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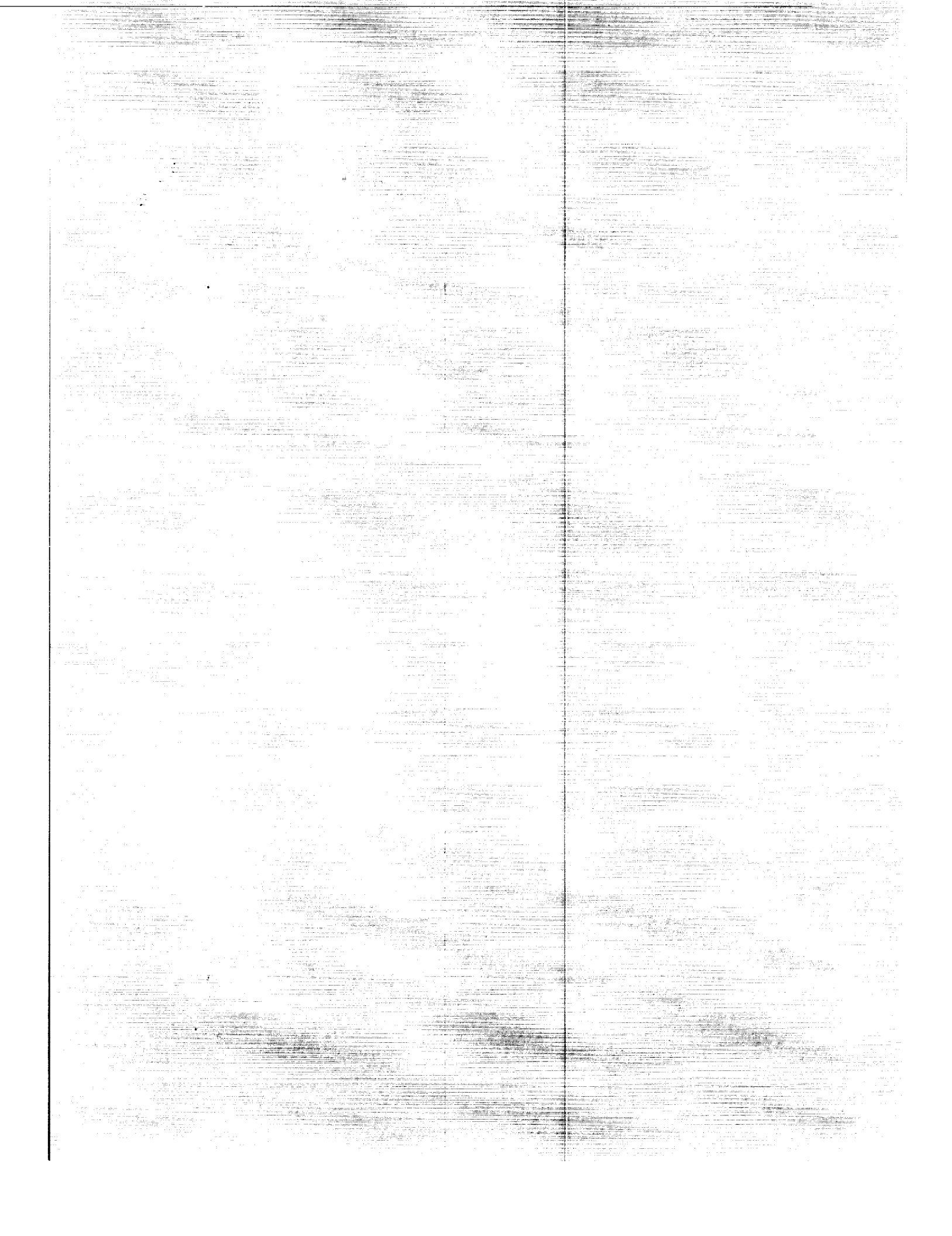
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FOR
UNITED STATES AIR FORCE

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RESPONSE OF A WB-47E AIRPLANE TO RUNWAY ROUGHNESS AT EIELSON AFB, ALASKA, SEPTEMBER 1964

by Garland J. Morris and Albert W. Hall
Langley Research Center
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ABSTRACT

An investigation has been conducted to measure the response of a WB-47E airplane to the roughness of the runway at Eielson AFB, Alaska. The acceleration level in the pilot's compartment and the pitching oscillation of the airplane were found to be sufficiently high to possibly cause pilot discomfort and have an adverse effect on the precision of take-off.

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SUMMARY

An investigation has been conducted to measure the response of a WB-47E airplane to the roughness of the runway at Eielson AFB, Alaska. The acceleration level in the pilot's compartment was found to be sufficiently high to possibly cause pilot discomfort and have an adverse effect on the precision of take-off. During the tests, accelerations as high as 0.7g were recorded in the pilot's compartment. Pitching oscillations were induced by roughness near the midsection of the runway as the airplane traversed it at a few knots below lift-off speed. A pitching oscillation of about $2\frac{1}{2}^{\circ}$ double amplitude was measured during one take-off.

INTRODUCTION

At the request of the Directorate of Civil Engineering, Headquarters, U.S. Air Force, the NASA Langley Research Center has participated in a program to measure the response of a WB-47E airplane to the roughness of the runway at Eielson AFB, Alaska. These response measurements were desired by the Air Force to determine whether a serious problem exists in the operation of the airplane on this runway and for possible use in planning runway repairs.

The airplane used in the investigation was provided and operated by the U.S. Air Force. The NASA provided and installed the instrumentation to measure the response of the airplane to roughness, assisted in planning and conducting the tests, and reduced and analyzed the data. The investigation consisted of measuring the airplane normal acceleration, attitude, and shock-strut positions during take-offs and constant-speed taxi runs.

The results of the investigation are presented herein in terms of time histories of airplane responses and tabulated values of peak accelerations. The airplane responses are correlated with the runway profile measured by the Air Force.

INSTRUMENTATION

The airplane was instrumented with three NASA acceleration transmitters, a pitch-velocity transmitter, a pitch-angle transmitter, two shock-strut-position transmitters, a 1/10-second timer, a flight oscillograph, and an airspeed recorder. Photographs of some of the instrumentation installed in the airplane are shown in figure 1.

One acceleration transmitter was located in the pilot's compartment, one near the center of gravity, and one in the tail of the airplane. Approximate locations of the accelerometers are shown in figure 2. The accelerometers had essentially a flat frequency response to 15 cps and had a damping ratio of about 0.7 critical.

One of the oscillograph traces was connected to a manual switch which was operated by the copilot to mark the film when the airplane was opposite each 1000-foot runway marker.

TESTS

The investigation consisted of constant-speed taxi runs and take-offs of the airplane, piloted by Air Force personnel, and were conducted at Eielson AFB, Alaska, during September 17-19, 1964. The weather was clear, calm, and dry.

The taxi tests were conducted at constant speeds in both directions of the runway. Starting from the end of the runway, the airplane was accelerated to the desired test speed. This speed was then maintained by throttle control over as much of the runway as was possible before it was necessary to initiate braking action. The conditions for the taxi tests along the runway center line are given in table I. Two additional taxi tests at 110 knots were made about 40 feet to the left of the runway center line.

The two take-off tests were made on runway 31 with water injection and under identical initial conditions. The weight at the start of roll was 175,500 pounds, the center of gravity at lift-off was 26.4 percent of mean aerodynamic chord, and the take-off roll was started 1300 feet from the end of the runway. The handbook values of lift-off speed and take-off distance were 152 knots and 6100 feet, respectively. No instructions were given to the pilot regarding the technique to be used in controlling the airplane during the take-offs.

In addition to the taxi and take-off tests just described, the take-off run was recorded when the airplane left Langley Air Force Base, Hampton, Virginia, after being instrumented, and two touch-and-go landings were made at both Eielson AFB and Elmendorf AFB, Alaska. For these tests, the airplane touched down and traversed a long stretch of each runway at speeds between 90 and 110 knots.

RESULTS AND DISCUSSION

Runway

The test runway, identified as runway 31 in one direction and as 13 in the other, is 14,500 feet long. A detailed profile of the entire runway is not available; however, the profile of a 4000-foot portion of runway 31 between 9000 feet and 5000 feet is shown in figure 3. Throughout this paper the runway locations will be given in terms of the 1000-foot markers (distance remaining) along runway 31. This profile is based on an Air Force survey made along the center line of the runway at 10-foot intervals during May 1964. The gradients to which the runway was constructed in 1949 are also shown.

A large long-wavelength bump in the runway is evident where two positive gradients of about 0.10 percent are joined by a negative gradient of about 0.07 percent at approximately the 8500-foot and 8000-foot stations. This portion of the runway has been the subject of the majority of the roughness complaints; especially those stemming from difficulties encountered in maintaining control of the airplane. Shorter wavelength irregularities such as those at the 8500-, 8100- and 7800-foot locations within this region are the apparent source of the objectionable responses. Examination of the profile beyond this location indicates the presence of a number of surface irregularities, such as those at 7400, 7250, and 6600 feet, which also might be expected to result in substantial airplane response.

Taxi Tests

Sample records of the responses of the airplane are shown in figures 4 and 5. These results were obtained during runs 4 and 8 (table I) for which taxiing speeds were 75 and 100 knots, respectively. The runway profile shown below the records indicates the approximate runway stations at which the responses were measured. The responses shown in the figures are airplane pitch attitude, pitch rate, and normal acceleration at the nose, center of gravity, and tail, as well as front- and rear-landing-gear strut positions. The magnitudes of several of the peak responses are indicated. The values of acceleration are in terms of incremental g units above (+) and below (-) the static 1.0g value. Airplane pitch attitude shown in figures 4 and 5 is referred to the static attitude (wing angle of attack approximately 8°) at the beginning of each run.

Examination of figures 4 and 5 shows several points of interest relative to the airplane responses to the runway roughness. It is evident that the roughness caused substantial acceleration response continually during the traverses of the runway and that certain locations along the runway are more conducive to high responses than are other locations. For example, figure 4 shows that, for the 75-knot taxiing speeds, the roughness near the 8000-foot location resulted in pilot-compartment accelerations as high as 0.35g. Likewise, the roughness between 7000 feet and 6300 feet caused sustained pitching motions and pilot compartment accelerations as high as 0.7g and -0.44g. The responses cited were

at a frequency of approximately 1.25 cps. Responses at this frequency and speed would be excited by runway irregularities having wavelengths of approximately 100 feet.

Several major frequency response modes are evident in figures 4 and 5 with frequencies ranging from around 0.8 cps to 4.0 cps. The wavelengths of runway irregularities which have the greatest effect on airplane response at these frequencies depend on the taxiing speed. For example, at a taxiing speed of 150 knots, runway irregularities having wavelengths of 316 feet and 63 feet would be expected to cause large response at 0.8 cps and 4.0 cps, respectively, whereas at 75 knots wavelengths of 158 feet and 32 feet would likely cause the most response at these frequencies. In addition to the dependence of the airplane response over a particular area on taxiing speed, the response on one area can be dependent on aircraft motions that were started by the previous area. The effect of speed is illustrated in figures 4 and 5 where a considerable response is shown near the 8000-foot station at a speed of 75 knots, but very little response to this area is shown at 100 knots. In each case the greatest response is caused by the rough area near the 6500-foot station.

A number of taxi runs at different speeds were made and correlated with the runway profile to detect the roughness throughout the speed range. Examination of all the taxi runs resulted in the identification of certain areas of the runway which caused significantly more response than the rest of the runway. Airplane accelerations for the eight constant-speed taxi runs performed on the center line of runways 13 and 31 are tabulated in table I. As shown in the table, 12 noticeably rough sections (ranging in length from 200 feet to 500 feet) were detected. The accelerations in the pilot's compartment during traverse of these 12 sections ranged from about 0.25 g to 0.70g. The center-of-gravity accelerations ranged up to 0.3g and the tail accelerations up to about 0.76g.

The peak values of the accelerations at the pilot's compartment (nose), the center of gravity, and the tail (table I) are plotted in figure 6 at the midpoint of each of the 12 sections of runway judged to have caused the major responses. It is noted that the acceleration of the pilot's compartment exceeded 0.4g in each of the areas during traverse at one or more of the four taxi speeds. Based on the acceleration of the pilot's compartment, the roughest area is between 6700 feet and 6300 feet.

Comparison of the results in figure 6 for taxiing in the two directions on the runway does not show a significant effect of taxi direction on the responses. In addition, results of two taxi runs on either side of the center line were not significantly different from those shown in figure 6. Thus, it is not believed that the roughness can be alleviated by operating on either side of the center line.

Take-Off Tests

Time histories of the airplane responses during the last 12 seconds of the two take-offs are given in figure 7. The elevation profiles of the section of runway traversed during this period are also shown in the figure. As previously

mentioned, the initial conditions (weight, center of gravity, and airplane configuration) were the same for both take-offs. However, due to piloting technique, the rear wheels lifted off before the nose wheel during the first take-off (fig. 7(a)), whereas the front wheels lifted off first during the second take-off (fig. 7(b)). As will be subsequently discussed, this difference in take-off technique resulted in significantly different airplane responses during the final stages of the take-offs while traversing the section of runway between about 8500 feet and 7000 feet.

First take-off.- Examination of the airplane-response time histories for the first take-off (fig. 7(a)) shows that the rear wheels lifted off first at about the 8500-foot runway position while the airspeed was approximately 135 knots. The rear wheels remained off the runway for the remainder of the take-off except for momentary contact at about 8400 feet and 7800 feet.

During this take-off (fig. 7(a)), the nose gear first left the runway at the break in the profile at about 7800 feet. Between this location and the final lift-off at 7000 feet, a pitch oscillation existed such that the nose wheel was alternately in and out of contact with the runway. Thus, both gears were off the ground for about 0.5 second near 7800 feet with an airspeed of approximately 143 knots and again near 7400 feet with an airspeed of 149 knots. The airspeed at final lift-off was 153 knots, which is in good agreement with the handbook value of 152 knots.

The acceleration response in the pilot's compartment (fig. 7(a)) was less than $\pm 0.25g$ except during the last 500 feet of travel where maximum accelerations of $-0.31g$ and $0.49g$ were experienced. These peak accelerations were associated with the pitching motions of the airplane and the attendant alternating contact of the nose gear with the runway. The pitch attitude response during the take-off was in the nose-down direction and a maximum value of 2.3° less than the normal ground attitude was experienced during the pitch oscillation prior to lift-off. Control motions were not recorded during these tests; therefore, it is not known whether there were inadvertent or deliberate elevator control motions to either increase or damp this oscillation.

Second take-off.- Examination of the airplane response time histories for the second take-off (fig. 7(b)) shows that the front wheels lifted off first at about the 8500-foot runway position at an airspeed of approximately 134 knots. The front wheels were off the runway for the remaining take-off distance except for momentary contact at four locations (near 8400, 8200, 8000, and 7600 feet) due to a slight pitching motion of the airplane.

The bump at the 7400-foot location caused the airplane to become completely airborne at a speed and attitude which were too low to maintain flight so that the rear wheels hit the next bump at 7300 feet. At this point, the airspeed was about 148 knots and the attitude was about 2° above normal. Although the lift-off speed was 4 knots below handbook lift-off speed, the airplane was able to maintain flight from this point on.

The acceleration response in the pilot's compartment was less than $\pm 0.25g$ except during the final stages of the take-off where maximum accelerations of $-0.40g$ and $0.35g$ were experienced. Thus, the maximum acceleration response

during the second take-off was not significantly different from that experienced during the first take-off (-0.31g and 0.49g).

Assessment of Roughness

Before attempting to assess the roughness of the Eielson AFB runway, it is worthwhile to consider some general aspects of the roughness problem. In this connection, it is noted that past experience has shown that the roughness of a particular runway may be a source of concern to pilots for the following reasons:

- (1) Apprehension of causing structural damage to the airplane
- (2) Crew discomfort associated with the imposed accelerations
- (3) A degradation of the ability to precisely control the airplane during the take-off maneuver

In addition, the roughness of a given runway may have significantly different effects on different types of airplanes (and even on airplanes of the same type if operated at different weight or power conditions). Thus, a runway may be a source of complaints or concern by crews of a particular airplane type, but be considered satisfactory by crews of other types of airplanes.

Due in part to the complex interaction between runway roughness and airplane response characteristics, there is no specific criterion by which to assess runway roughness quantitatively. Consequently, assessment of roughness and its effect on the crew can only be done in a qualitative manner. Such an assessment of the roughness for runways 13 and 31 is given in the following paragraphs.

As was noted in a previous section of this paper, the maximum accelerations recorded in the pilot's compartment during the constant-speed taxi test and during the two take-offs were 0.7g and -0.4g. In comparison, the maximum accelerations recorded during a take-off from Langley AFB (where the airplane was instrumented) was 0.38g and -0.31g. It is noted that some complaints of roughness of the Langley runway have been made by crews of large multiengine jet airplanes. As a further comparison, the test crew made two touch-and-go landings at both Eielson AFB and Elmendorf AFB traversing a long stretch of each runway at speeds between 90 and 110 knots. In the opinion of the pilot, these runs showed that the runway at Eielson was rougher than the one at Elmendorf. Other pilot-compartment acceleration values which have been measured on runways which have caused pilot complaints are 0.5g on a commercial Boeing 720 and 0.8g on a B-52 airplane.

Based on the foregoing comparisons, the roughness at Eielson AFB would be expected to be a source of complaints by WB-47E crews. The loads imposed on the airplane are not thought to be high enough to cause structural damage to the airplanes, except fatigue damage through the cumulative effect of the repeated loadings. The pilot-compartment accelerations could, however, cause pilot discomfort and have an adverse effect on the precision of the take-off. It should

be noted that the pilot's opinion of the roughness is influenced to some extent by the frequency as well as the amplitude of the acceleration response since the human body is more sensitive to some frequencies than to others.

Probably the most disturbing effect of the roughness is the porpoising, or pitching oscillations, induced by the rough area near the midsection of the runway as the airplane traversed it at a speed a few knots below lift-off speed. A severe pitching oscillation occurred during the take-off in which the rear main gear lifted off the runway first. The oscillation was much less noticeable for the take-off in which the nose wheel lifted off first. However, early lifting of the nose wheel may not be satisfactory due to the loss of nose-wheel steering and because a nose-high attitude at lift-off may progress to a pitch-up condition as the airplane climbs out of ground effect (ref. 1).

Runway Repair Considerations

In view of the foregoing discussion, it is thought that two aspects of the roughness should be considered in determining the extent of repairs which may be deemed necessary to the runway. First, in order to reduce the pilot-compartment accelerations, repairs to a number of sections of the runway apparently would be required as indicated by the results in figure 6. Second, the pitching oscillations (which appear to be the cause for concern) could apparently be alleviated significantly by eliminating the bumps or irregularities between the 8500- and 7200-foot stations.

In determining detailed repairs to the runway, further comparisons of the existing measured airplane responses with a complete elevation profile of the runway could be useful. In addition, the use of the analytical method described in references 2 and 3 could prove useful in determining optimum repairs to the runway.

CONCLUDING REMARKS

An investigation has been conducted to measure the response of a WB-47E airplane to runway roughness at Eielson AFB, Alaska. The results of this investigation indicate that the roughness could result in crew discomfort and cause an adverse effect on the precision of the take-off. During the taxi tests, accelerations as high as 0.7g were recorded in the pilot's compartment. Probably the most disturbing effect of the roughness is the porpoising, or pitching oscillations, which were caused by roughness near the midsection of the runway when the airplane was approaching lift-off speed. A pitching oscillation of about $2\frac{1}{2}^{\circ}$ double amplitude was measured during one take-off.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 16, 1965.

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2. Hall, Albert W.; and Kopelson, Sheldon: The Location and Simulated Repair of Rough Areas of a Given Runway by an Analytical Method. NASA TN D-1486, 1962.
3. Coleman, Thomas L.; and Hall, Albert W.: Implications of Recent Investigations on Runway Roughness Criteria. AGARD Rept. 416, Jan. 1963.

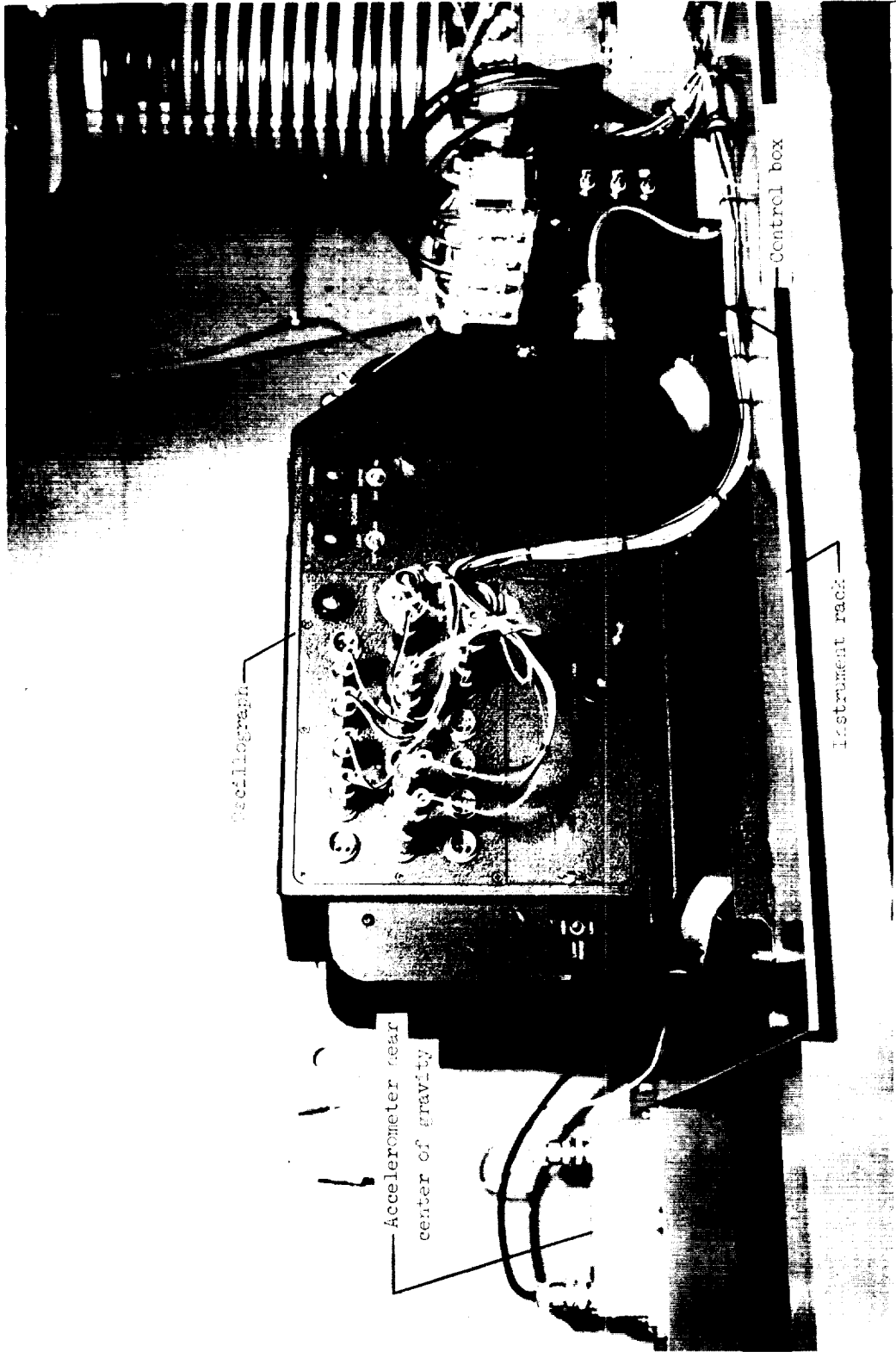
TABLE I.- SUMMARY OF OPERATING CONDITIONS AND MAXIMUM NORMAL ACCELERATION RESPONSE OF AIRPLANE
DURING TAXIING ON CENTER LINE OF RUNWAYS 13 AND 31

| Run | Speed, knots | Heading | Airplane weight, lb | Airplane response resulting from rough sections of runway from ^a - | | | | | | | | | | | | | | | | | |
|-----|--------------|---------|-------------------------|---|------|-------|--------------------|------|------|-------------------|------|-------|-------------------|------|------|-------------------|------|------|-------------------|------|------|
| | | | | 11,250 to 11,000 ft | | | 10,250 to 9,900 ft | | | 8,550 to 8,350 ft | | | 8,100 to 7,800 ft | | | 7,500 to 7,200 ft | | | 6,800 to 6,300 ft | | |
| | | | | Acceleration, g | | | Acceleration, g | | | Acceleration, g | | | Acceleration, g | | | Acceleration, g | | | Acceleration, g | | |
| | | | | Nose | c.g. | Tail | Nose | c.g. | Tail | Nose | c.g. | Tail | Nose | c.g. | Tail | Nose | c.g. | Tail | Nose | c.g. | Tail |
| 1 | 50 | 13 | 180.5 × 10 ³ | -0.31 | 0.21 | -0.58 | 0.40 | 0.18 | 0.46 | 0.24 | 0.14 | -0.58 | 0.47 | 0.20 | 0.54 | 0.44 | 0.12 | 0.45 | 0.40 | 0.13 | 0.50 |
| 2 | 50 | 31 | 179.5 | .30 | .16 | .55 | .35 | .16 | .48 | .30 | -.15 | .65 | .36 | -.15 | -.42 | .34 | .11 | .41 | .36 | .13 | .48 |
| 3 | 75 | 13 | 179.0 | (b) | | | | | | .40 | .21 | -.54 | .43 | .21 | .43 | .38 | .15 | .56 | .58 | .22 | .39 |
| 4 | 75 | 31 | 176.0 | .41 | .23 | .51 | .33 | .16 | .60 | .30 | .10 | .30 | .35 | .18 | .46 | .42 | .20 | -.34 | .70 | .30 | .49 |
| 5 | 100 | 13 | 174.0 | | | | | | | .38 | -.13 | .25 | .35 | -.13 | -.26 | .40 | .16 | .41 | .49 | .22 | .52 |
| 6 | 110 | 31 | 169.0 | .43 | .18 | .27 | .20 | .10 | .29 | -.35 | .10 | .33 | .22 | .12 | .18 | .25 | .16 | .26 | .41 | .16 | .40 |
| 7 | 110 | 13 | 166.0 | | | | | | | .28 | .12 | .18 | .25 | .10 | .31 | .23 | .14 | .18 | .39 | .21 | .35 |
| 8 | 100 | 31 | 166.0 | .42 | .16 | .32 | .28 | .12 | .35 | .33 | .15 | .35 | .29 | .14 | .26 | .38 | -.17 | .24 | .49 | .23 | .44 |

| Run | Speed, knots | Heading | Airplane weight, lb | Airplane response resulting from rough sections of runway from ^b - | | | | | | | | | | | | | | | | | |
|-----|--------------|---------|-------------------------|---|------|------|-------------------|------|------|-------------------|------|------|-------------------|------|------|-------------------|------|-------|-------------------|------|-------|
| | | | | 6,200 to 5,800 ft | | | 4,500 to 4,200 ft | | | 4,100 to 3,800 ft | | | 2,700 to 2,500 ft | | | 1,900 to 1,700 ft | | | 1,400 to 1,200 ft | | |
| | | | | Acceleration, g | | | Acceleration, g | | | Acceleration, g | | | Acceleration, g | | | Acceleration, g | | | Acceleration, g | | |
| | | | | Nose | c.g. | Tail | Nose | c.g. | Tail | Nose | c.g. | Tail | Nose | c.g. | Tail | Nose | c.g. | Tail | Nose | c.g. | Tail |
| 1 | 50 | 13 | 180.5 × 10 ³ | 0.58 | 0.24 | 0.64 | 0.28 | 0.16 | 0.70 | 0.53 | 0.29 | 0.65 | 0.40 | 0.13 | 0.33 | 0.47 | 0.22 | -0.76 | 0.26 | 0.17 | -0.70 |
| 2 | 50 | 31 | 179.5 | .55 | .20 | .60 | .33 | .16 | -.50 | .40 | -.15 | .62 | | | | | | | | | |
| 3 | 75 | 13 | 179.0 | .58 | .21 | .61 | -.38 | .21 | .59 | .43 | .17 | .69 | .33 | .22 | .53 | .49 | .19 | .50 | -.44 | .15 | .53 |
| 4 | 75 | 31 | 176.0 | .45 | .18 | -.46 | | | | | | | | | | | | | | | |
| 5 | 100 | 13 | 174.0 | .41 | .19 | .43 | .42 | .22 | .35 | .26 | .16 | .50 | | | | | | | | | |
| 6 | 110 | 31 | 169.0 | .35 | .16 | .39 | | | | | | | | | | | | | | | |
| 7 | 110 | 13 | 166.0 | .37 | .17 | .39 | .18 | .08 | .20 | .26 | .16 | .33 | | | | | | | | | |
| 8 | 100 | 31 | 166.0 | .40 | .16 | .30 | | | | | | | | | | | | | | | |

^aLocations based on runway 31 distance remaining.

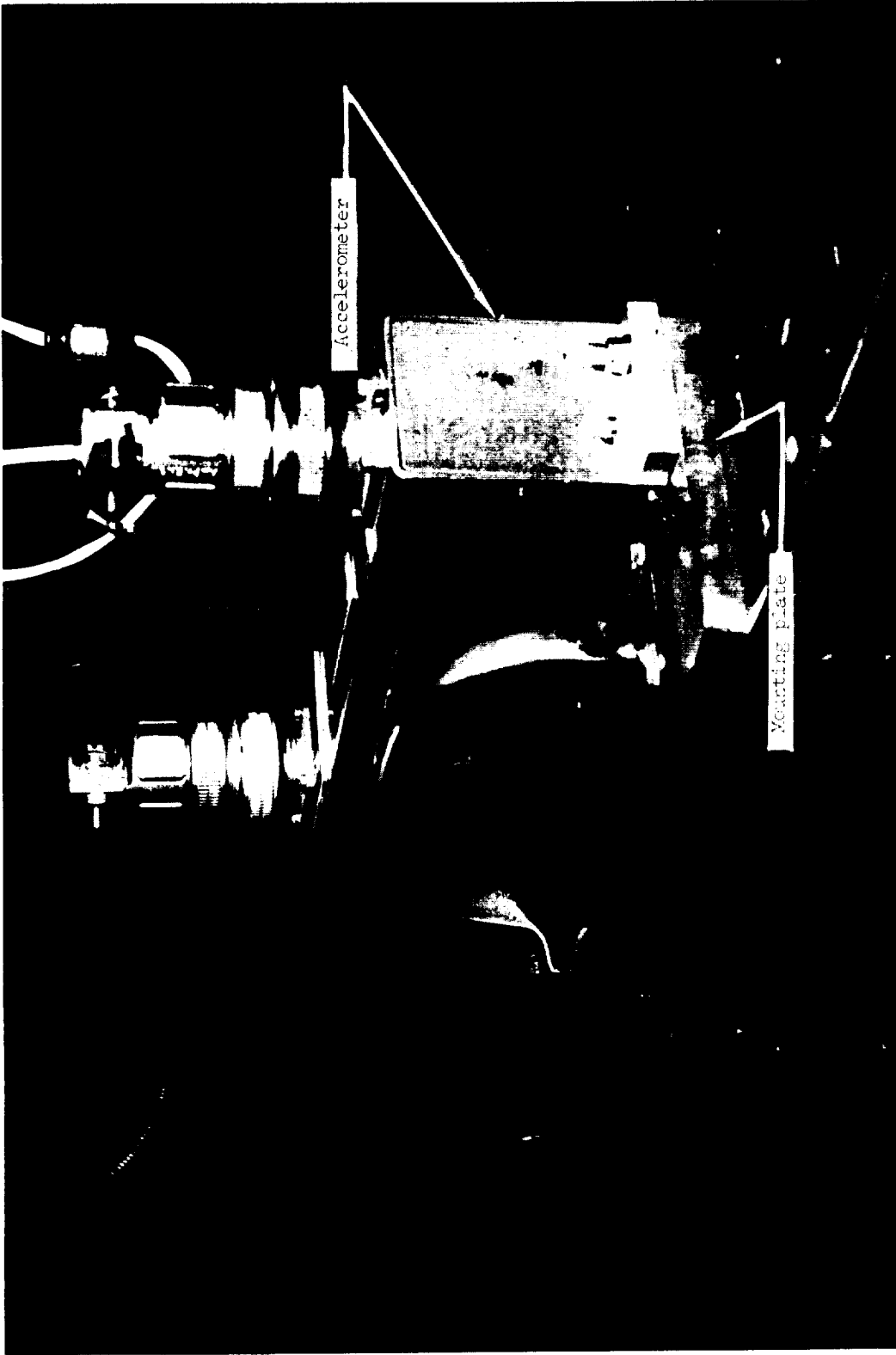
^bAbsence of values indicates that the runway section not traversed at test speed.



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(a) Installation in bomb bay.

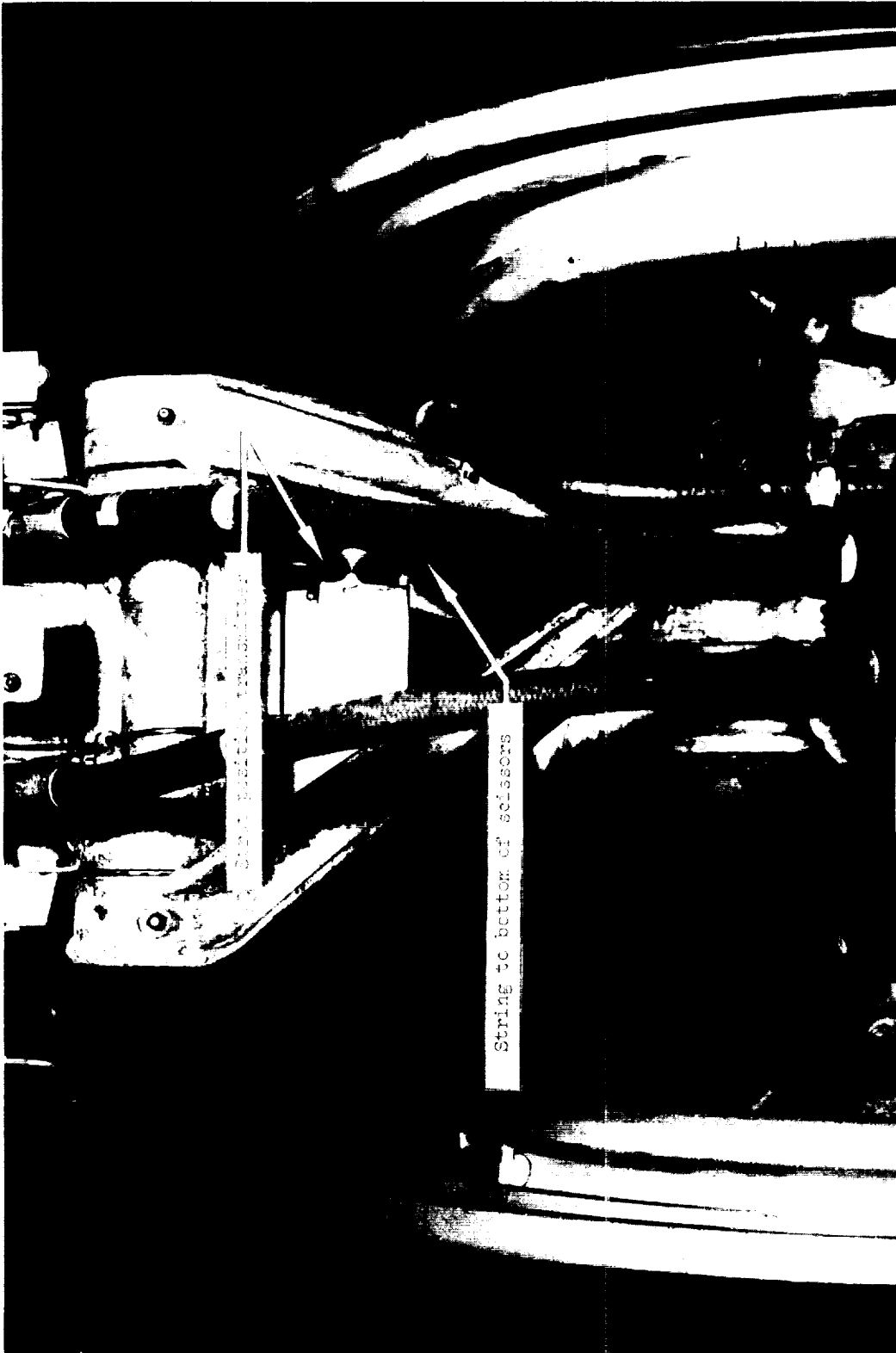
Figure 1.- Instruments installed in test airplane.



(b) Accelerometer in pilot's compartment.

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Figure 1.- Continued.



(c) Front strut-position transmitter.

Figure 1.- Concluded.

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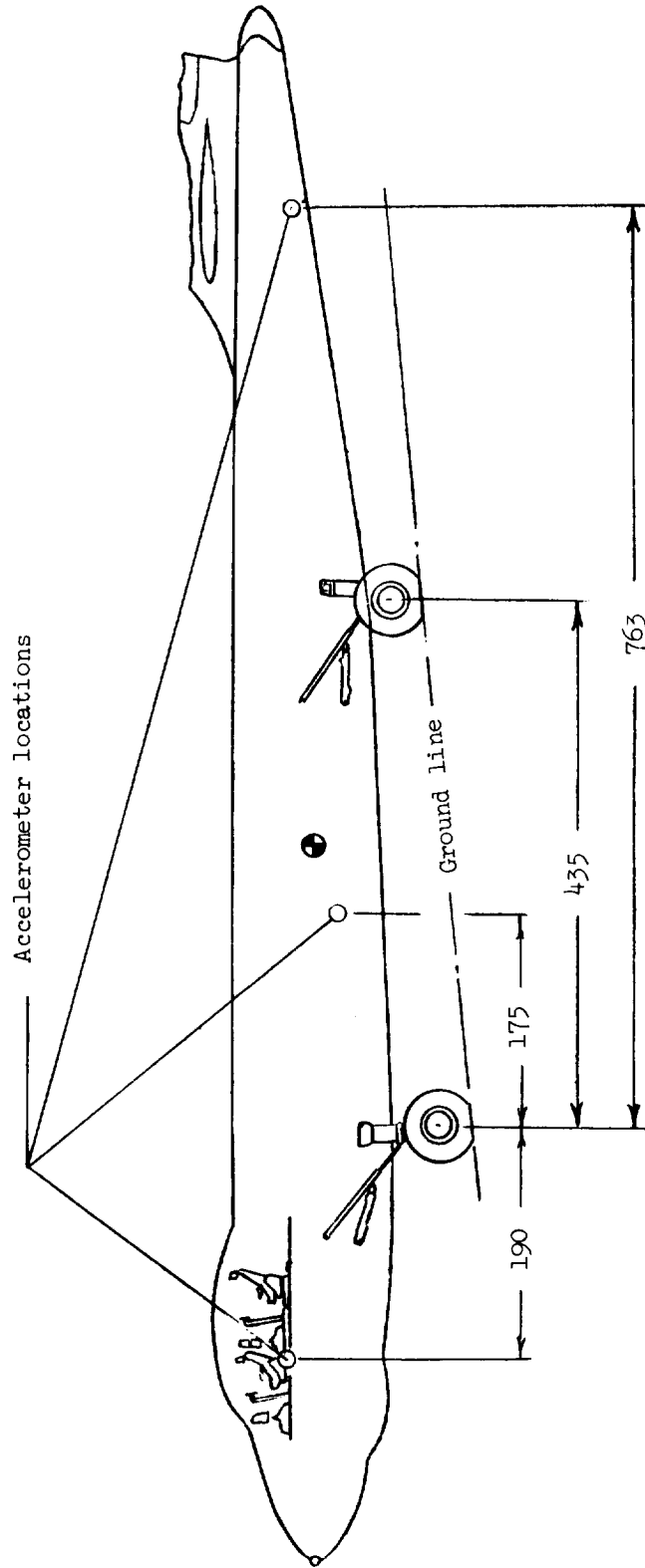


Figure 2.- Accelerometer locations in airplane. (All dimensions are in inches.)

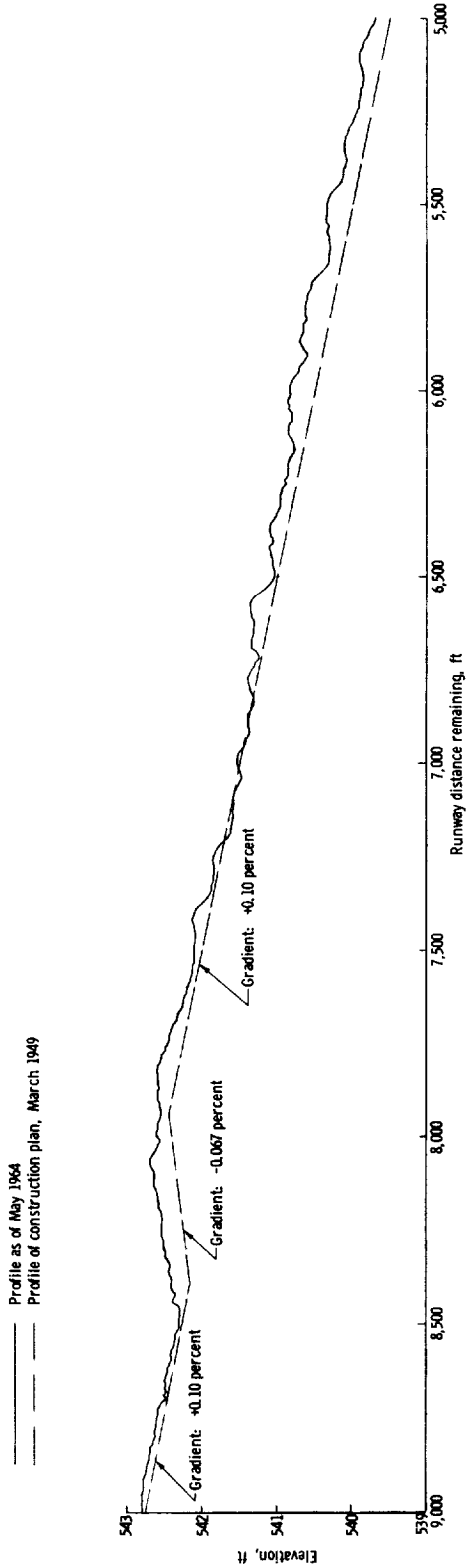


Figure 3.- Elevation profile for center line of runway 3L, Eielson AFB, Alaska (U.S. Air Force survey).

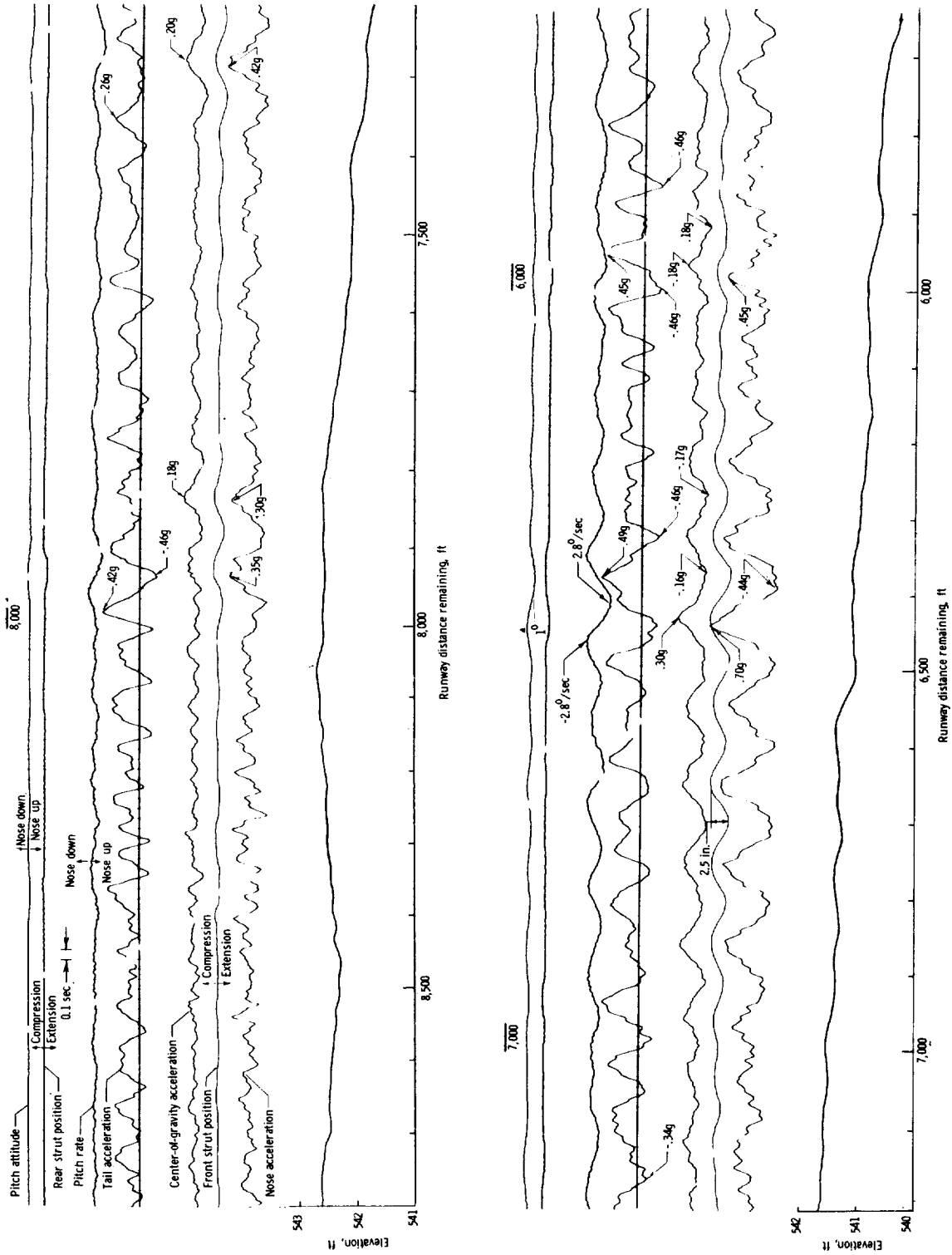


Figure 4.- Elevation variation of runway 31 and resulting airplane response at 75 knots taxiing speed.

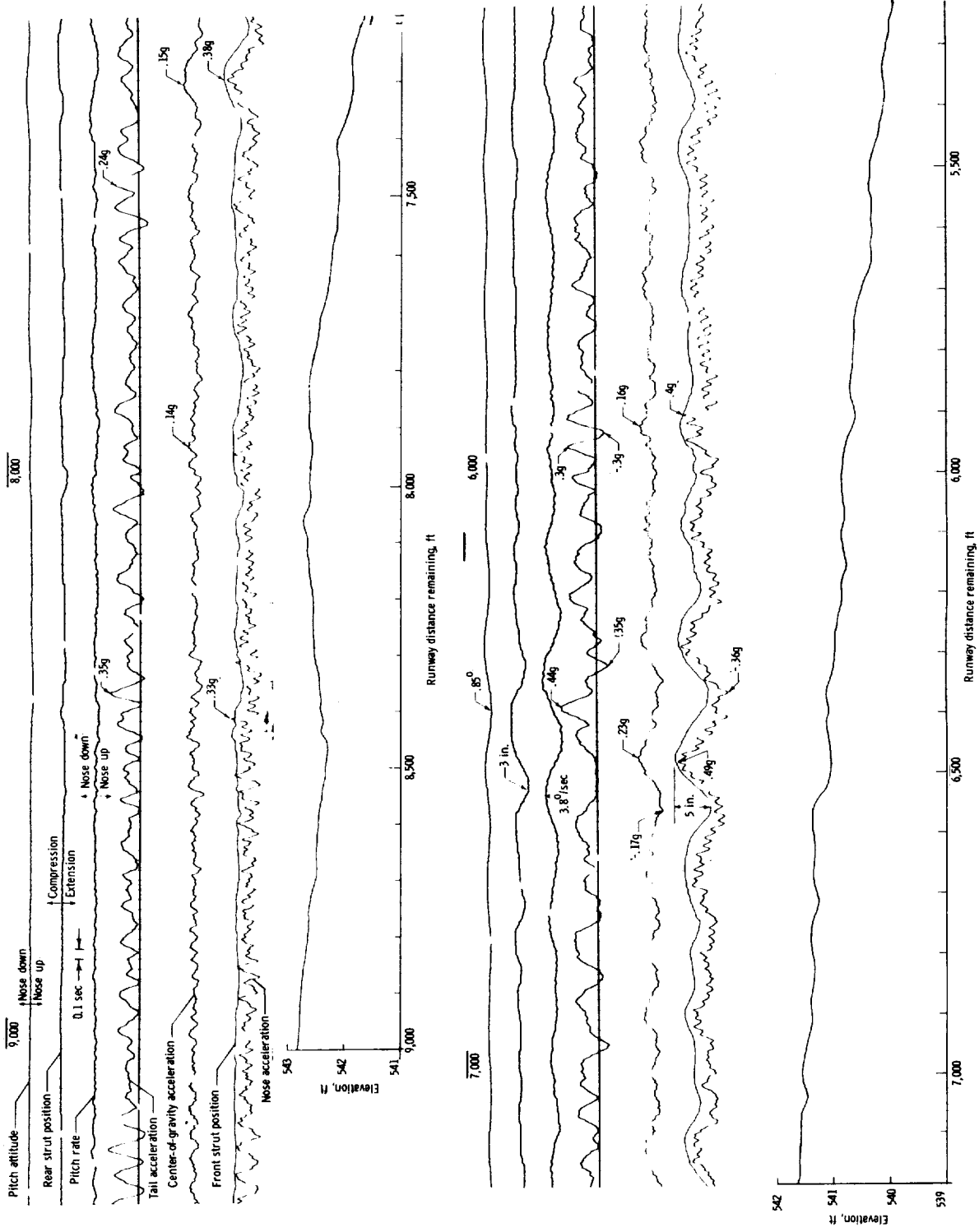


Figure 5.- Elevation variation of runway 51 and resulting airplane response at 100 knots taxiing speed.

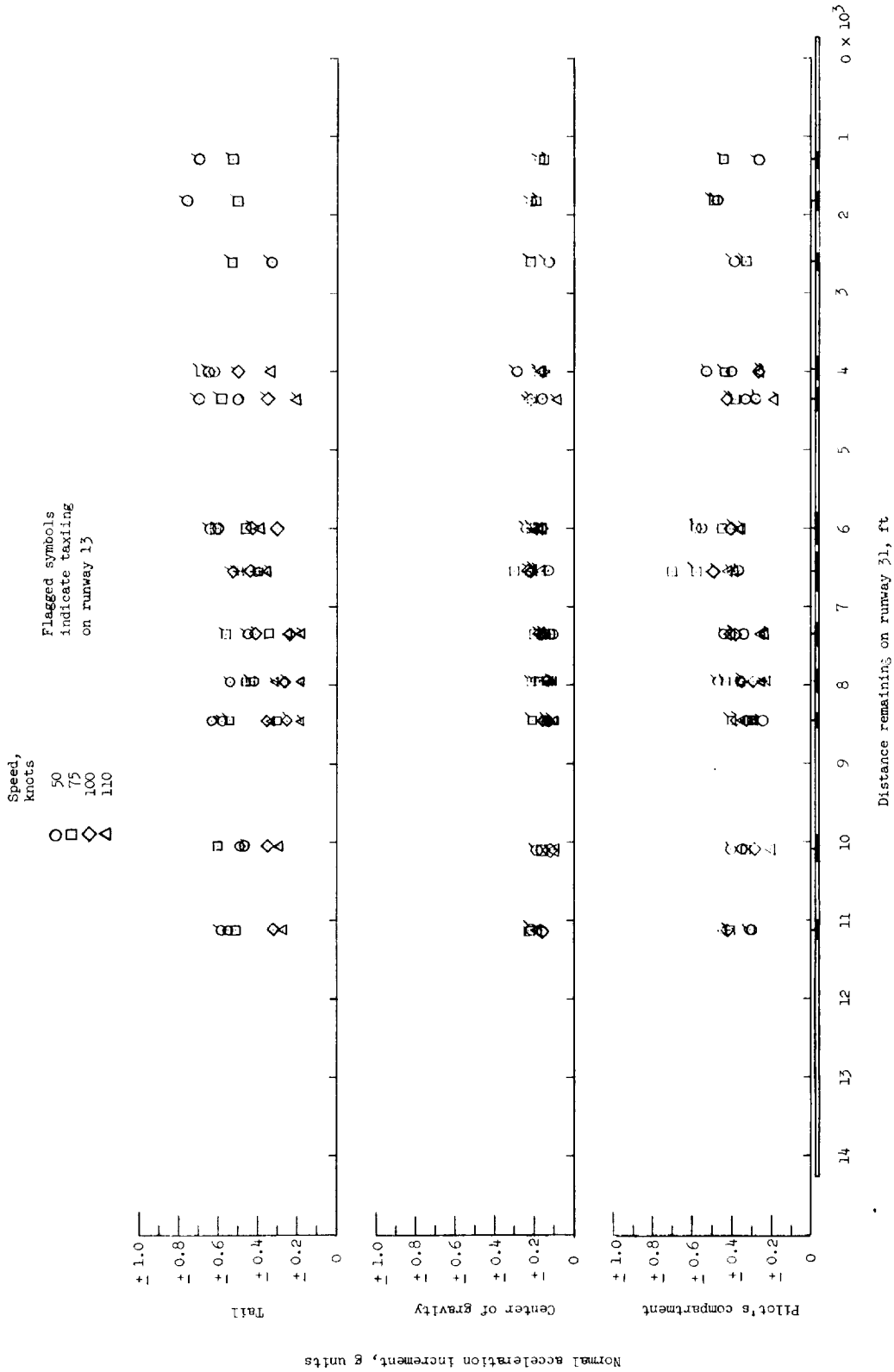
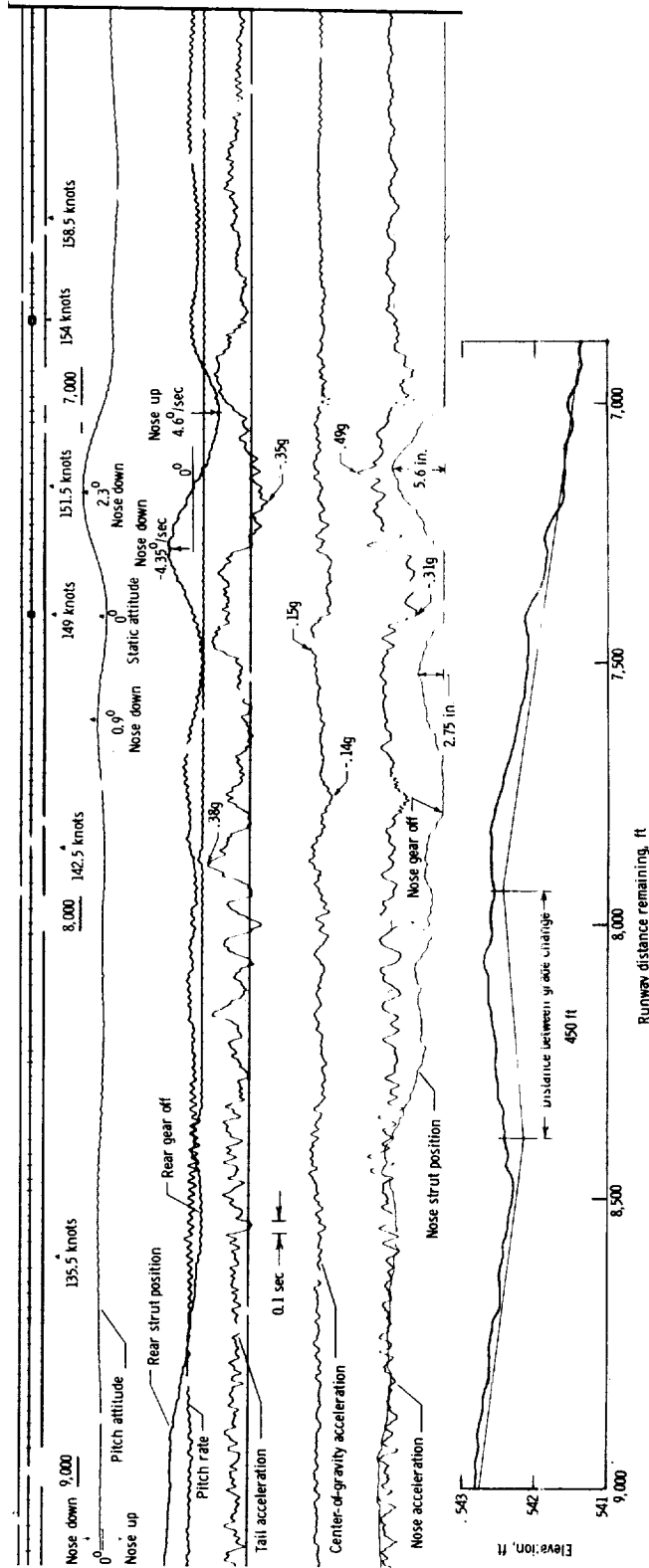
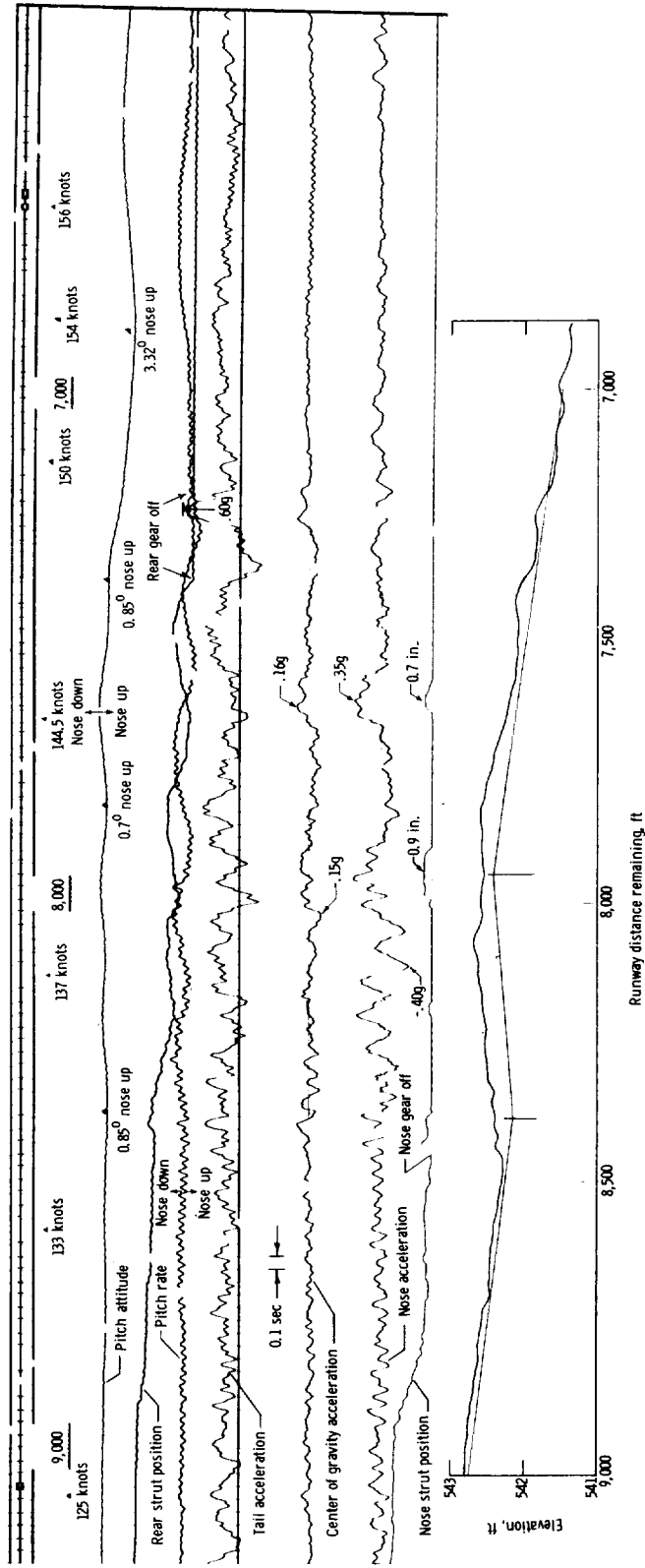


Figure 6.- Maximum acceleration response of airplane measured during taxiing on various sections of runway 31.



(a) First take-off. (Rear wheels lift off first.)

Figure 7.- Time history of take-offs on runway 31 during last 12 seconds before take-off.



(b) Second take-off. (Front wheels lift off first.)

Figure 7.- Concluded.

