot to have a temporary relapse where his response might be completely out of phase with the correct controlling motions. The usual case was for the pilot to realize his error very quickly and regain the correct phase relationship. However, during the interval for which the pilot's controlling action was incorrect the oscillations might build up to uncontrollable amplitude, depending largely upon the inherent damping of the system and also how much the pilot may have aided the oscillation. This reasoning tends to indicate that the limiting period will be slightly greater than 1 second. This limit does not mean that pilots cannot control oscillations of shorter periods, but rather that the average pilot with practice in responding to short-period yawing oscillations can consistently respond correctly to oscillations of a period longer than that set as the limit.

It should be emphasized that the boundaries indicating pilot ability to control short-period yawing oscillations (fig. 7) are not meant to define an emergency operation (automatic-pilot inoperative) requirement. The pilots who provided the data shown in figure 7 had had practice in the yaw chair and also knew in advance the characteristics of the oscillations they were to damp. They also were able to devote their undivided attention to the yawing oscillation - a distinct advantage that cannot be utilized in actual flight. If a boundary for emergency operation was defined it would probably lie somewhere between the boundaries shown in figure 7 and the curve representing present flying-qualities requirements.

Comparison with flight tests.- In the course of the present investigation, questions arose concerning the validity of applying results found in the yaw chair to the ability of pilots flying actual aircraft. Fortunately, some flight records taken from a typical fighter airplane were available for which the quantities N_F/I, period, and damping were about the same as in some conditions simulated in the yaw chair. In these runs the pilot knew the approximate characteristics of the oscillations in advance and was able to give his undivided attention to damping them out. Figure 8 shows a comparison of data from similar runs made by the same pilot. In the case of the flight records the pilot chose to begin his controlling motions at a right angle of yaw whereas in the yaw chair he began at a left angle of yaw. The important thing to note, however, is that his control motions were very much the same and he was able to damp the oscillations to a small amplitude in very close to the same time. The amplitude of the oscillation in the case of the yaw chair was much greater than in the case of actual flight and this difference probably accounts for the fact that the oscillation was not as completely damped with the first rudder controlling motion. The indications from this comparison and other flight and yaw-chair tests are that a pilot responds in approximately the same way in both cases and that a pilot damps an oscillation in flight equally as well as a similar oscillation in the yaw chair.

CONCLUDING REMARKS

A pilot's ability to control short-period yawing oscillations has been determined as a function of period, control effectiveness, and inherent damping. This ability to control the oscillations is also a function of pilot response judged on a basis of the phase relationship between his controlling motions and the yawing oscillation. This response improved appreciably with practice. It was not feasible to set forth a precise period as the shortest to which an average pilot with practice in controlling short-period yawing oscillations can correctly respond with consistency, because of the variations found even in a given pilot's ability. The tests indicated, however, that this period was in the range slightly greater than 1 second. It was found that a pilot responded in approximately the same way to oscillations in the "yaw chair" as to similar oscillations in actual flight tests. His success in damping the oscillations was also about the same in both cases.

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2. Anon.: Specification for Flying Qualities of Piloted Airplanes. NAVAER SR-119B, Bur. Aero., June 1, 1948.

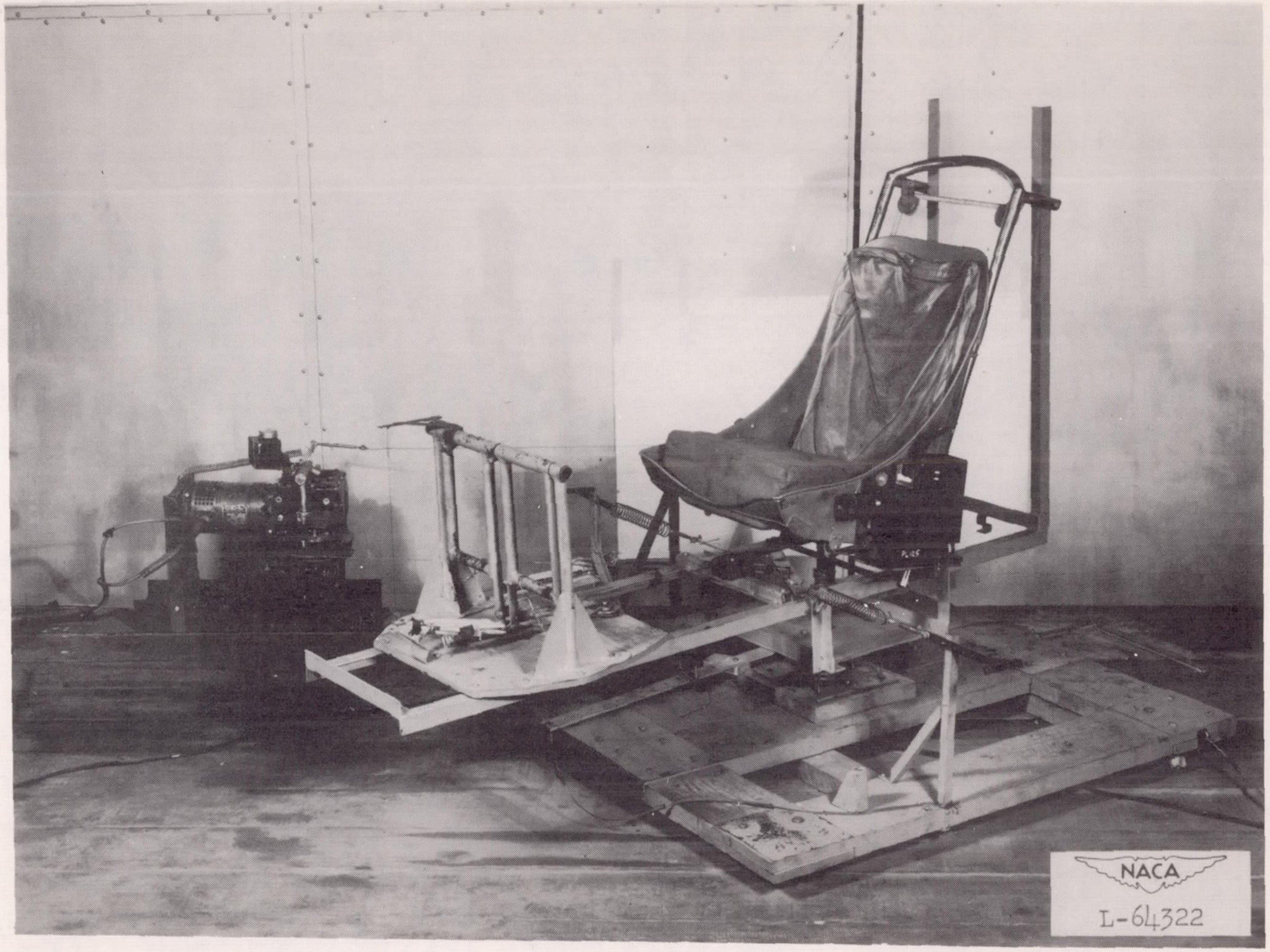
TABLE I.- VALUES OF CORRELATION PARAMETERS

(a) Yaw chair.

Approx. period (sec)	N_{δ_r}/I	N_F/I	$d\psi/d\delta_r$	$d\psi/dF$
Control spring 1				
2.4	6.3	0.19	0.92	0.027
1.7	6.3	.19	.49	.015
1.2	6.3	.19	.25	.007
Control spring 2				
2.4	11	0.31	1.6	0.046
1.7	11	.31	.86	.024
1.2	11	.31	.44	.012
1.0	11	.31	.31	.008
Control spring 3				
2.4	19	0.51	2.5	.069
1.7	19	.51	1.4	.038
1.2	19	.51	.68	.020
1.0	19	.51	.47	.013

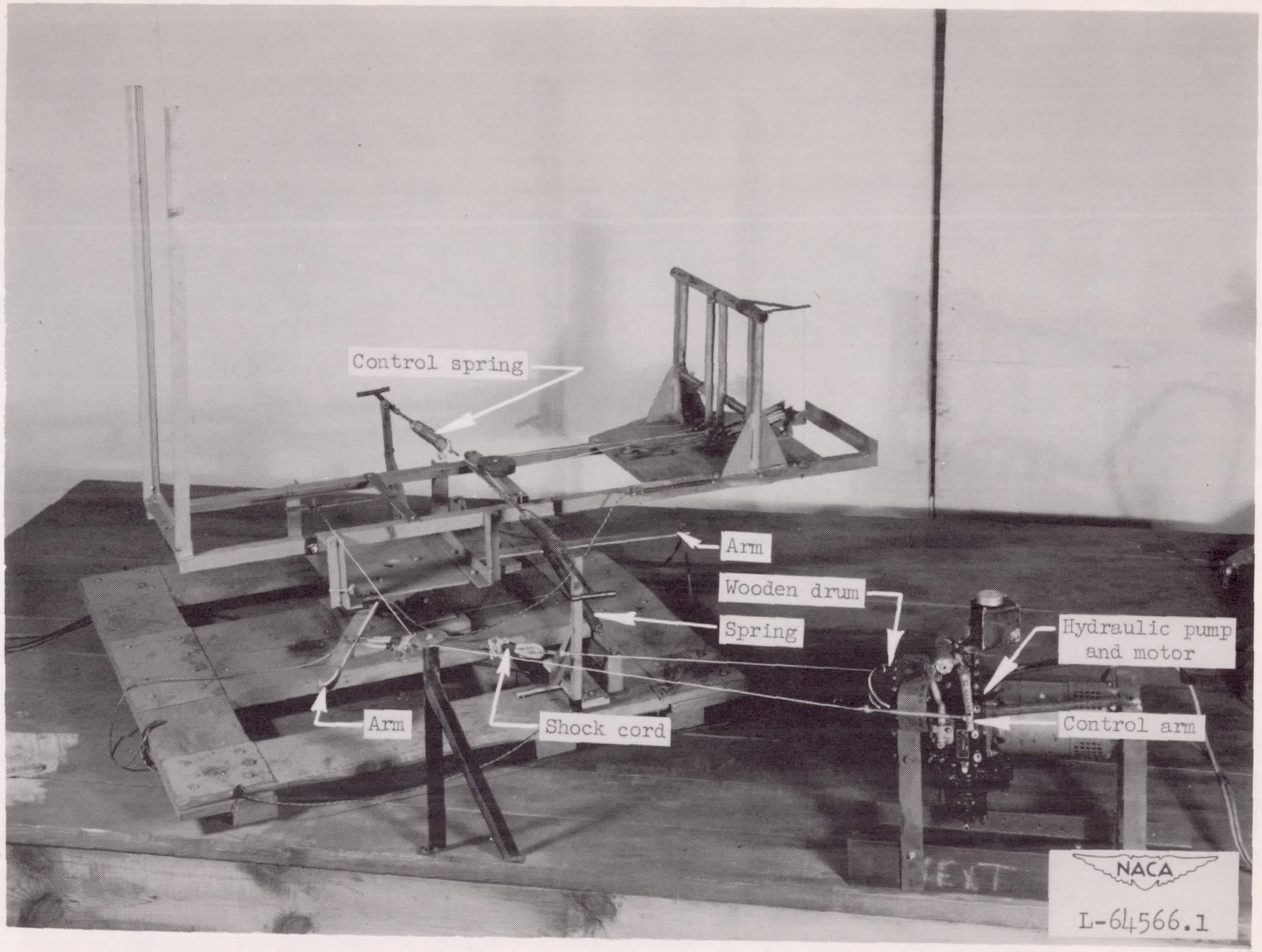
(b) Typical airplane.

Period (sec)	N_{δ_r}/I	N_F/I	V_i (mph)
2.7	24	0.40	250
1.7	71	.40	350
1.3	150	.40	440



(a) General arrangement.

Figure 1.– Yaw chair.



(b) Yaw chair with seat removed to show operating components of the oscillatory system.

Figure 1.- Concluded.

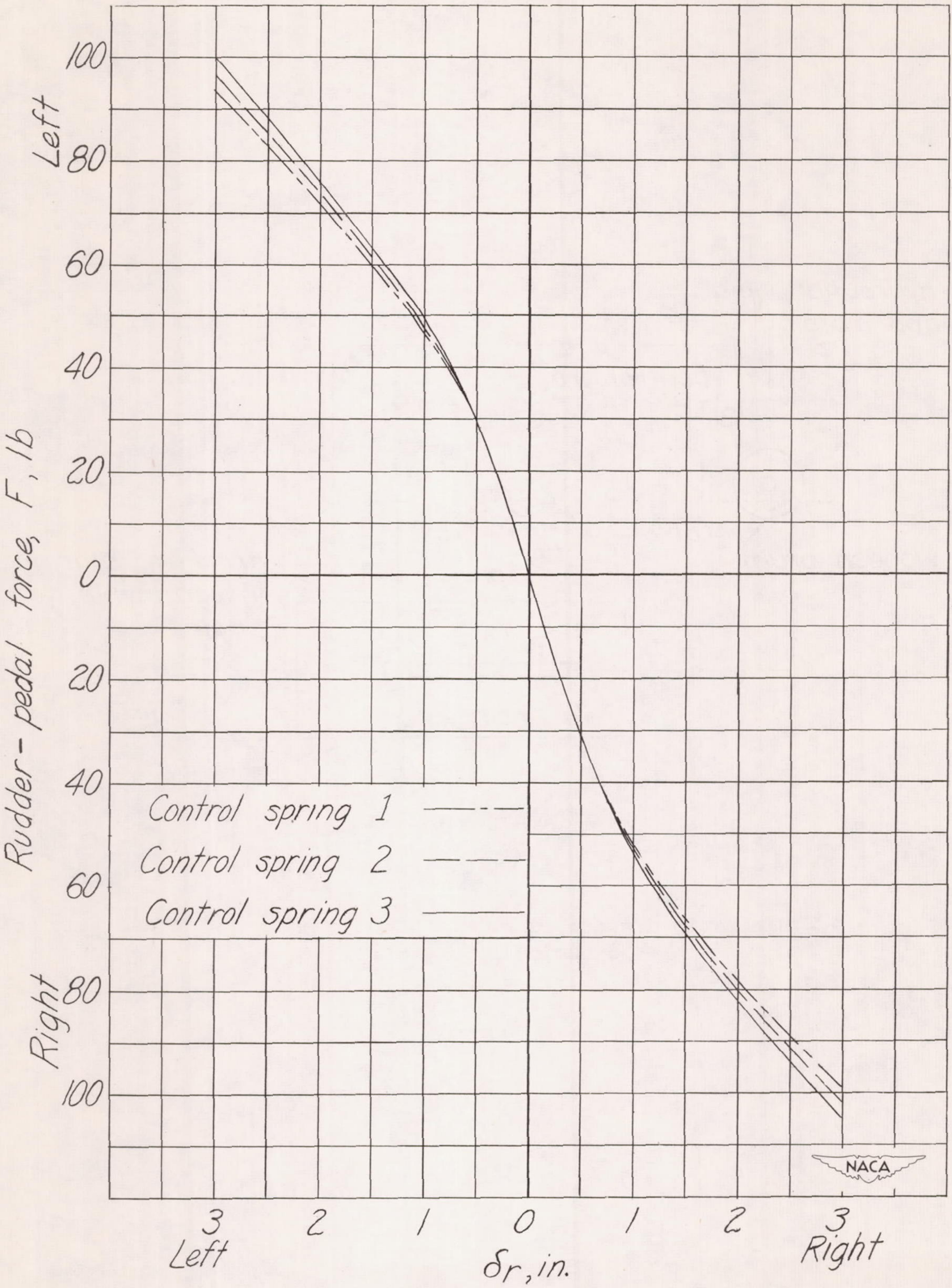


Figure 2.- Variation of rudder-pedal force with rudder-pedal travel.

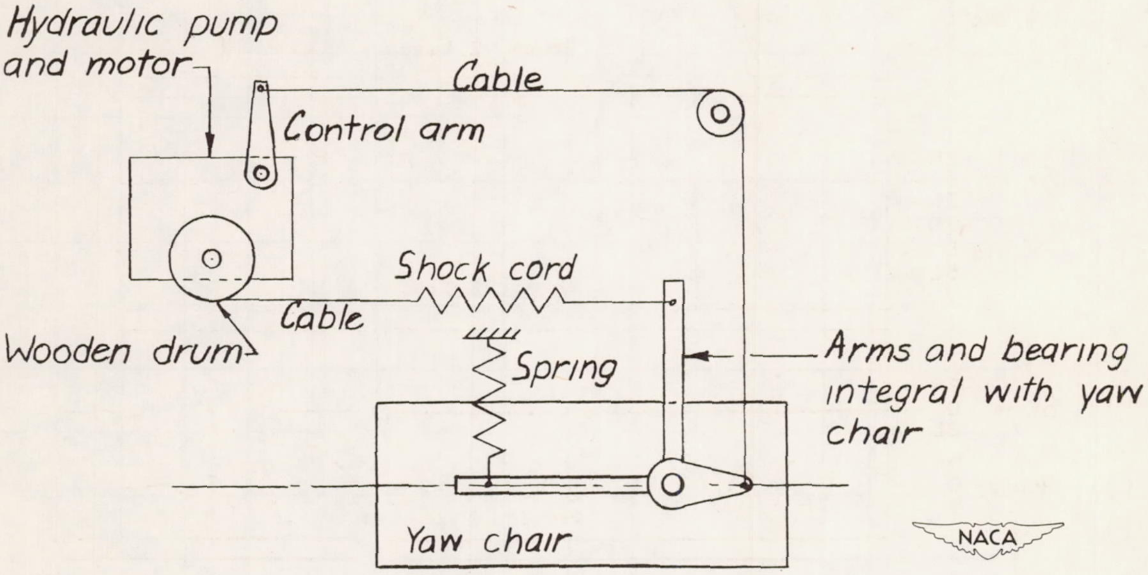


Figure 3.- Schematic drawing of method used to make yawing oscillations dynamically unstable.

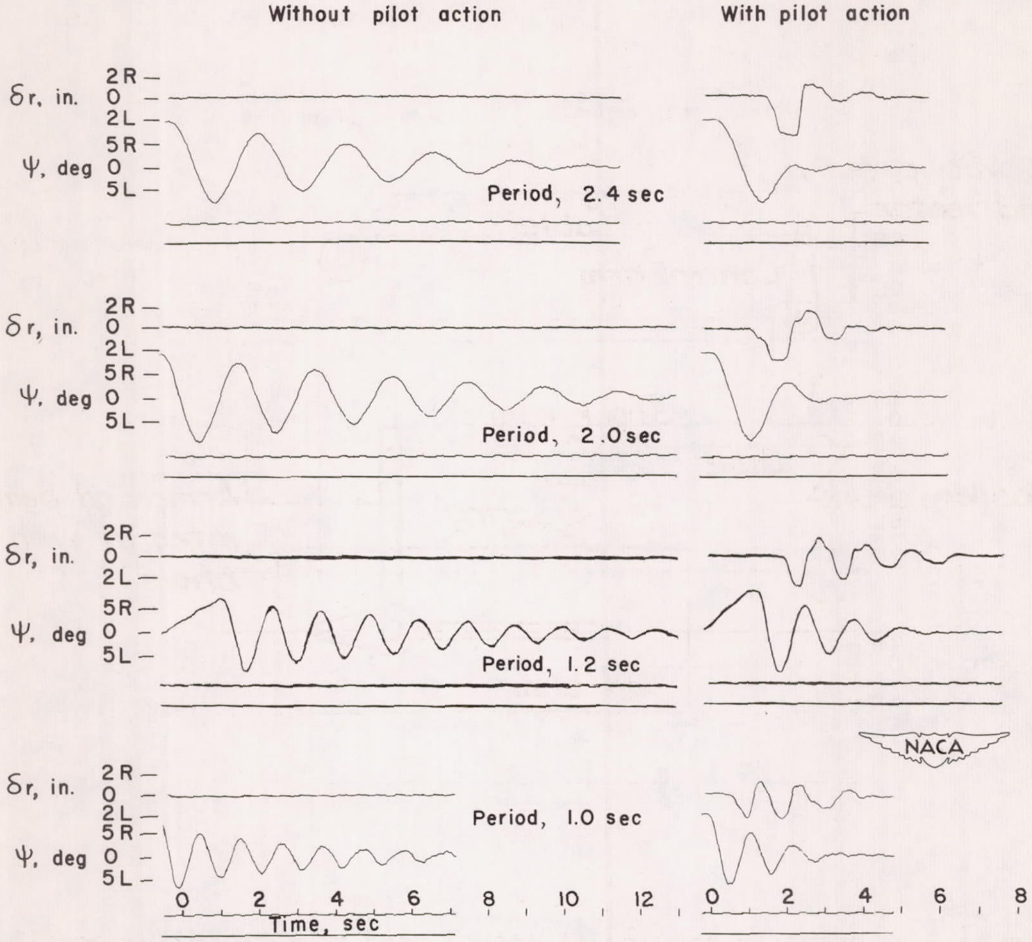


Figure 4.- Effect of decreasing period upon a pilot's ability to damp short-period yawing oscillations with the same control effectiveness.

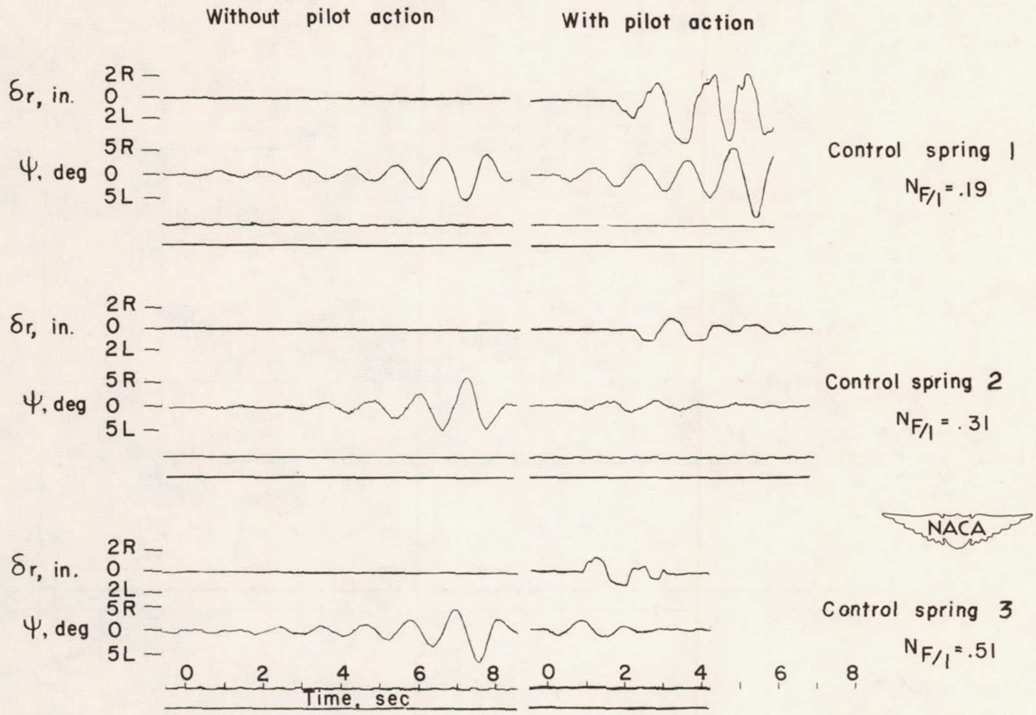


Figure 5.- Effect of increasing control effectiveness upon the ability of a pilot to control short-period yawing oscillations of approximately the same inherent damping. Period, 1.2 seconds.

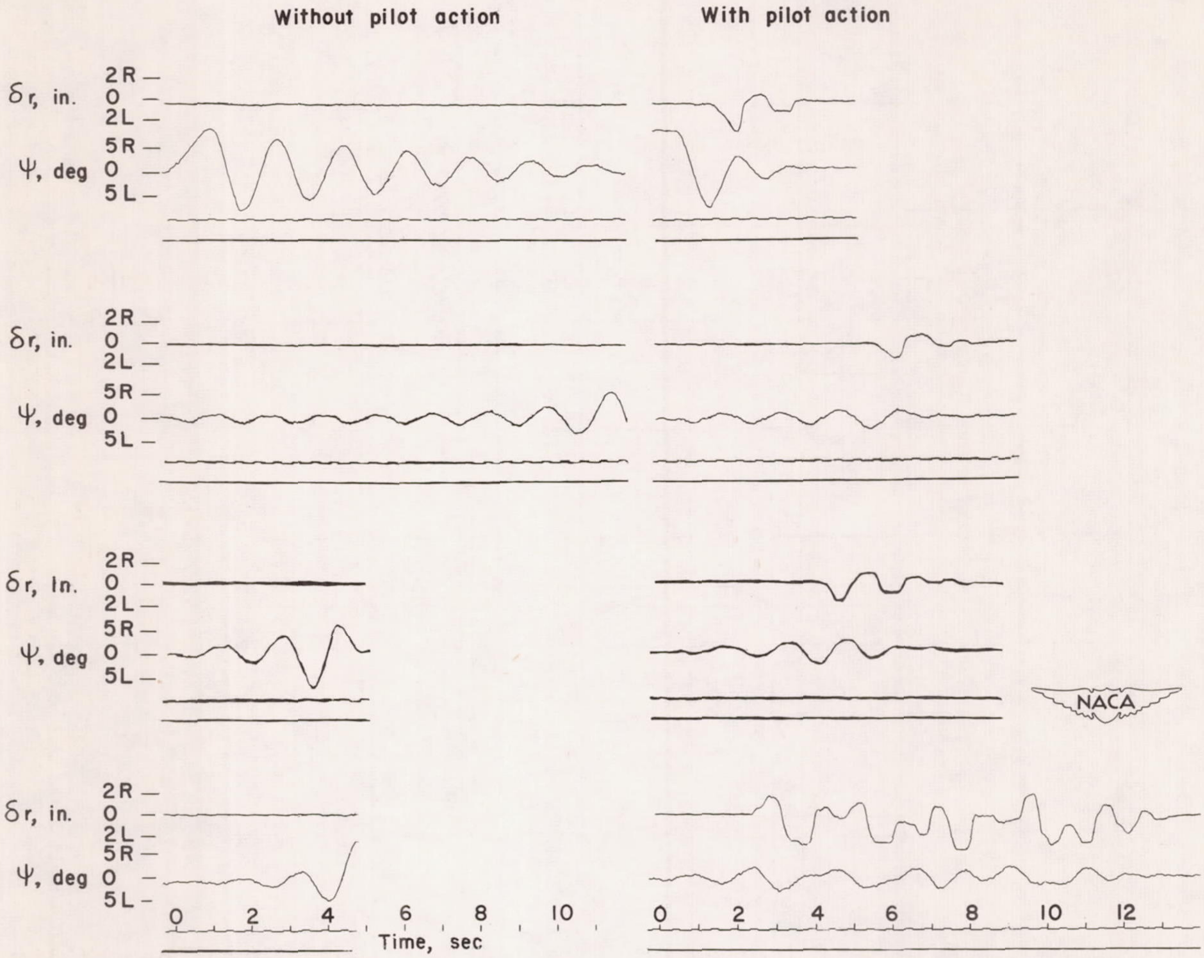


Figure 6.– Effect of decreasing inherent damping upon a pilot's ability to control short-period yawing oscillations with the same control effectiveness. Period, 1.7 seconds.

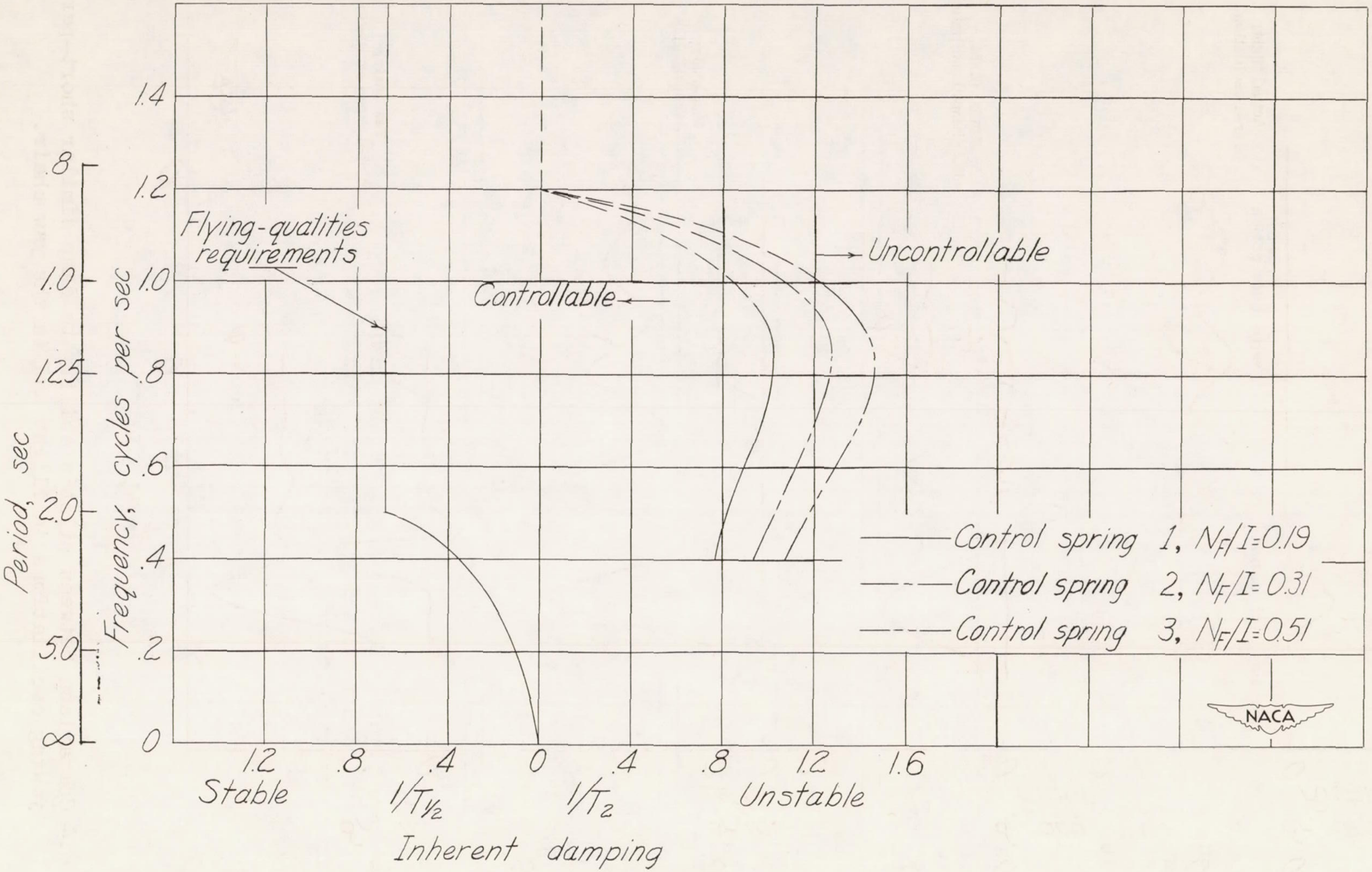


Figure 7.– Boundaries of pilot's ability to control short-period yawing oscillations.

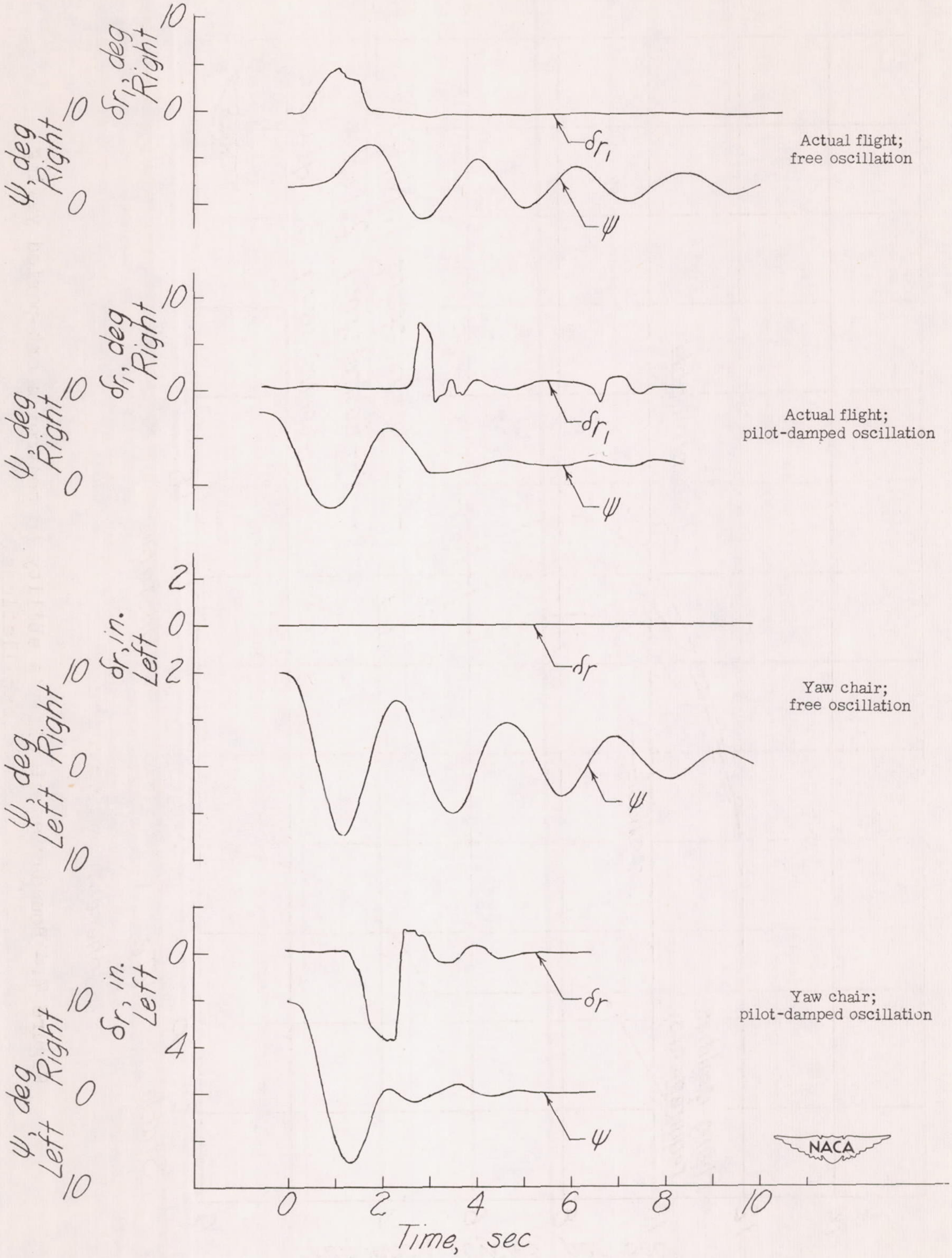


Figure 8.– Comparison between pilot's ability to damp similar short–period yawing oscillations in flight and in the yaw chair.

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