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# RESEARCH MEMORANDUM

## TOLERABLE LIMITS OF OSCILLATORY ACCELERATIONS DUE TO ROLLING MOTIONS EXPERIENCED BY ONE PILOT DURING AUTOMATIC-INTERCEPTOR FLIGHT TESTS

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and Robert A. Champine

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RESEARCH MEMORANDUM

# TOLERABLE LIMITS OF OSCILLATORY ACCELERATIONS DUE TO ROLLING MOTIONS EXPERIENCED BY ONE PILOT DURING AUTOMATIC-INTERCEPTOR FLIGHT TESTS

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## SUMMARY

Limited flight-test data obtained from an automatically controlled interceptor during runs in which oscillatory rolling motions were encountered have been correlated with the pilot's comments regarding his ability to tolerate the imposed lateral accelerations. The results of this correlation indicate that the tolerable limit of the lateral oscillatory acceleration was about ±0.4 to ±0.5g, measured at the pilot's head in the frequency range from 4 to 9 radians per second.

## INTRODUCTION

An automatic interceptor, to be an effective weapon, is required to track a target within small error limitations. To do so in the presence of target maneuvers leads to high-gain control systems. With such control-system characteristics, the motions of the interceptor may become very oscillatory in the presence of radar noise or atmospheric turbulence. Lightly damped airplane and control-system oscillations of short period do not necessarily affect the tracking adversely. However, for at least an interim period the pilot is required to occupy automatic interceptors, and these oscillatory motions must be smoothed and limited so that the accelerations they produce will not exceed human tolerance levels. It is desirable, then, to know what levels of oscillatory acceleration can be tolerated by a pilot during this particular task. Reference 1 presents a general simulator study of this problem.

This paper presents a limited amount of data on the levels of oscillatory accelerations found to be tolerable and intolerable by one pilot during flight tests of a prototype automatic interceptor (ref. 2). Since it is generally recognized that the pilot was most sensitive to accelerations imposed at his head, the data analyzed apply to that location.

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## APPARATUS, TESTS, AND INSTRUMENTATION

The airplane with which flight-test data were obtained for this paper was a prototype automatic interceptor and is described in reference 2. A photograph of the test aircraft is presented in figure 1. All the flight tests were conducted at an altitude of 20,000 feet and a Mach number of 0.76. The same pilot made all the flights. It should be noted that the data used in this paper were obtained incidentally to a flight-test program involving this interceptor. Some results of the primary flight-test program are reported in reference 3.

Extensive instrumentation was available in the test aircraft; however, the majority of the data of interest for this paper were measured by a lateral accelerometer located at a point at the bottom of the fuselage approximately 5 feet ahead of the center of gravity. These data were corrected to the pilot's head. On later flights, a second accelerometer was located immediately behind the pilot's head, approximately 12 feet ahead of the center of gravity. A comparison of the records from these two accelerometers during parts of runs in which uncomfortable oscillations were encountered showed that the corrected data from the lower accelerometer agreed with the data from the upper accelerometer.

## RESULTS AND DISCUSSION

### Calculation of Acceleration Effects Due to Rolling Oscillations

The lateral acceleration at a given point in a rigid airframe is the summation of the lateral acceleration at the center-of-gravity position and the tangential accelerations due to rolling and yawing motions. The resultant acceleration may be expressed by the equation

$$\ddot{Y} + h\ddot{\varphi} + l\ddot{\psi} = R$$

where

| | |
|---|---|
| $R$ | resultant lateral acceleration recorded by accelerometer |
| $\ddot{Y}$ | lateral acceleration at center of gravity (including gravity effect due to bank angle), ft/sec$^2$ |
| $h$ | height above roll axis, ft |
| $\ddot{\varphi}$ | rolling angular acceleration, radians/sec$^2$ |
| $l$ | distance from the yaw axis, ft |
| $\ddot{\psi}$ | yawing angular acceleration, radians/sec$^2$ |

During the flight tests the rudder was used only for yaw damping and sideslip regulation, and the system was successful in maintaining the yawing motions and sideslip to fairly low angles. The principal lateral control was through the use of the ailerons to roll the airplane, and it was found that when lateral oscillations were encountered they involved motions that were predominantly in roll. Thus, $\ddot{Y}$, which includes the gravity effect due to bank angle, was small; and the acceleration component due to yaw $l\ddot{\psi}$ was also negligibly small, even though the pilot sat about 12 feet in front of the center of gravity. Therefore, most of the oscillatory acceleration at the pilot's head could be attributed to the tangential effects of the rolling motions, denoted by $h\ddot{\varphi}$.

Calculations were made for several cases where measured roll- and yaw-angle amplitude and frequencies were used to calculate the lateral acceleration at the pilot's head. Good agreement was obtained with the corrected accelerometer data.

In order to show the effect of varying the distance of the pilot's head from the roll axis of the airplane, the peak tangential acceleration was calculated (assuming a single degree of freedom in roll and neglecting the effect of gravity) for values of $h$ from 2 feet to 20 feet over a frequency range up to 8 radians per second at a constant amplitude of oscillation of $\pm 0.174$ radian ($10^\circ$). This information is plotted in figure 2(a). For a given frequency, the acceleration varies directly with the distance from the axis of motion. Thus, at 3.6 feet from the roll axis for a pure rolling oscillation of $\pm 10^\circ$ amplitude and a frequency of 6 radians per second, a peak acceleration at the pilot's head of about 0.7g is produced. The effect of varying the amplitude of rolling oscillation up to $24^\circ$ over a frequency range up to 8 radians per second for a constant distance from the roll axis of 3.6 feet is shown in figure 2(b). This figure applies to the test aircraft, but a similar figure could be made for any aircraft in which the distance from the pilot's head to the motion axis is known.

## Flight Determination of Pilot Tolerance to Accelerations Resulting From Rolling Oscillations

As previously mentioned, the flight-test data used in this paper were obtained incidentally to a flight-test program involving a prototype automatic interceptor. During this program, oscillatory motions of the interceptor were encountered that subjected the pilot to an objectionably uncomfortable ride. These oscillatory motions were usually the result of using high gains in the automatic control system, and it was not uncommon to encounter roll-angle amplitudes of $\pm 15^\circ$ to $\pm 20^\circ$ coupled with yaw-angle amplitudes up to $\pm 2^\circ$.

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It is of interest to note that an earlier investigation (ref. 4) established the magnitude of transverse oscillatory accelerations which could be perceived by the pilot and also the magnitudes which were considered unsatisfactory because of the unpleasantness or tiring effect of the ride. The accelerations encountered during the flight-test runs of interest to this paper are of a magnitude that would have been highly unsatisfactory by the standards of reference 4. It is important to note that the results presented herein are based mostly upon a consideration of the physical effects upon the pilot over fairly short periods of time.

When uncomfortable oscillatory motions were encountered, the interceptor pilot classified them as to his ability to tolerate the imposed accelerations. The following classifications were used:

Intolerable - An oscillation that the pilot was unable to withstand for more than 15 to 20 seconds without experiencing nausea effects, excessive sweating, or a feeling of fatigue.

Marginal - An oscillation that the pilot could endure for a longer period but would experience nausea effects if continually subjected for more than about 2 minutes.

Tolerable - An oscillation that the pilot objected to from a comfort standpoint, but one that could be endured for a considerable period of time.

Since it is generally recognized that the pilot is most sensitive to accelerations imposed at his head, the data were analyzed for that location.

Time histories of the lateral acceleration corrected to a point at the pilot's head during parts of three typical runs are presented in figure 3. An example is given of each of the classifications used by the pilot. Note that the marginal and tolerable accelerations are somewhat irregular; varied frequencies and levels of acceleration are combined. It is believed that, in general, a pilot will judge an irregular oscillation slightly more severely than a smooth oscillation of equal amplitude and frequency because the irregularity deprives him of any anticipation of the acceleration forces that will be imposed.

All the data points concerning the pilot's tolerance of lateral oscillations were plotted as acceleration against frequency of oscillation. (See fig. 4.) Each of the data points, obtained from separate runs, represents the peak acceleration averaged over several consecutive cycles. The data points fall within a range of frequency from about 4 to about 9 radians per second. Oscillations were noted at other frequencies during the primary tests of the interceptor, but they either did not produce uncomfortable acceleration on the pilot or else data were incomplete.

The data of figure 4 indicate a general grouping of the classifications; however, the data were not quantitative enough for sharp definition. It is to be expected that the pilot's tolerance to forces of this type may vary from flight to flight for various reasons and also probably changes during a flight due to cumulative effects of experiencing uncomfortable oscillations. Figure 4 shows that in the frequency range from 4 to 9 radians per second the marginal limit of oscillatory acceleration due to rolling motions is about 0.4 to 0.5g.

The amplitude of the roll oscillation during the runs represented by the data of figure 4 was as high as $\pm 24^{\circ}$, which occurred at a frequency of 5.7 radians per second. (This run was intolerable to the pilot.) It is of interest to note that on all runs the yawing component of the lateral oscillations was small.

Similar data are not available for pitching motion or vertical acceleration; however, on one flight motions were encountered that combined a vertical oscillation with a frequency of about 2 radians per second with lateral oscillations that varied in frequency from 5 to 12 radians per second. The vertical acceleration was about ±0.5g and the tangential acceleration at the pilot's head due to roll averaged about ±0.3g. This combination was objectionable to the pilot, and after approximately 10 minutes of run time spaced over about 10 runs during a one-hour flight, he became nauseated. It appears probable that the addition of oscillations about the other two axes caused a lowering of the lateral oscillatory limit.

## OTHER CONSIDERATIONS

### Alleviation of Undesirable Effects of Oscillatory Lateral Accelerations

The undesirable effects of oscillatory lateral oscillations on the pilot obviously could be alleviated by eliminating the motions; however, the means by which the motions could be eliminated may penalize the tracking performance of the system. It is desirable then to consider other factors that may tend to alleviate the undesirable effects.

Reference 5 shows that the manner in which the pilot is restrained is an important factor. In the present tests the usual seat belt and shoulder harness arrangement was used. Since this arrangement allows considerable freedom of head movement the corrected acceleration records do not necessarily represent the true forces on the pilot's head. In almost all cases the pilot attempted to restrain his head and upper body by bracing against the side of the cockpit. This helped to minimize movements of his head relative to the cockpit and reduced the probability of the head and upper body striking the side of the canopy or cockpit enclosure. In addition, bracing against the side helps keep the head relatively stationary with respect to the instrument panel so that the pilot can observe and interpret the instruments. On some runs where the pilot did not brace his head, he said it was not possible to interpret the instruments because he could not keep his eyes trained on them. (The pilot also noted that the instruments were sometimes shaking within their mounts and that the indicators of the instruments were oscillating at the same frequency as the lateral oscillation.) The use of a lateral head brace would prevent head movement relative to the cockpit enclosure and alleviate the previously mentioned objectionable factors. Information contained in reference 5 shows that a head brace would also be advantageous in eliminating the nausea of motion sickness due to lateral acceleration. In addition, reference 1, which indicates a higher level of pilot tolerance to acceleration forces than the present paper, utilized head braces. For these reasons a lateral head brace appears to be worthy of consideration in future designs. However, such a device would not eliminate the acceleration forces, and more data are needed to determine the effect of the head brace upon tolerable limits.

Reference 6, referring to the effect of nausea, discounts the use of anti-motion-sickness drugs to alleviate this condition because of the possible deleterious effects upon mental and physical processes.

## Effects on Piloting Task

During a typical flight test the pilot had a multitude of tasks to perform before and after a test run, but during the run he acted primarily as an observer. It is probable that, if he had a more complicated task to perform during the test runs, such as interpreting an instrument or adjusting a system gain, his classification of the objectionable oscillations might have been different and a different tolerance limit might have been established.

After several of the flights in which particularly uncomfortable oscillations were experienced the pilot described a "don't care" feeling that is attendant to the feeling of nausea, and he strongly emphasized the danger of this feeling if one is required to perform a complicated task (such as an instrument let-down) in which proficient piloting is required.

## Need for Additional Data and Application to Other Designs

The data presented and the pilot opinions expressed relate to a single pilot. It is recognized that additional data from a representative group of pilots should be obtained before a specific limit of oscillatory acceleration is established.

A survey of current fighter and interceptor designs indicates that the pilot's head may be located as much as 5 to 6 feet above the roll axis and up to 20 feet in front of the yaw axis. At these distances, the possibilities of encountering accelerations of the level found to be intolerable in the present tests is greatly increased. It is believed that such factors should be considered in interceptor design.

## CONCLUDING REMARKS

The analysis of a limited amount of data regarding the tolerable limit of one pilot to oscillatory accelerations has shown that, at frequencies of oscillation in the range of 4 to 9 radians per second, the marginally tolerable limit of acceleration forces upon the pilot's head due to the rolling motion of an interceptor was about 0.4 to 0.5g. Consideration should be given in future designs to the problem of keeping these oscillatory accelerations within tolerable limits. The use of a lateral head brace may be a desirable means of alleviating some of the undesirable effects associated with oscillatory accelerations due to lateral motions.

Experimental data from a cross section of pilots regarding their tolerance of oscillatory accelerations are desirable. Further studies should be made of the factors affecting this tolerance.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., October, 31, 1956.

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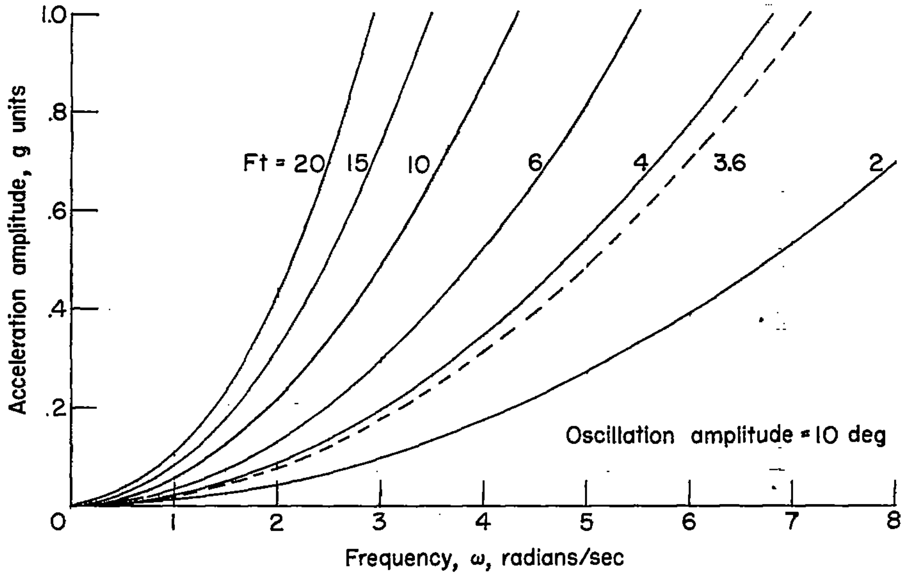
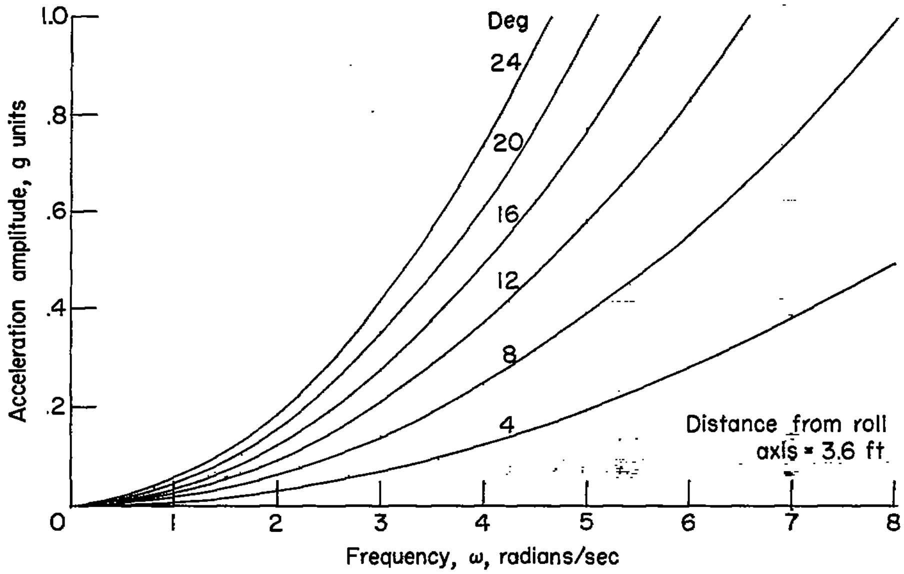
Figure 1.- Side view of test aircraft. L-91217



(a) Effect of varying distance above roll axis for constant amplitude of oscillation.



(b) Effect of varying amplitude of oscillation for constant distance above roll axis.

Figure 2.- Calculated variation of lateral acceleration due to single degree of freedom oscillatory rolling motions.

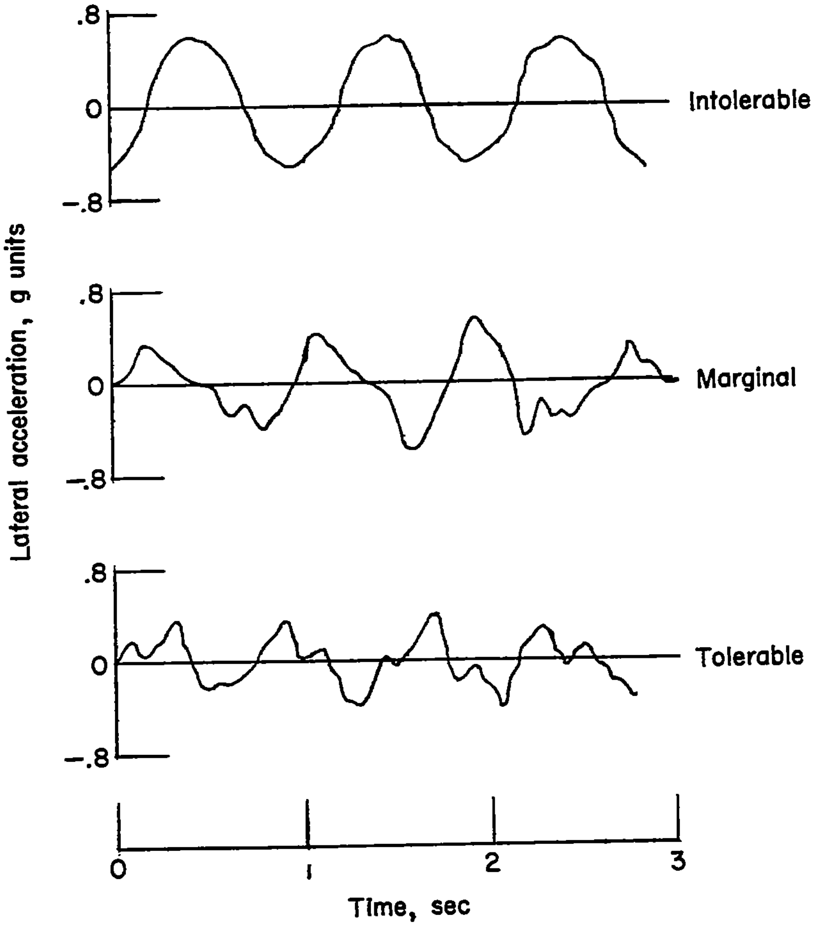


Figure 3.- Time histories of lateral acceleration measured at pilot's head during three interception runs showing an example of each classification of run as judged by pilot.

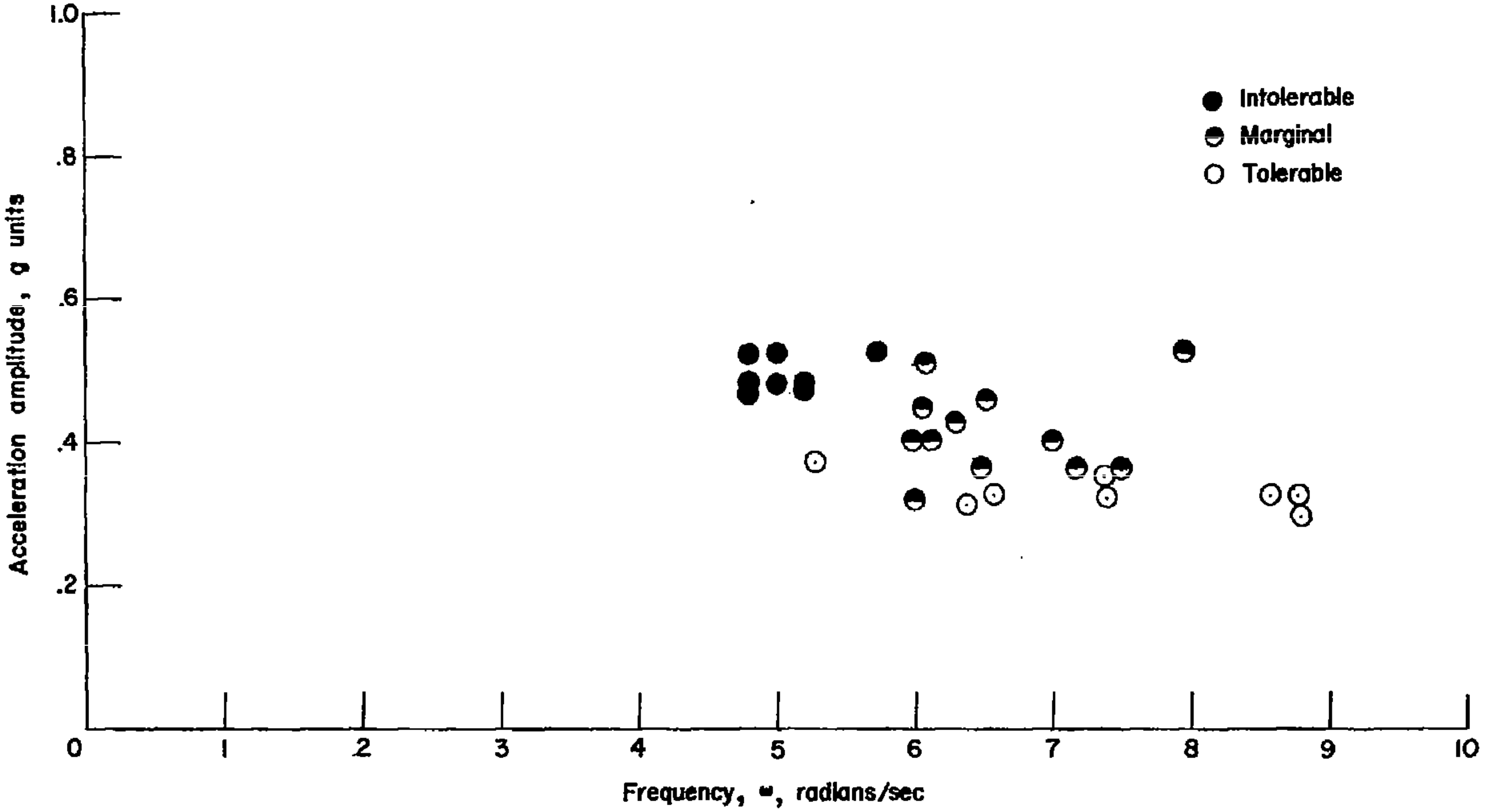


Figure 4.- Distribution of data points concerning tolerable or intolerable lateral accelerations due to oscillatory rolling motions.

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