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RESPONSE OF SEVERAL TURBOJET AIRPLANES TO RUNWAY ROUGHNESS

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16. Abstract

Studies have been made of the responses of a heavy bomber, medium bomber, tanker, trainer, civil transport, and business jet to runway roughness. Airplane responses were measured on both satisfactory runways and on runways which had been the subject of roughness complaints from operational personnel. Measurements included pitching velocity, landing-gear-strut motions, and normal acceleration at the cockpit, center of gravity, and tail.

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RESPONSE OF SEVERAL TURBOJET AIRPLANES TO RUNWAY ROUGHNESS

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SUMMARY

An investigation has been conducted to determine the response characteristics of two bombers, a tanker, a trainer, a civil transport, and a business jet to runway roughness and to relate objectionable response levels to runway profiles. Landing-gear-strut motions of the airplanes were diverse – some moved continuously in an approximate sinusoidal motion, some hardly moved at all, and others moved in steps. The range of significant acceleration responses of the airplanes extended over a frequency interval from 3/4 to 13 cps (1 cps = 1 Hz). The different airplanes responded at different acceleration levels on the same runway at similar taxiing speeds. The highest acceleration increment obtained during taxiing runs was 1.27g and was measured in the cockpit of the trainer. The average of the ratios of maximum cockpit to maximum center-of-gravity acceleration for the taxiing runs varied from approximately $1\frac{1}{3}$ for the trainer to $2\frac{1}{4}$ for the heavy bomber. Large airplane responses were generally associated with runway-surface irregularities with crest-to-trough elevation differences of from 0.05 to 0.25 foot (0.015 to 0.076 meter) for wavelengths up to 250 feet (76.2 meters).

INTRODUCTION

The need for the airplane designer to provide a landing-gear and airframe structure which can operate safely and comfortably on existing runways without excessive fatigue damage and the need to provide and maintain runways at a satisfactory smoothness level have led to several investigations covering various phases of the runway roughness problem. Past studies have been directed toward evaluating the roughness characteristics of existing runways, determining and correlating with runway roughness the responses of different types of airplanes, and defining acceptable levels of roughness and responses. (See refs. 1 to 7.)

As a continuation of these studies, investigations have been made of the responses to roughness of four military and two civil turbojet airplanes. The investigations using military airplanes were initiated in response to requests for participation in programs to measure the responses of the airplanes to the roughness of runways which had been subject to roughness complaints at a number of military bases. The response measurements were made to determine whether serious problems existed in the operations of the airplanes on these runways and for use in planning any needed runway repairs. For comparison purposes, two of the military airplanes were also tested on runways which were considered satisfactory by pilots. The civil airplanes were tested only on satisfactory runways to determine their general response characteristics. Airplane responses were measured during constant-speed taxiing runs, take-offs, and landings. The results of these studies provide an indication of the range and nature of responses from a variety of airplanes on runways having a wide range of roughness characteristics. Results of the investigation are given in the form of runway profiles and power spectra; time histories of airplane normal accelerations, pitch and roll rates, and landing-gear-strut motions; and maximum values, root-mean-square values, and power spectra of accelerations for individual runs. Ratios of accelerations at the cockpit and tail to those at the center of gravity are also given.

SYMBOLS

The units used for the physical quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units (SI). Factors relating these two systems of units are presented in reference 8.

a_n	airplane normal-acceleration increment, g units
$a_{n,max}$	maximum normal-acceleration increment, g units
a_t	transverse acceleration, g units
f	frequency, cycles per second (1 cycle per second = 1 hertz)
g	acceleration due to gravity ($1g = 32.2$ feet/second^2 = 9.8 meters/second^2)
p	airplane rolling velocity, degrees/second
q	airplane pitching velocity, degrees/second
λ	wavelength, feet (meters)
σ_{a_n}	root-mean-square value of airplane normal-acceleration increment, g units

$\Phi_{a_n}(f)$ power-spectral-density function of airplane normal-acceleration increment, $\frac{(\text{g units})^2}{\text{cycle per second}}$

$\Phi_h(\Omega)$ power-spectral-density function of runway elevation, feet^2/radian/foot (meters^2/radian/meter)

Ω reduced (spatial) frequency, $2\pi/\lambda$, radians/foot (radians/meter)

APPARATUS AND METHODS

Description of Airplanes

Drawings of the heavy bomber, medium bomber, tanker, trainer, civil transport, and business jet used in the investigations are shown in figure 1. The four military airplanes were owned and operated by the U.S. Air Force. The transport was owned and operated by the Federal Aviation Administration, and the business jet was owned and operated by the National Aeronautics and Space Administration. The NASA provided all instrumentation and installed it in all the airplanes except the heavy bomber, which was instrumented by the U.S. Air Force. The two bombers were equipped with bicycle landing gears with outriggers on the wings; the others had conventional tricycle gears.

For the taxiing tests, the weight of the heavy bomber varied from 288 000 to 300 000 lbm (130 634 to 136 077 kg) except for a lightweight run at 80 knots for which the airplane weighed only 203 000 lbm (92 079 kg). For the landing, the heavy bomber had a weight of 300 000 lbm (136 077 kg). The taxiing weight of the medium bomber was 166 000 to 180 500 lbm (75 296 to 81 873 kg), and the take-off weight was 175 500 lbm (79 605 kg). The taxiing weight of the tanker was 145 000 to 173 000 lbm (65 771 to 78 471 kg), and the take-off weight was 271 000 lbm (122 923 kg). The test weight of the trainer was 14 000 to 15 000 lbm (6350 to 6804 kg), except for tests when the wing-tip fuel tanks were empty; then the trainer weighed 11 500 lbm (5216 kg). Test weights were 138 000 to 142 000 lbm (62 595 to 64 410 kg) for the transport and approximately 9600 lbm (4354 kg) for the business jet.

Instrumentation

The instrumentation for each airplane is listed in table I. Instruments used for the various investigations included accelerometers, pitch- and roll-rate gyros, pitch-attitude gyros, landing-gear-strut and elevator-control-column position transmitters, and airspeed recorders. Accelerometers and angular-velocity and attitude-angle transducers were either fastened directly to the airplane structure or mounted on thick dural panels or angles which were rigidly attached to the structure. Accelerometer locations are shown on the drawings of the airplanes in figure 1. All data were recorded on photographic film and synchronized by means of a timer.

Runways

A diagram of the runways used for the investigation is shown in figure 2. The part of the runway for which test results are given for each airplane is shown. All runways, except one at an NASA installation, are located on military bases. One runway serves both a military base and civil airport. The parts of the runways for which elevation profiles are given have been marked.

Elevation profiles of the center lines of runways 2 and 3 were surveyed by NASA at 2-foot (0.61-meter) intervals with a surveyor's precision level, rod, and steel tape. The profile measurements of the center lines of runways 1, 4, 5-I, 6-I, and 6-II were provided by the U.S. Air Force. The profile of runway 1 was obtained from measurements at 1/2-foot (0.152-meter) intervals with the profile cart described in reference 9. Readings of the profile cart for parts of the runway were adjusted to be compatible with rod and level readings. Runways 4, 5-I, 6-I, and 6-II were measured with conventional surveying equipment at 10-, 25-, and $12\frac{1}{2}$-foot (3.05-, 7.62-, and 3.81-meter) intervals, respectively.

Test Procedures

Tests generally consisted of several constant-speed taxiing runs and a take-off and landing on each runway. The airplanes were taxied with the nose wheel on or near the center lines of the runways. The pilots maintained the desired taxiing speed by monitoring the airspeed indicator at speeds for which it was suitable and by following a pace car during the low-speed runs. The pilots were instructed to avoid braking during the tests. The heavy bomber was tracked with a digital optical tracking system to accurately correlate airplane time histories with runway stations and to provide groundspeed data. For the other tests, an operator onboard the airplane correlated response records with runway station by pushing a button marking the record as the airplane passed distance markers in intervals of 1000 feet (304.8 meters) along the runway. Test conditions were planned to provide both general information and answers to specific problems being investigated.

Data Reduction

Power spectra of the runway profiles were computed by the general method described in reference 5. Three sets of 60 power estimates were computed for each runway by using elevation-profile data at 2-, 4-, and 8-foot (0.61-, 1.22-, and 2.44-meter) runway-station intervals. These estimates were used to define the profiles of runways 1, 2, and 3 for wavelengths from 320 to 4 feet (97.54 to 1.22 meters).

Spectra and root-mean-square values were computed from the normal acceleration records of the heavy bomber which were read at 0.025-second intervals and of the medium bomber and tanker which were read at 0.05-second intervals. Spectra of incremental acceleration consisting of 81 uniformly spaced power estimates for the heavy bomber were computed over the frequency range from 0 to 20 cps and 41 estimates were computed from 0 to 10 cps for the medium bomber and tanker by the method used in references 5 and 6.

Taxiing speeds were determined from the recorded time required for the airplanes to travel over known runway distances.

DISCUSSION

Runways

Of the 13 runways shown schematically in figure 2, runways 2, 3, 7-II, 8-II, and 9 were considered by personnel using them to be satisfactorily smooth for operational purposes. The others had been the subject of roughness complaints from pilots.

Elevation profiles.- Profiles of seven of these runways for which elevation measurements are available are shown in figures 3 and 4. The profiles given in figure 3 cover the surveyed lengths of the runways and allow comparison of surface irregularities at different runway locations. A larger scale plot of the profile of a 1000-foot (304.8-meter) section of each runway is given in figure 4. In order to allow sufficient vertical amplification for examination of the surface irregularities of runways with large elevation changes, deviation from gradelines is given in place of the true profiles. Small-scale plots of the unaltered profiles with the gradelines are given in figure 3 for some of the runways to establish the relationship between the true profile and elevation deviations from the gradelines. Grades have no significant influence on runway roughness.

The profile of runway 1 contains irregularities of various wavelengths with extensive roughness at short wavelengths of less than 30 feet (9.1 meters). (See fig. 3(a).) The area from about 3500 to 5500 feet (1066.8 to 1676.4 meters) was considered by the test pilot to be the rougher of two sections where roughness levels higher than the general runway average were noted. Operational pilots also complained of this general area. The other objectionable section was from 7500 to 8500 feet (2286.0 to 2590.8 meters). Spikes extending below the general runway profile are thought to represent damaged joints.

Runways 2 and 3 (figs. 3(b) and 3(c)) were not considered exceptionally smooth but generally had been classified satisfactory from an operational standpoint. The profiles of these two runways appear to be much smoother than the others shown. A few rough areas, such as are indicated on runway 2 near stations 3500, 5800, and 6700 feet (1066.8, 1767.8, and 2042.2 meters), are the sources of infrequent complaints by users. Profile irregularities are evident on runway 3 near the 1800-, 4600-, 5700-, 6900-, and 7700-foot (548.6-, 1402.1-, 1737.4-, 2103.1-, and 2347.0-meter) stations.

The profile of a 4000-foot (1219.2-meter) section of the central part of runway 4 (fig. 3(d)) indicates a number of rough areas with crest-to-trough elevation differences of from 0.15 to 0.25 foot (0.046 to 0.076 meter) for wavelengths up to 250 feet (76.2 meters). Surface irregularities in the first half of the profile shown, because of their critical location relative to lift-off for medium-bomber operations, were the sources of complaints of serious difficulties encountered in maintaining airplane control during take-off. The part of the profile beyond the normal take-off area for these airplanes is indicated to be equally as rough and would be expected to cause difficulties when used.

Examination of a 6500-foot (1981.2-meter) section of runway 5-I shown in figure 3(e) indicates a large part is rough with irregularities in the profile of up to about 0.15-foot (0.046-meter) differences in elevation between crests and troughs of waves near the 5000-foot (1524-meter) station. In this region and near the end of the runway, operational pilots had complained of control difficulties.

Numerous irregularities with crest-to-trough deviations of from 0.05 to 0.15 foot (0.015 to 0.046 meter) for 75- to 150-foot (22.9- to 45.7-meter) wavelengths in the profiles of runways 6-I and 6-II (figs. 3(f) and 3(g)) indicate that both are rough runways. Generally, runway 6-II appears to be the rougher of these two. This classification is consistent with the opinions of both operational and test pilots who found runway 6-II to be exceptionally rough. The intersections and several other locations on these runways were considered by the test pilots to be especially objectionable.

The large-scale plot of a 1000-foot (304.8-meter) section of each runway presented in figure 3 is shown in figure 4. This plot facilitates detailed examination of the profile roughness and comparison of the runways with each other. Runways 2 and 3, classified as satisfactory, appear to be similar to each other as regards surface irregularities. Except for the spikes thought to represent damaged joints, runway 1 appears to be somewhat rougher than but, in general, similar to the two satisfactory runways. The roughness level for runway 6-I is indicated to be higher than for 1, 2, and 3 but lower than for 4, 5-I, and 6-II which are indicated to have the highest roughness levels.

Spectra of profiles.- The power-spectral-density functions of the profiles of the center lines of runways 1, 2, and 3 are given in figure 5. Included in the figure are the criteria given in reference 3 for "new construction" which suggest a roughness level not to be exceeded in runway construction. A comparison of the spectra of profile section ABC of runway 1 (see fig. 2(a)) with the new-construction criteria indicates that this profile is rougher than the criteria at wavelengths shorter than 67 feet (20.4 meters). (See fig. 5(a).) An increased roughness peak in the profile spectrum occurs at a wavelength of 28 feet (8.5 meters) which corresponds to the length of the runway blocks. The profile of section ABC was divided into three 2000-foot (609.6-meter) lengths, designated "sections A, B, and C"; and spectra of each section were computed to determine to what extent spectral indication of relative roughness would correlate with the pilot's opinions. Some differences in spectral roughness levels are apparent from comparison of the spectra of the sections. This comparison indicates section A, considered the roughest area by the pilot, has a generally higher spectrum than the other sections at most wavelengths shorter than 30 feet (9.1 meters).

A comparison of the spectrum of the profile of runway 2 with the new-construction criteria indicates that it approximates the criteria over much of the range of wavelengths. (See fig. 5(b).) Runway 3 is smoother than the criteria at wavelengths from 5 to 40 feet (1.5 to 12.2 meters) but rougher at longer wavelengths. This runway is also smoother than runway 2 at wavelengths shorter than 50 feet (15.2 meters). Both runways have been described by pilots as being generally adequate; consequently, the pilots' opinion and indications from the profile spectra are in agreement.

Airplane Response Characteristics

General response characteristics.- Examples of the responses of the test airplanes to both rough and satisfactory runways are given in figures 6 to 11.

Heavy bomber: Acceleration responses of the large flexible bomber on runway 1 are given in figure 6(a) for a landing run and in figure 6(b) for a taxiing run at 56 knots. High acceleration increments starting at the 4600-foot (1402.1-meter) station about 8 seconds after initial touchdown of "a rather hard landing" illustrate the high responses which are thought to arise from complex interrelationships of landing impact, automatic braking systems, and runway roughness. Pilots operating airplanes similar to the test airplane on this runway considered landing the most severe of all phases and stated that there was actual physical discomfort and considerable doubt as to one's ability to control the airplane while passing over the rough section. They also noted that vibrations made it difficult to read the airspeed indicator.

A correlation of airplane acceleration with runway station for sections A, B, and C of runway 1 at a taxiing speed of 56 knots is given in figure 6(b). Accelerations larger than 0.6g in the cockpit, shown near the center of section A, were higher than the average for the runway. The test pilot noted that objectionable oscillations of moderate severity occurred in this area. He indicated no objections to the responses for section B where accelerations were generally less than 0.4g in the cockpit. The responses shown in the first part of section C were described by the pilot as oscillations of slight severity.

Acceleration frequencies covered a range from about 1 to 13 cps with response amplitudes at the cockpit and tail substantially larger than those at the center of gravity. Although not shown, airplane pitching motions of less than 1° per second at about 1 cps were measured.

Medium bomber: Responses of the medium bomber on runway 4 are shown in figures 7(a) and 7(b) for two take-offs and in figure 7(c) for a taxiing run at 78 knots. The part of the runway shown in figures 7(a) and 7(b) is the area about which complaints were made of difficulties encountered in maintaining control of the airplane during take-off. The influence of operating technique on the airplane response is shown by comparison of the two take-offs made over this area. The first take-off (fig. 7(a)) in which the rear wheels of the bicycle landing gear lifted off first resulted in a severe pitching oscillation as the airplane traversed the critical area at a few knots below lift-off speed. The oscillation was less severe for the second take-off (fig. 7(b)) for which the front wheels lifted off first. However, early lifting of the front wheel is not a satisfactory solution of the problem because of the loss of front wheel steering and the possibility of a nose-high attitude at lift-off progressing to a pitch-up. Runway repairs to this area provided a solution to the problem.

High acceleration responses occurred during the 78-knot taxi run at several runway locations. (See fig. 7(c).) Large accelerations are shown for the area where high responses occurred during the take-offs. Even higher responses beyond the normal take-off area occurred, where an acceleration of 0.7g was measured at the cockpit near the runway station at 7800 feet (2377.4 meters).

Front landing-gear-strut oscillatory motions which occurred during taxiing are shown to be approximately sinusoidal and of larger amplitude than rear-strut motions. Front-strut oscillations of 5 inches (0.127 meter), peak to peak, and rear-strut oscillations of 3 inches (0.076 meter) were measured during a taxiing run, not shown, at 100 knots. Average strut extensions were small for speeds up to 100 knots, but either the front, rear, or both gears were near full extension for several seconds prior to lift-off at approximately 152 knots.

Tanker: The responses of a large tanker airplane on runway 5-I during a heavy-weight take-off are shown in figure 8(a) and during taxiing at 76 knots in figure 8(b). Runway elevation deviations from gradelines are presented instead of the actual profile to allow sufficient vertical amplification to show profile irregularities for correlation with airplane responses. The use of two different gradelines over the length of the convex-shaped profile (see fig. 3(e)) gives the misleading appearance of two hill-shaped profiles.

The highest responses for the test airplane occurred near the 5000-foot (1524-meter) station in the vicinity of runway irregularities having peak-to-peak elevation differences of 0.15 foot (0.046 meter) for wavelengths on the order of 190 feet (57.9 meters). Cockpit accelerations of 0.45g at a speed of about 130 knots for the heavyweight take-off and 0.42g for the 76-knot taxiing run are shown at this location. Acceleration response frequencies of 3/4 cps and higher and low amplitude airplane pitching motions at frequencies from about 2/3 to 1 cps are indicated for these runs.

Landing-gear-strut oscillatory motions were approximately sinusoidal with maximum main- and nose-gear peak-to-peak movements of 3 and 6.3 inches (0.076 and 0.160 meter) during the take-off and 4 and 8 inches (0.102 and 0.203 meter) during taxiing. For the heavyweight take-off shown (fig. 8(a)), only slight average extension of the main landing-gear strut took place before airplane rotation; however, for other take-offs at lighter weights, the strut extension increased gradually with forward speed and approached full extension at take-off. The average position of the nose-wheel strut was essentially constant with speed.

The sections of the runway near the 5000-foot (1524-meter) station and near the end of the runway had been the source of complaints for heavyweight take-offs. Near the 5000-foot (1524-meter) station, operational pilots had complained of control difficulties with inability to damp out undesirable motions, the impression of nose-strut bottoming, and high accelerations indicated on the instrument-panel accelerometer. The test pilot reported excessive roughness at this runway location but no control difficulties during the take-off. It is thought that airplane responses over this rough part of the runway may be strongly influenced by piloting technique and that a pilot unfamiliar with this runway would be most susceptible to encountering difficulties.

Trainer: The response of the trainer at two taxiing speeds on runway 7-II is shown in figures 9(a) and 9(b). Figures 9(c) and 9(d) show the response of the trainer at two taxiing speeds on runway 6-II. Operational personnel have considered runway 7-II to be "satisfactory," but runway 6-II is considered to be "especially rough." On each runway, higher accelerations are evident for the higher taxiing speed. Responses higher than the general level for the test runs on the satisfactory runway (figs. 9(a) and 9(b)) such as near the 4000-foot (1219.2-meter) marker are indicative of occasional rough areas which were evidently not extensive enough to cause serious objections. Airplane response increased at this area for runs shown at both 81- and 111-knot taxiing speeds for which maximum accelerations at the cockpit were 0.46g and 0.57g, respectively. Low roll rate and nose landing-gear responses and hardly any pitching or main landing-gear responses are evident. No profile is available for correlation with these runs.

For the rough runway, the general level of responses shown in figures 9(c) and 9(d) was higher than the level for the satisfactory runway, and responses substantially higher than the general level were distributed extensively throughout the time history. Unusually high responses were measured near the 3500- to 3800-foot (1066.8- to 1158.2-meter) stations, where cockpit accelerations were 0.83g and 1.27g for the 87- and 108-knot taxiing speeds, respectively. It follows that the profile which resulted in these high responses represents an unsatisfactory roughness level for this airplane. The airplane rolled at about $1\frac{1}{10}$ cps and pitched at $1\frac{1}{2}$ to $1\frac{3}{4}$ cps.

The main landing-gear struts appear to be sticking during taxiing on the satisfactory runway with very little motion shown even over the section near the 4000-foot (1219.2-meter) marker, where relatively high accelerations were measured. In contrast, both nose and main landing-gear struts were in motion on runway 6-II. Nose-strut motions were approximately sinusoidal, but both main gears moved more as step or pulse functions, which indicates a sticking tendency here also. Although the average position of the nose-gear strut remained near full compression prior to airplane rotation, the main-gear struts extended with increasing airplane speed so that they were near full extension at speeds near 65 knots. Maximum peak-to-peak strut oscillations on the rough runway approximated 4 inches (0.102 meter) at the nose gear and $1\frac{1}{2}$ inches (0.038 meter) at the main gear.

Civil transport: The responses of the civil transport during taxiing to the roughness of two satisfactory runways, runway 2 at 61 knots and runway 3 at 58 and 104 knots, are shown in figure 10. Airplane responses appeared to be generally similar for taxiing on the two runways at approximately 60 knots. Although these runways are considered satisfactory, responses higher than the overall average for runway 2 are shown between the 7000- and 6000-foot (2133.6- and 1828.8-meter) sections, where a cockpit acceleration of 0.46g was measured. This part of the runway is one of the areas about which occasional comments of roughness have been made.

Major acceleration responses at about $1\frac{1}{2}$ cps are shown for the lower speed runs; but at 104 knots, responses at about 2 cps at the tail, 2 and 4 cps at the center of gravity, and 4 cps at the cockpit are evident. Cockpit accelerations were greater than those at the center of gravity and aft end of the passenger compartment. The airplane pitch and roll motions, not shown in the figure, were at approximately 1 cps.

Sinusoidal motions of the nose-gear strut are evident, and a small increase in average strut extension occurred with an increase in taxiing speed. Maximum strut response to roughness was less than 4 inches (0.102 meter). Oscillatory strut motions of the main gear were less than 1 inch (0.0254 meter) and the struts remained at the static position near full compression over the speed range. The test pilot considered the gear to be stiff and of little benefit in decreasing the roughness of the ride.

Business jet: The responses of the business jet during taxiing runs at 64 and 108 knots to the roughness of runway 3 is shown in figure 11. Increased responses for both speeds are noticeable near the 4500- and 5800-foot (1371.6- and 1767.8-meter) sections, where profile irregularities are evident. Generally, low accelerations, 0.12g maximum, at the center of gravity are shown for the 64-knot taxi run on this satisfactory runway. Both acceleration and pitch response have frequencies of approximately 1 cps. Maximum pitching rate was slightly over 4° per second. Roll frequency was approximately 0.85 cps.

Response frequencies.- Variations in response characteristics shown in figures 6 to 11 for the different airplanes would be expected because of the wide variations in size and flexibility of the airplanes investigated. Acceleration responses of significant amplitude covered a frequency range from about 3/4 to 13 cps for the various airplanes with major responses occurring at somewhat different frequencies for different airplanes and operating conditions. Frequency differences at the nose, center of gravity, and tail are also evident.

Certain response frequencies tend to predominate and are evident in the acceleration time histories. All airplanes had major acceleration responses at frequencies in the range from 3/4 to 2 cps and all except the business jet had significant responses at from $3\frac{1}{2}$ to $4\frac{1}{2}$ cps. Although some higher frequency content is evident in the response histories for all the airplanes, only the heavy bomber shows high magnitude acceleration responses in the 9- to 13-cps frequency range.

Airplane pitching motions are indicated at frequencies varying from approximately $\frac{2}{3}$ to $1\frac{3}{4}$ cps.

Landing-gear-strut motions.- Diverse landing-gear-strut motions are evident for the test airplanes. Some of the struts moved as much as several inches with hardly any motions for others; some motions were nearly sinusoidal, others resembled steps which indicated sticking. Since the airplane-response transfer function is changed by sticking struts, which can be a function of maintenance, it would appear to be necessary in analyses to consider both the sticking and free conditions.

Maximum acceleration values.- Maximum positive and negative values of airplane normal acceleration for the different taxiing speeds on the various runways are shown in figure 12. The variations of maximum accelerations with speed are dissimilar for the different test airplanes. With increasing speed, positive and negative maximum acceleration increments generally decreased for the medium bomber, were approximately constant for the tanker, increased for the heavy bomber and transport, and increased most rapidly for the business jet and trainer. Acceleration variations with speed for the heavy and medium bomber and tanker were not always alike at the cockpit, center of gravity, and tail locations and for the tanker were not always alike on different runways.

Response to runway roughness can be significantly affected by variations in airplane weight and weight distribution. An example of this effect is shown in figure 12(a). Maximum accelerations at the tail of the heavy bomber, weighing 203 000 lbm (920 792 kg), were substantially higher than those of this bomber, weighing 300 000 lbm (136 077 kg), while taxiing at 75 to 80 knots. Tests at 85 knots with empty wing-tip tanks resulted in increased positive acceleration values for the trainer, figure 12(d).

An indication of the range of acceleration response to be expected on runways having different roughness characteristics is shown in figure 12 for the test airplanes. Accelerations greater than ±0.4g at the cockpit are shown for the heavy and medium bomber, transport, and trainer on all runways. Accelerations at the cockpit of the tanker also were greater than 0.4g for two of the rough runways, 5-I and 5-II, but were less than 0.4g on two other runways considered rough, 4 and 8-I and on runways 2, 8-II, and 9 which were considered smooth. The highest responses are shown for the trainer on runway 6-II with 1.27g and 0.76g accelerations at the cockpit and center of gravity, respectively.

Inasmuch as cockpit accelerations greater than ±0.4g were measured on runways considered satisfactory and less than ±0.4g on runways considered rough, it is apparent that no sharp dividing line exists between accelerations for a satisfactory and rough runway. It is thought that pilots' opinions concerning the overall roughness of a specific runway are dependent on both the number and magnitude of responses encountered and on when they occur relative to critical aircraft maneuvers. There is some indication that a pilot may become more tolerant of high responses from a rough-riding airplane and less tolerant for one with a normally smooth ride. Nevertheless, although the division has no sharp cutoff, from an overall viewpoint it appears that the acceleration level of ±0.4g in the cockpit, proposed in reference 7, is approximately the dividing line between satisfactory and unsatisfactory runways from the pilots' viewpoint.

Variations in acceleration magnitude for different airplanes on the same runway at similar speeds are shown in figure 13. On runway 3, the maximum acceleration response at the center of gravity of the business jet was only about one-half that of the transport at low speeds; but at higher speeds, the responses were about equal. On runway 2, accelerations were higher for the transport than for the tanker and highest for the trainer. Responses for the tanker were lower than those for the medium bomber on runway 4.

Ratios of the maximum acceleration at the cockpit to the maximum at the center of gravity and of the maximum acceleration at the tail to the maximum at the center of gravity for each taxiing run are given in figure 14. These ratios were determined from maximum acceleration values obtained by averaging the absolute value of the maximum positive and negative acceleration increments. The data, in general, show considerable scatter and, except for the transport, indicate no systematic variation with speed. The ratio of maximum cockpit to maximum center-of-gravity acceleration for the transport tended to decrease steadily with speed for both runways on which it was tested. Less scatter is evident for the ratios of tail to center-of-gravity acceleration than for those of cockpit to center-of-gravity acceleration. The average of the ratios of maximum cockpit to maximum center-of-gravity acceleration for all taxiing runs of each airplane varied from approximately $1\frac{1}{3}$ for the trainer to $2\frac{1}{4}$ for the heavy bomber.

Root-mean-square accelerations.- The root-mean-square (rms) values of the normal-acceleration response of the heavy bomber for various taxiing speeds on section ABC of runway 1 are given in figure 15. Acceleration response at the center of gravity and tail increased with speed up to approximately 100 knots, then decreased with further speed increases; cockpit responses first decreased and then increased with increasing speed. Accelerations varied over the speed range from 0.06g to 0.10g at the center of gravity, 0.14g to 0.21g at the cockpit, and 0.12g to 0.17g at the tail.

Ratios of cockpit to center-of-gravity rms normal accelerations and ratios of tail to center-of-gravity rms normal accelerations for the heavy bomber are given in figure 16 for the runs at various taxiing speeds. The ratios of rms accelerations are similar to the ratios of maximum accelerations both in magnitude and in variation with speed. A minimum value of 1.36 for the ratios of cockpit to center-of-gravity response and for those of tail to center-of-gravity response is indicated at 75 knots. The maximum value for the cockpit to center-of-gravity ratios is 3.13 and for the tail to center-of-gravity ratio is 2.25 at 56 knots.

Power spectra of acceleration response.- The power-spectral-density functions of acceleration response at the cockpit, center of gravity, and tail of the heavy bomber taxiing at 56 knots on different sections of runway 1 are shown in figure 17. The spectra of acceleration responses of the heavy bomber are similar in general shape and appearance for sections A, B, and C and for the combination, section ABC. The highest responses over most of the frequency range for the cockpit, center of gravity, and tail locations are shown for section A where the root-mean-square value of acceleration in the cockpit is 0.226 as compared with 0.134 and 0.156 for sections B and C, respectively.

The power-spectral-density functions of normal-acceleration response of the heavy bomber taxiing at several speeds on section ABC of runway 1 are shown in figure 18. Response modes at similar frequencies are evident at the cockpit, center of gravity, and tail locations; but a wide range of magnitudes is apparent for modes at a given frequency interval for the different locations in the airplane and at different speeds. Response for most frequencies is markedly lower at the center of gravity than at the cockpit and tail. The spectra indicate major response modes for the cockpit throughout the speed range at frequency intervals of $3\frac{1}{2}$ to $4\frac{3}{4}$ cps, 6 to $6\frac{3}{4}$ cps, and $\frac{3}{4}$ to $1\frac{1}{4}$ cps and for the midspeeds also at $9\frac{3}{4}$ to 11 cps. Response modes at the center of gravity with frequencies of $3\frac{3}{4}$ to $4\frac{3}{4}$ cps and 1 to $1\frac{1}{2}$ cps and those at the tail with $1\frac{1}{4}$ to $1\frac{3}{4}$ cps extend over the speed range. High frequency modes at $9\frac{1}{2}$ to 13 cps also are present for the center of gravity and tail at the low and midspeed range.

Power-spectral-density functions of normal-acceleration response at the cockpit, center of gravity, and tail of the tanker are given in figure 19(a) for a heavyweight take-off and for taxiing on the test section of runway 5-I. Responses at each of the airplane locations are substantially higher for the 103- to 165-knot take-off run than for the 75-knot taxiing run, and acceleration at the cockpit is greater than $1\frac{1}{2}$ times the value at the center of gravity for both the taxiing and take-off run. Major response modes are shown at $\frac{3}{4}$ to $1\frac{1}{2}$ cps, $3\frac{1}{2}$ to 4 cps, and $6\frac{1}{2}$ to 7 cps.

Spectra of responses at the cockpit and center of gravity of the medium bomber on runway 4 given in figure 19(b) indicate major response modes at $1\frac{1}{4}$ and $3\frac{1}{2}$ cps with response at the cockpit approximately twice that at the center of gravity. Magnitudes of the spectra for the heavy bomber (fig. 18), the tanker, and the medium bomber are not directly comparable with each other inasmuch as they are for different runways.

CONCLUDING REMARKS

An investigation has been conducted to determine the response characteristics of two bombers, a tanker, a trainer, a civil transport, and a business jet to runway roughness and to relate objectionable response levels to runway profiles.

Landing-gear-strut motions of the airplane were diverse – the main gear of the tanker moved continuously in a sinusoidal manner, the main gear of the trainer tended to move in steps, and the rear gear of the medium bomber and transport indicated little or no appreciable motion during taxiing.

The range of significant acceleration responses of the airplanes extended over a frequency interval from 3/4 to over 13 cps (1 cps = 1 Hz). Pitching frequencies ranged from $\frac{2}{3}$ to $1\frac{3}{4}$ cps.

The different airplanes responded at different acceleration levels on the same runway at similar taxiing speeds. Of the three airplanes taxiing on a satisfactory runway, the tanker had the lowest response, the transport had a higher response, and the trainer had the highest response.

The highest acceleration increment for the taxiing runs was 1.27g measured in the cockpit of the trainer.

The average of the ratios of maximum cockpit to maximum center-of-gravity acceleration for all taxiing runs of each airplane varied from approximately $1\frac{1}{3}$ for the trainer to $2\frac{1}{4}$ for the heavy bomber.

Studies of roughness problems encountered during take-off, landing, and taxiing indicated that a pilot's classification of a runway as satisfactory or rough is dependent on the magnitude and number of responses and their occurrence relative to critical procedures and airplane maneuvers. There was some indication that the level of acceleration a pilot will accept without calling a runway rough may vary with airplane type. It is believed that a higher level of acceleration may be expected and accepted on some airplanes than on others because, in some instances, accelerations measured in the cockpit of an airplane during taxiing on a satisfactory runway were higher than responses in the cockpit of a different type airplane on runways considered rough. An acceleration response of 0.4g in the cockpit generally was considered objectionable.

Large airplane responses were generally associated with runway surface irregularities having crest-to-trough elevation differences of from 0.05 to 0.25 foot (0.015 to 0.076 meter) for wavelengths up to 250 feet (76.2 meters).

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., December 22, 1969.

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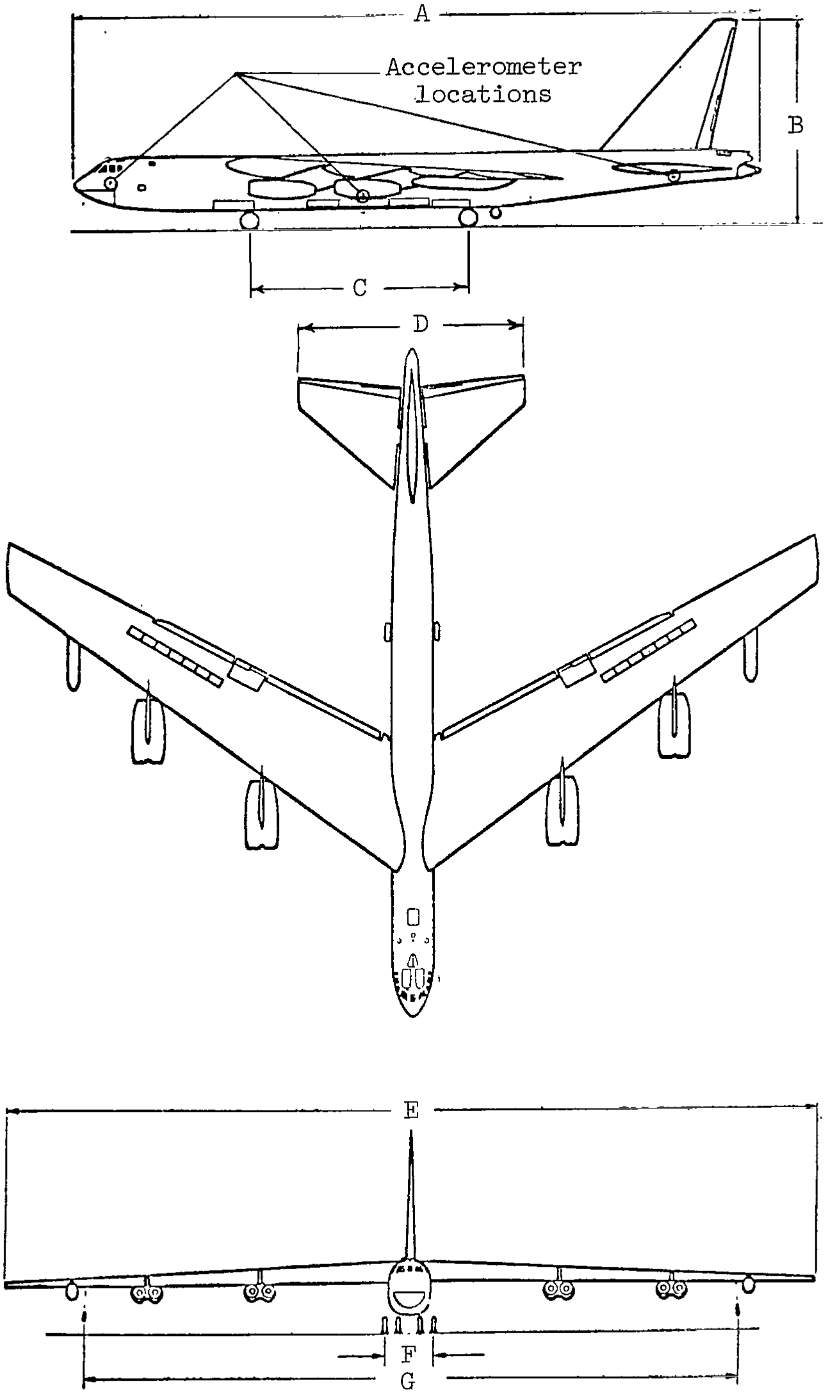
2494

TABLE I.- RUNWAY ROUGHNESS INSTRUMENTATION

Instrument	Location of accelerometers and position transmitters
Heavy bomber	
Normal accelerometer	Cockpit Center of gravity Tail
Pitch-rate gyro	
1/10-second timer	
Medium bomber	
Normal accelerometer	Cockpit Center of gravity Tail
Position transmitter	Front landing-gear strut Rear landing-gear strut
Pitch-rate gyro	
Pitch-attitude gyro	
Airspeed recorder	
1/10-second timer	
Tanker	
Normal accelerometer	Cockpit Center of gravity Tail
Position transmitter	Main landing-gear strut Nose landing-gear strut Elevator control column
Pitch-rate gyro	
Pitch-attitude gyro	
Airspeed recorder	
1/10-second timer	

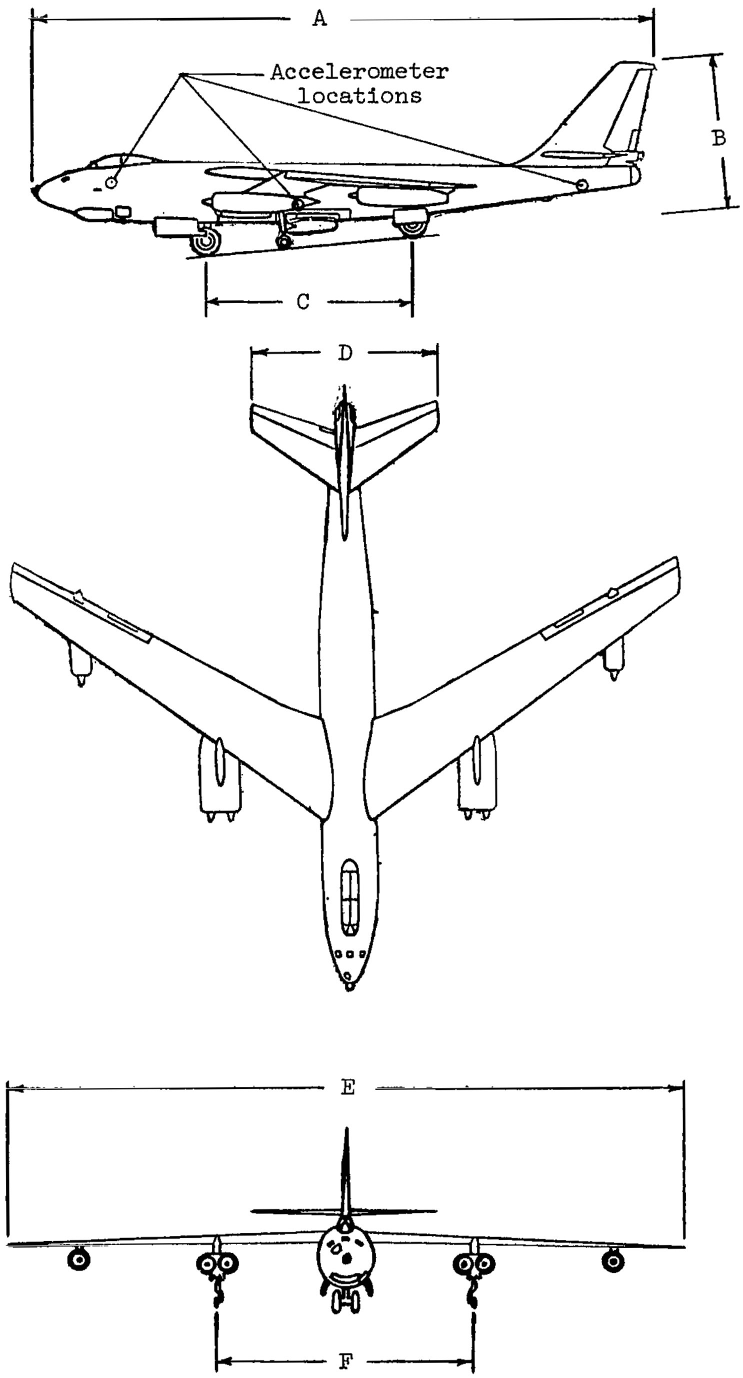
Instrument	Location of accelerometers and position transmitters
Trainer	
Normal accelerometer	Cockpit Center of gravity
Position transmitter	Nose landing-gear strut Left main landing-gear strut Right main landing-gear strut
Pitch-rate gyro	
Roll-rate gyro	
Airspeed recorder	
1/10-second timer	
Transport	
Normal accelerometer	Cockpit Center of gravity Tail
Position transmitter	Nose landing-gear strut Right main landing-gear strut Left main landing-gear strut
Pitch-rate gyro	
Roll-rate gyro	
Airspeed recorder	
1-second timer	
Business jet	
Normal accelerometer	Center of gravity
Transverse accelerometer	Center of gravity
Pitch-rate gyro	
Roll-rate gyro	
Pitch-attitude gyro	
Airspeed recorder	
1-second timer	



	Feet	Meters
A	156.58	47.73
B	48.30	14.72
C	49.75	15.16
D	52.00	15.85
E	185.00	56.39
F	11.33	3.45
G	148.42	45.24

(a) Heavy bomber.

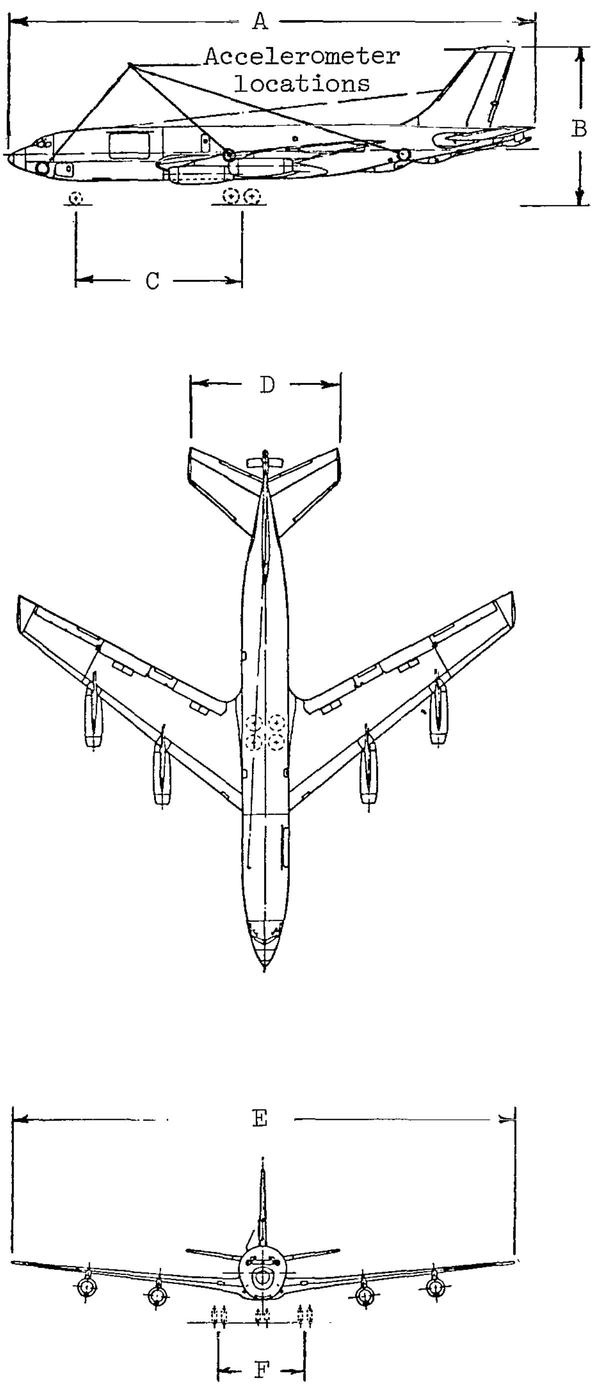
Figure 1.- Three-view drawings of test airplanes.



	Feet	Meters
A	107.13	32.65
B	28.00	8.53
C	36.25	11.05
D	33.00	10.06
E	116.00	35.36
F	44.33	13.51

(b) Medium bomber.

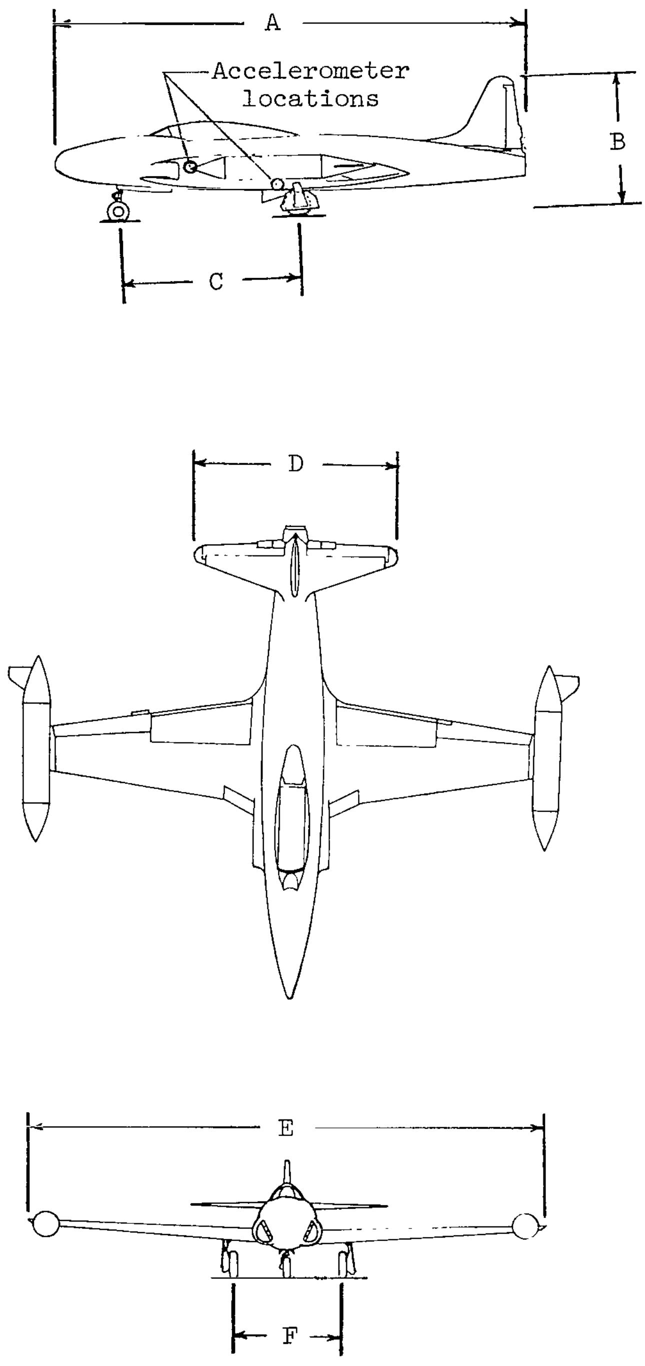
Figure 1.- Continued.



	Feet	Meters
A	136.25	41.53
B	38.42	11.71
C	45.67	13.92
D	39.33	11.99
E	130.83	39.88
F	22.08	6.73

(c) Tanker.

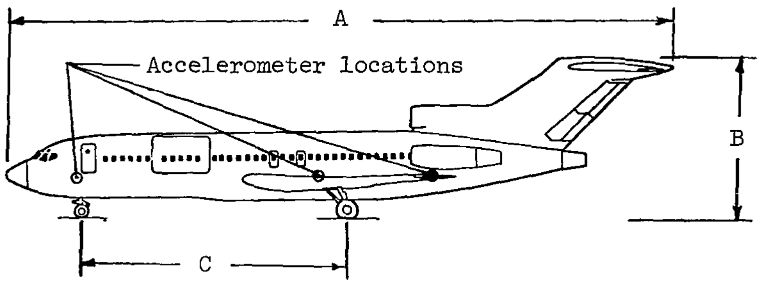
Figure 1.- Continued.

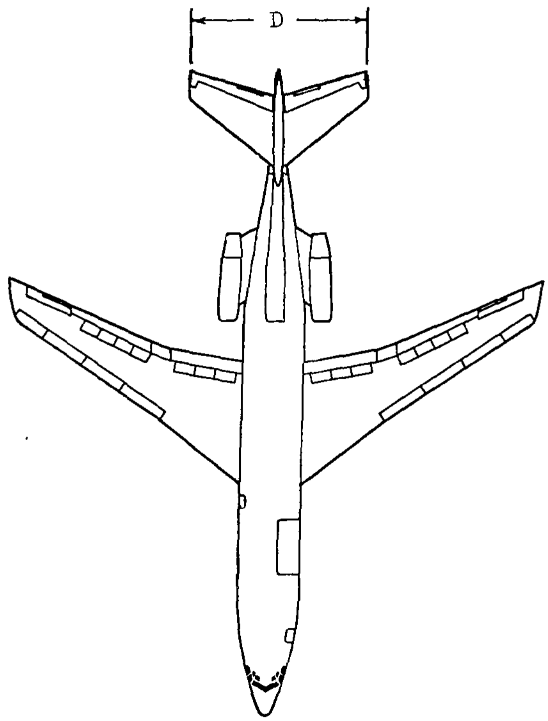


	Feet	Meters
A	37.72	11.50
B	11.70	3.57
C	14.16	4.32
D	15.58	4.75
E	38.88	11.85
F	8.75	2.67

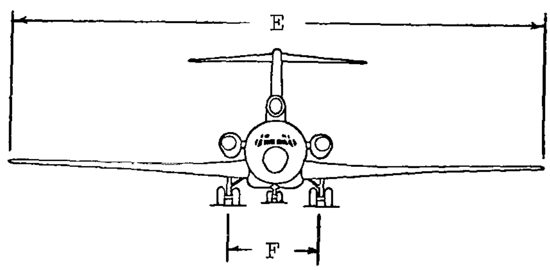
(d) Trainer.

Figure 1.- Continued.



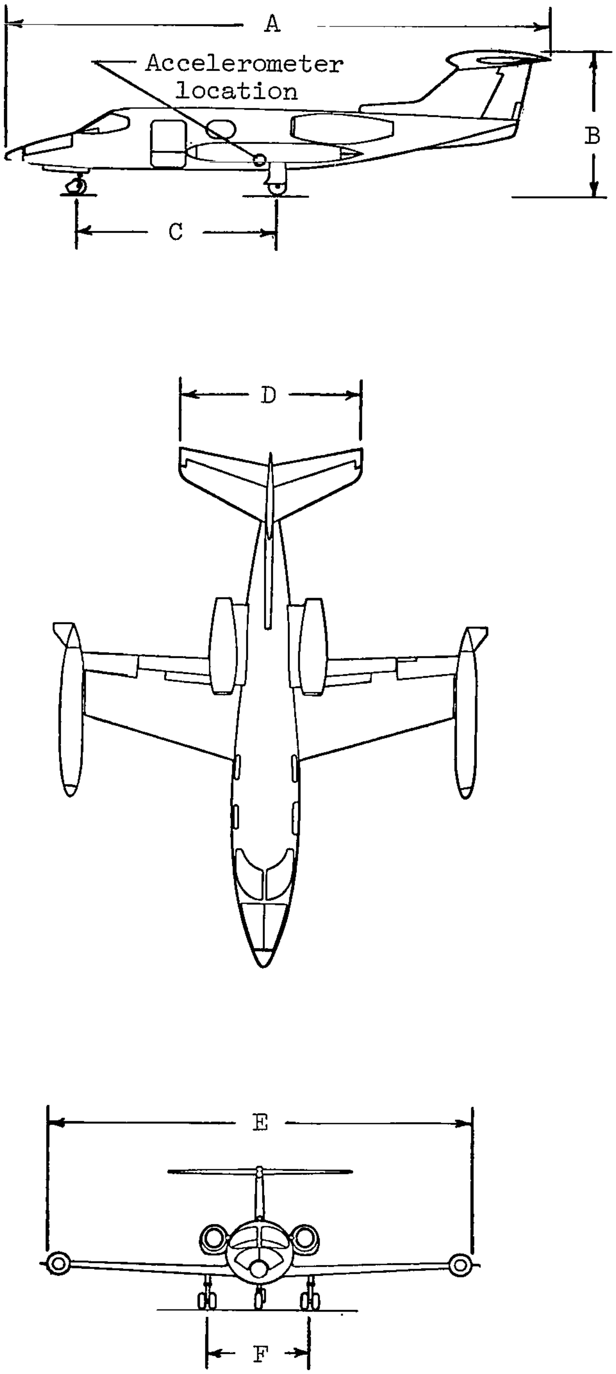


	Feet	Meters
A	133.17	40.59
B	34.00	10.36
C	53.25	16.23
D	35.75	10.90
E	108.00	32.92
F	18.75	5.72



(e) Civil transport.

Figure 1.- Continued.



	Feet	Meters
A	43.25	13.18
B	12.58	3.83
C	16.17	4.93
D	14.67	4.47
E	34.08	10.39
F	8.25	2.51

(f) Business jet.

Figure 1.- Concluded.

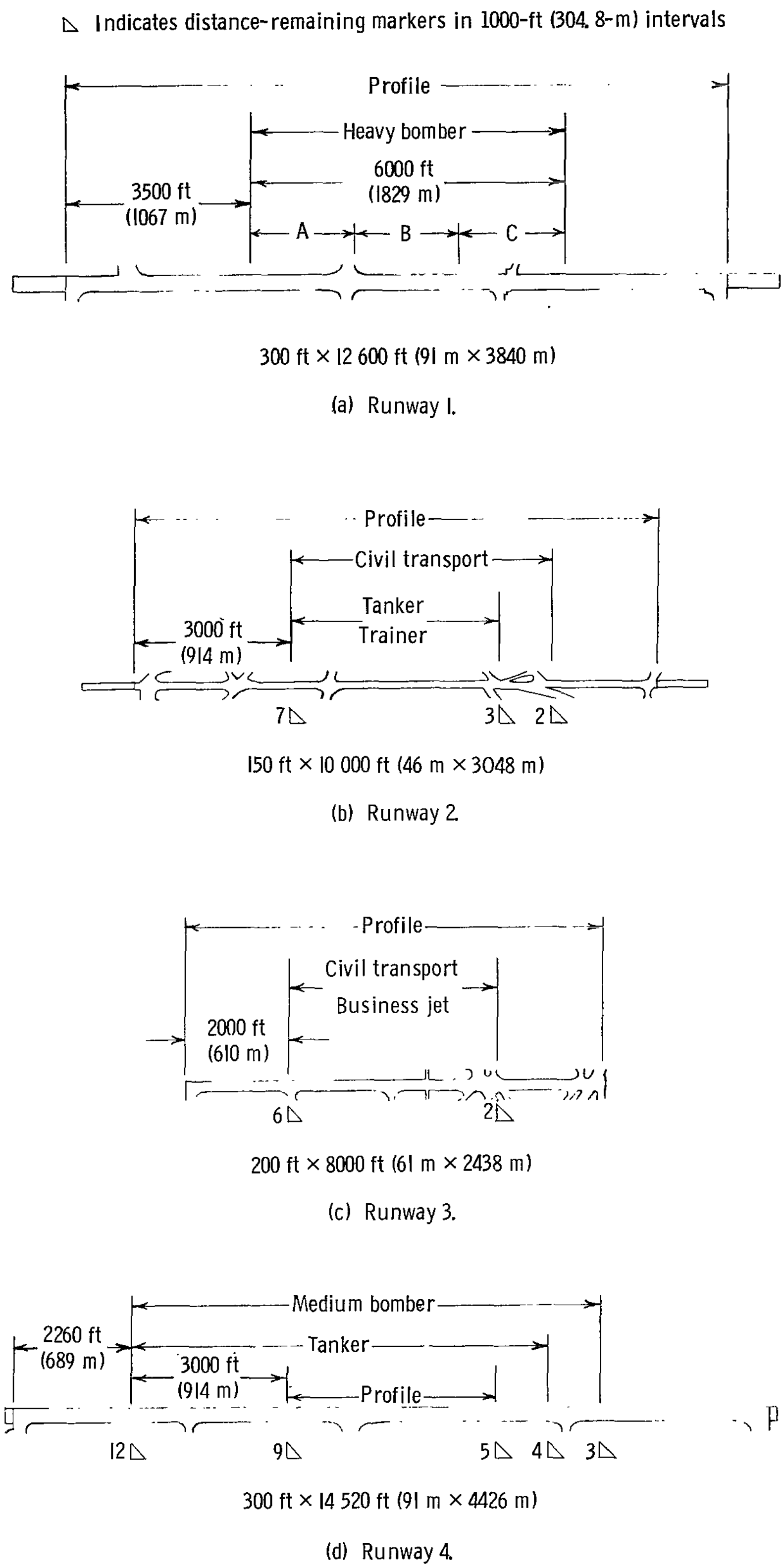
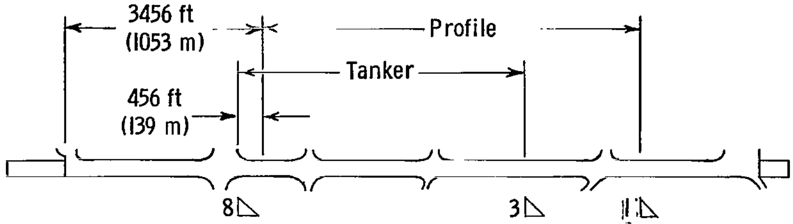
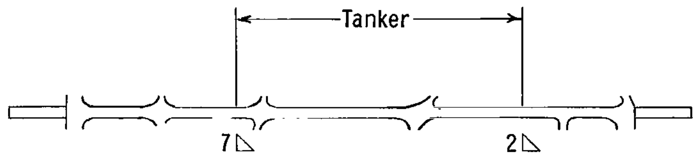


Figure 2.- Diagrams of runways used for investigations which show areas traversed by various airplanes.



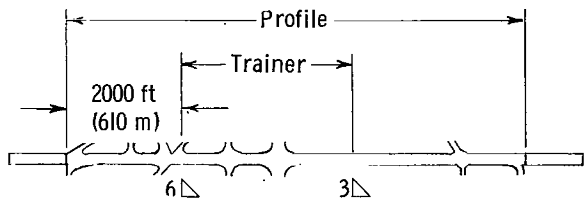
300 ft × 12 100 ft (91 m × 3688 m)

(e) Runway 5-I.



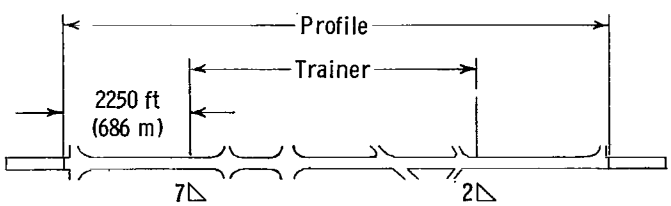
200 ft × 9900 ft (61 m × 3018 m)

(f) Runway 5-II.



200 ft × 8000 ft (61 m × 2438 m)

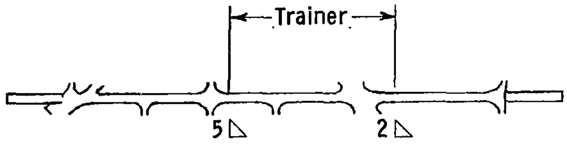
(g) Runway 6-I.



200 ft × 9500 ft (61 m × 2896 m)

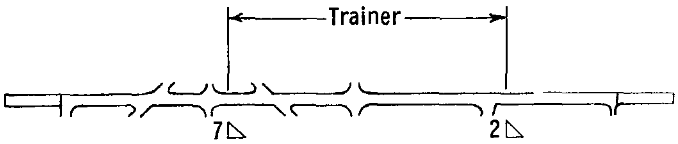
(h) Runway 6-II.

Figure 2.- Continued.



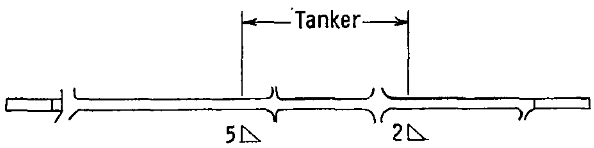
150 ft × 8100 ft (46 m × 2469 m)

(i) Runway 7-I.



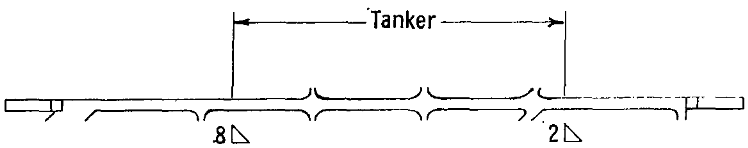
200 ft × 10 000 ft (61 m × 3048 m)

(j) Runway 7-II.



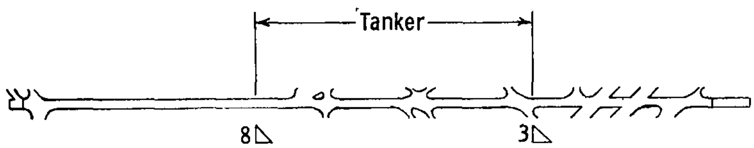
180 ft × 8500 ft (55 m × 2591 m)

(k) Runway 8-I.



200 ft × 11 182 ft (61 m × 3408 m)

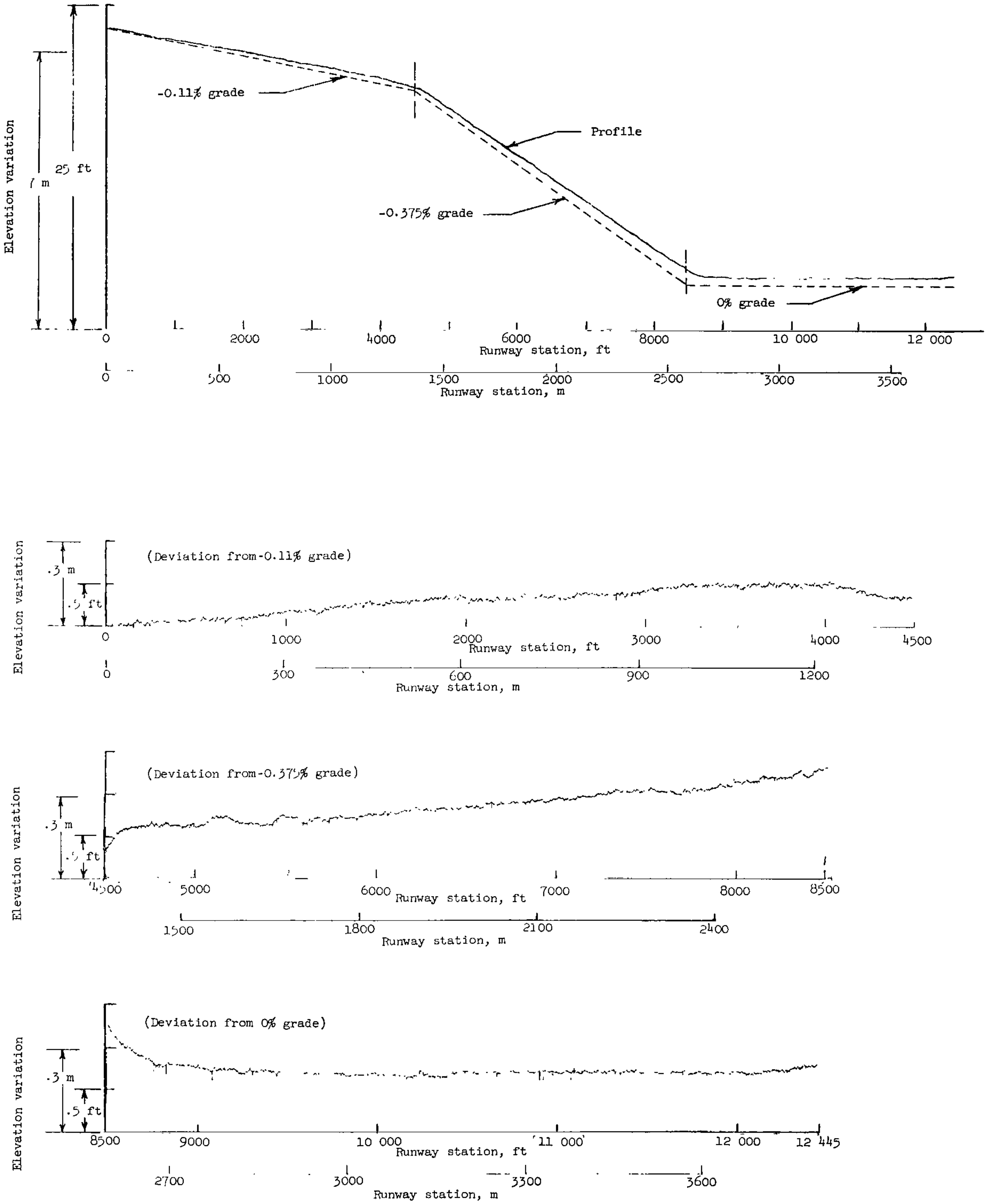
(l) Runway 8-II.



150 ft × 12 371 ft (46 m × 3771 m)

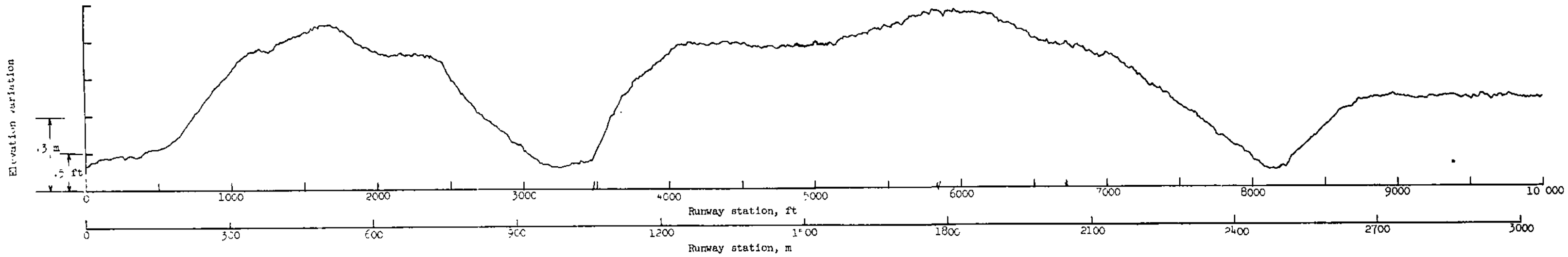
(m) Runway 9.

Figure 2.- Concluded.

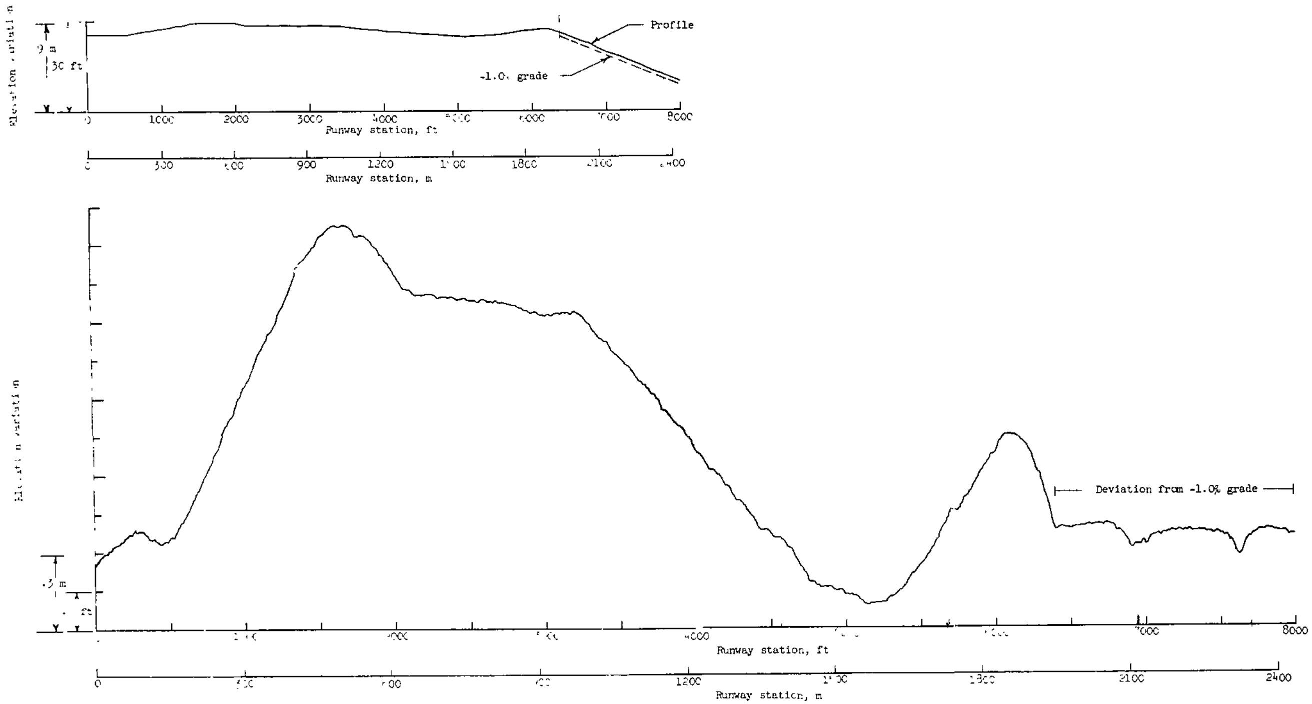


(a) Runway 1.

Figure 3.- Profiles of some runways used in this investigation.

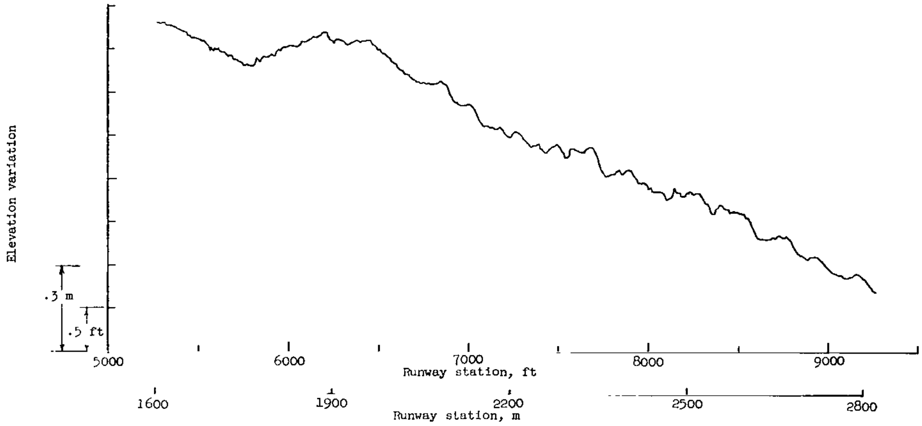


(b) Runway 2.

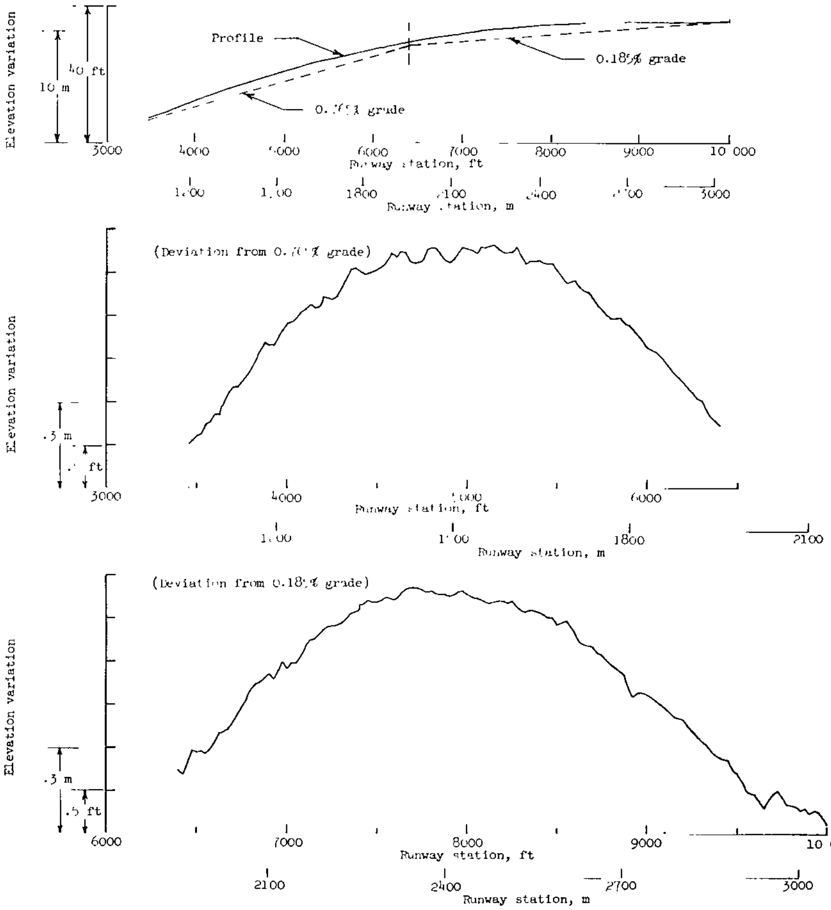


(c) Runway 3.

Figure 3.- Continued.

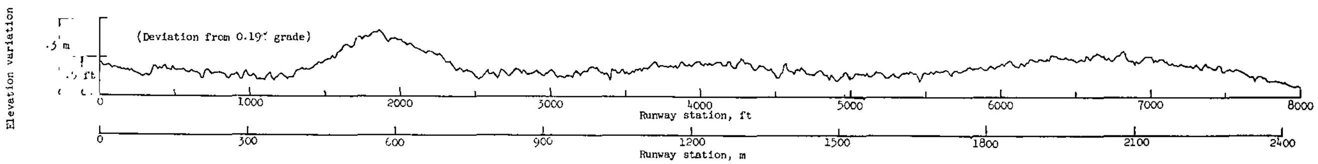


(d) Runway 4.

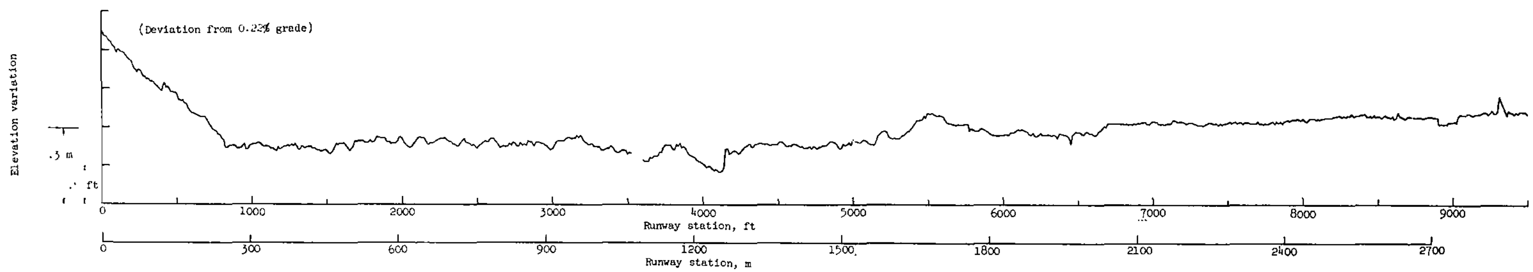


(e) Runway 5-I.

Figure 3.- Continued.



(f) Runway 6-I.



(g) Runway 6-II.

Figure 3.- Concluded.

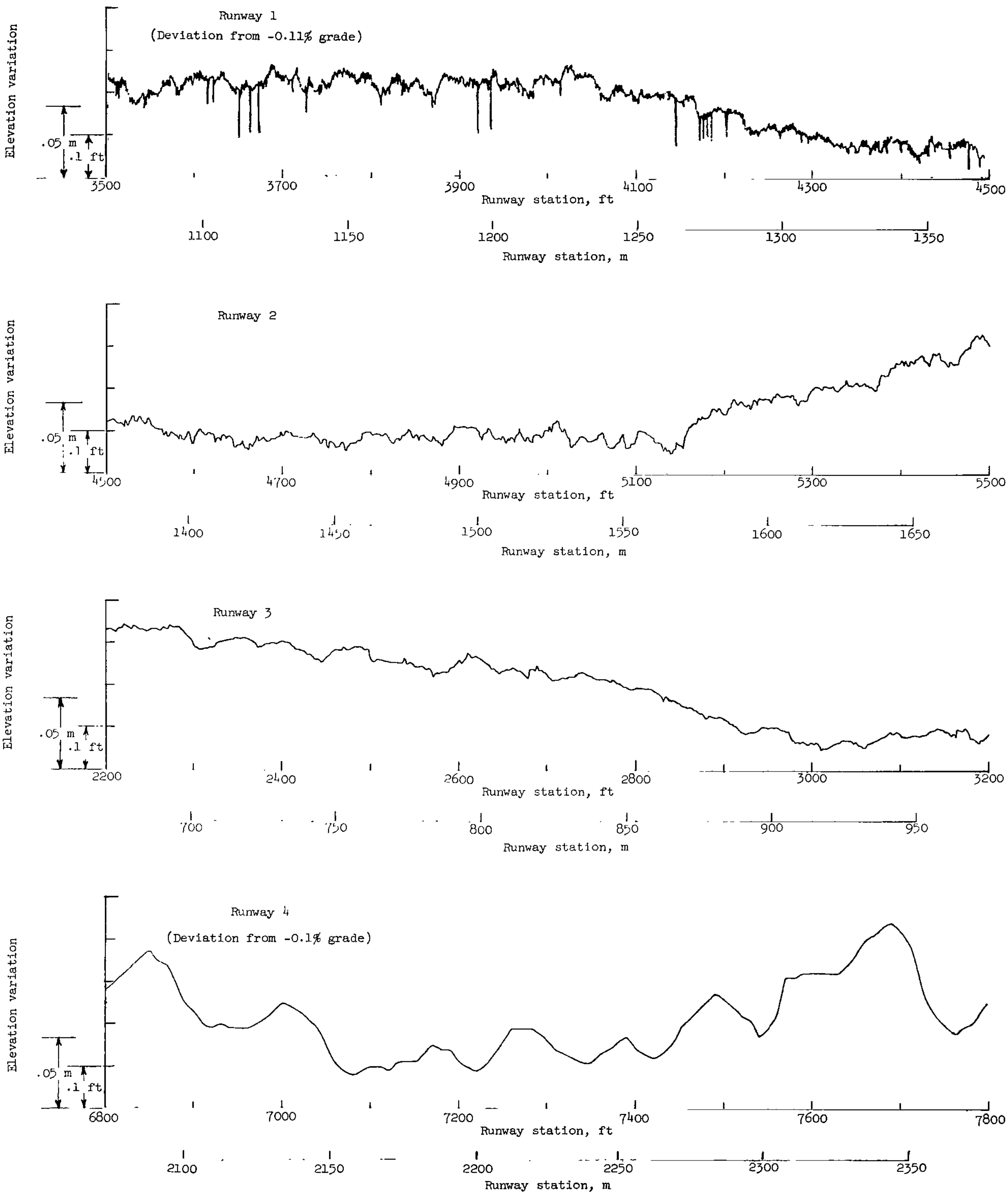


Figure 4.- Profiles for 1000-ft (304.8-m) test sections of several runways.

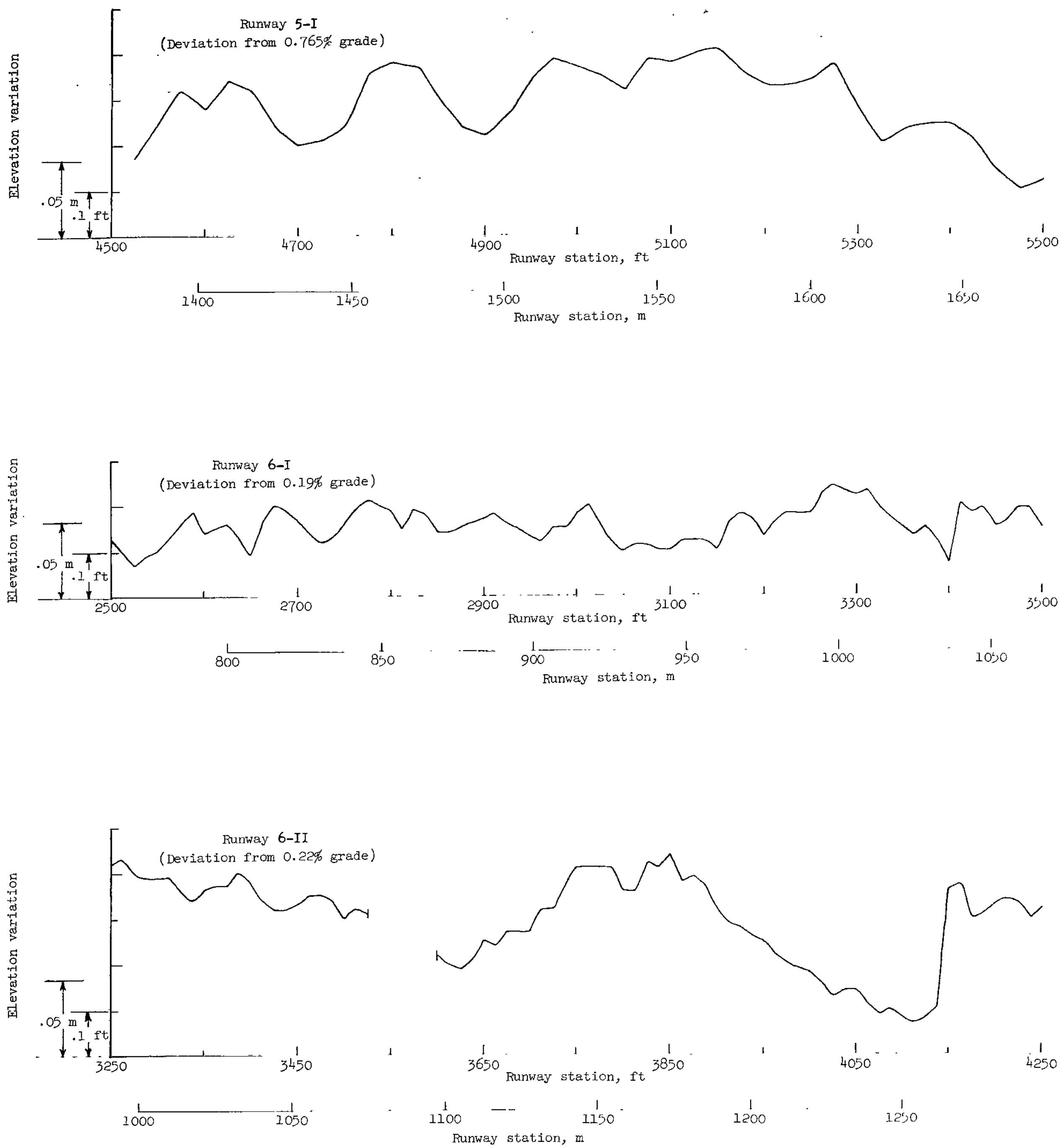
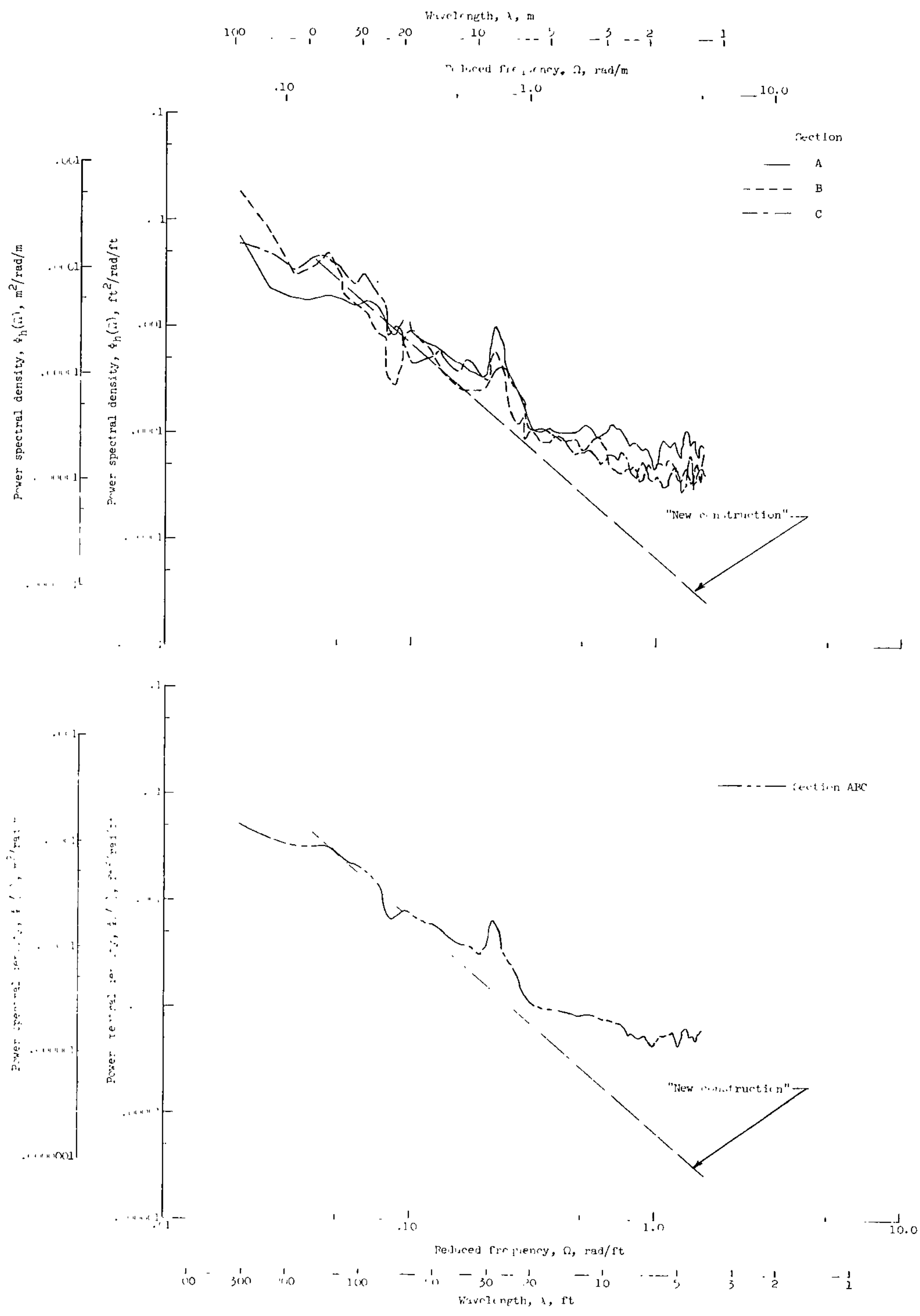
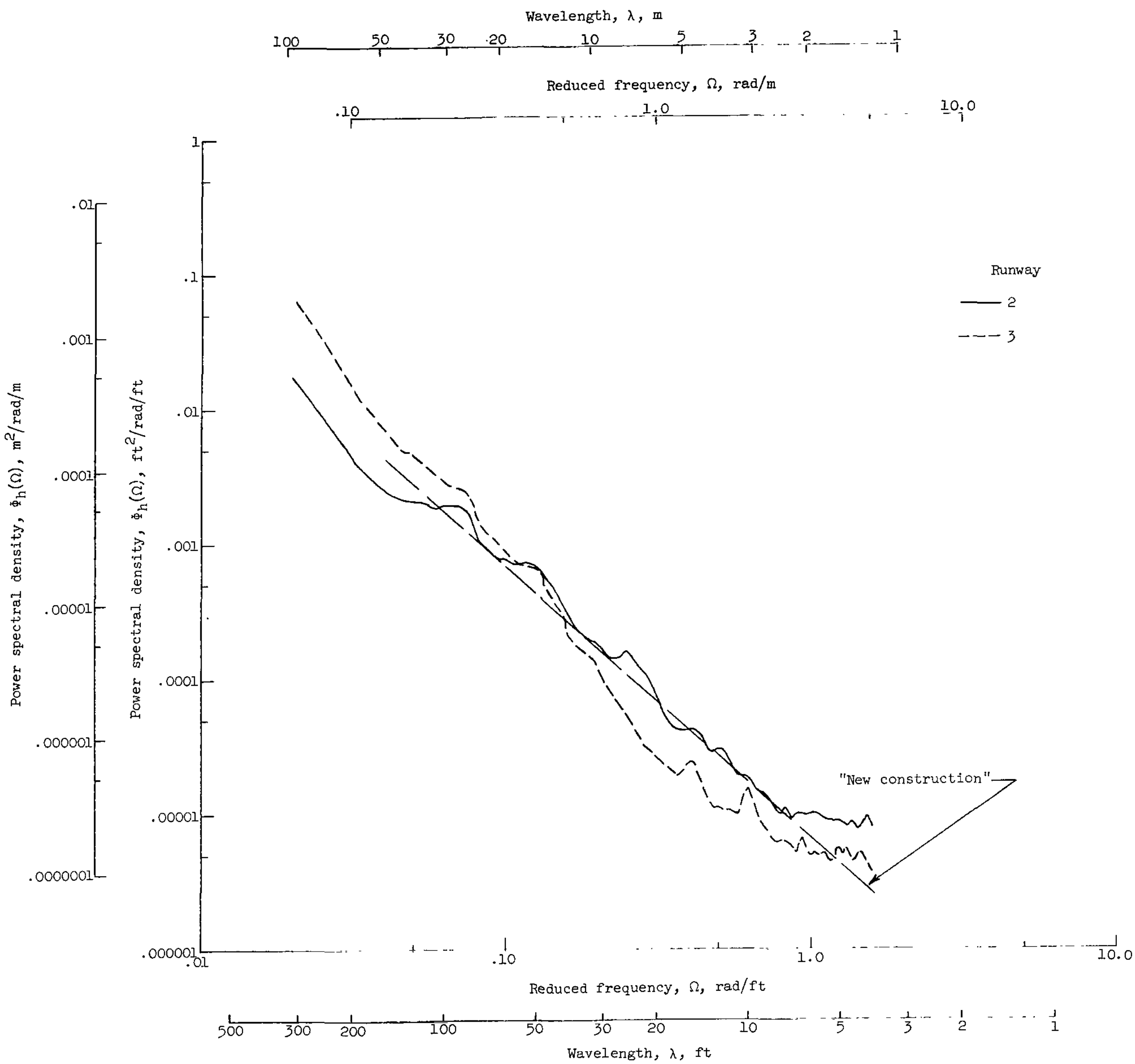


Figure 4.- Concluded.



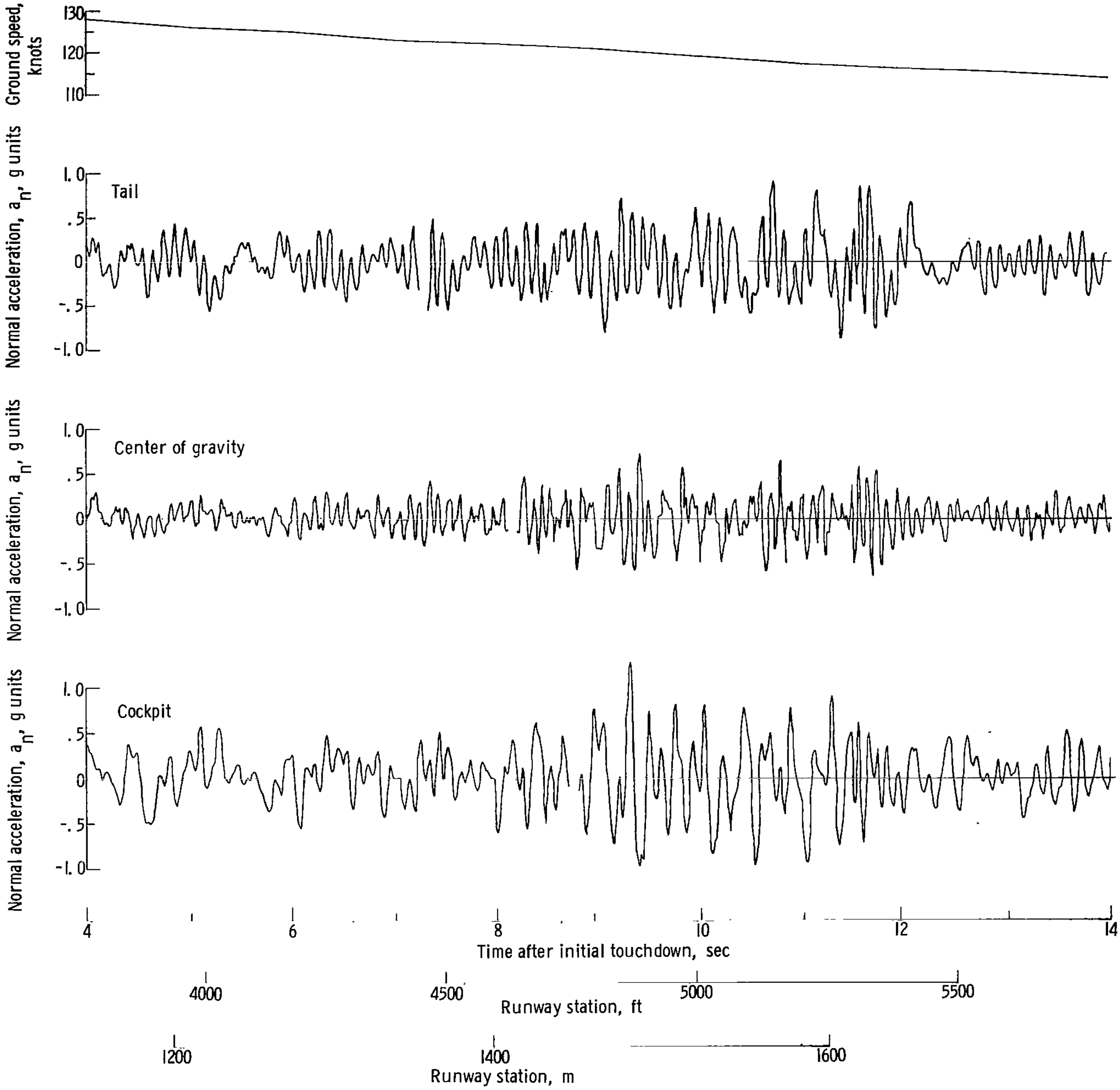
(a) Runway 1.

Figure 5.- Power-spectral-density functions for profiles of runways 1, 2, and 3 of this investigation.



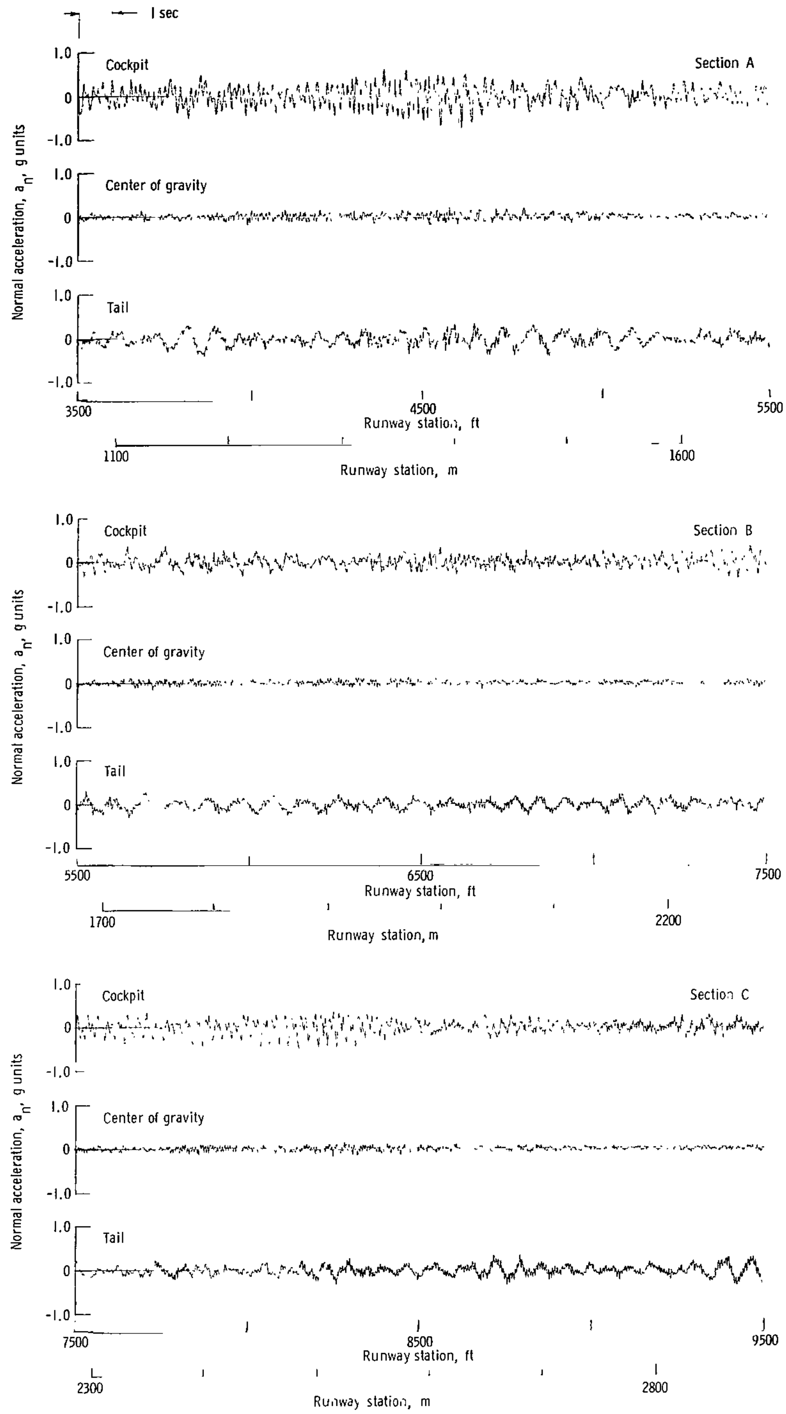
(b) Runways 2 and 3.

Figure 5.- Concluded.



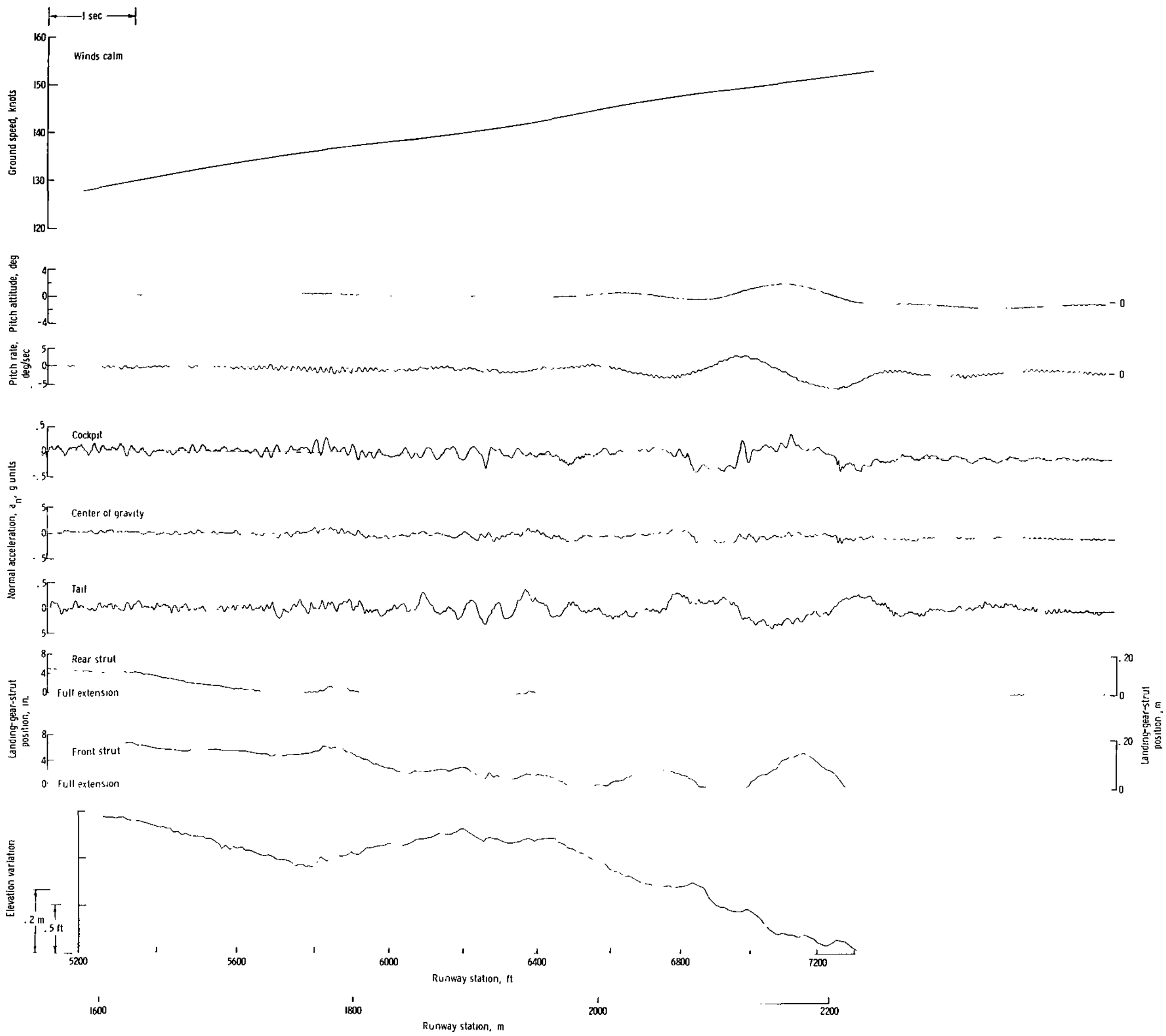
(a) Landing run.

Figure 6.- Response of heavy bomber on runway 1.



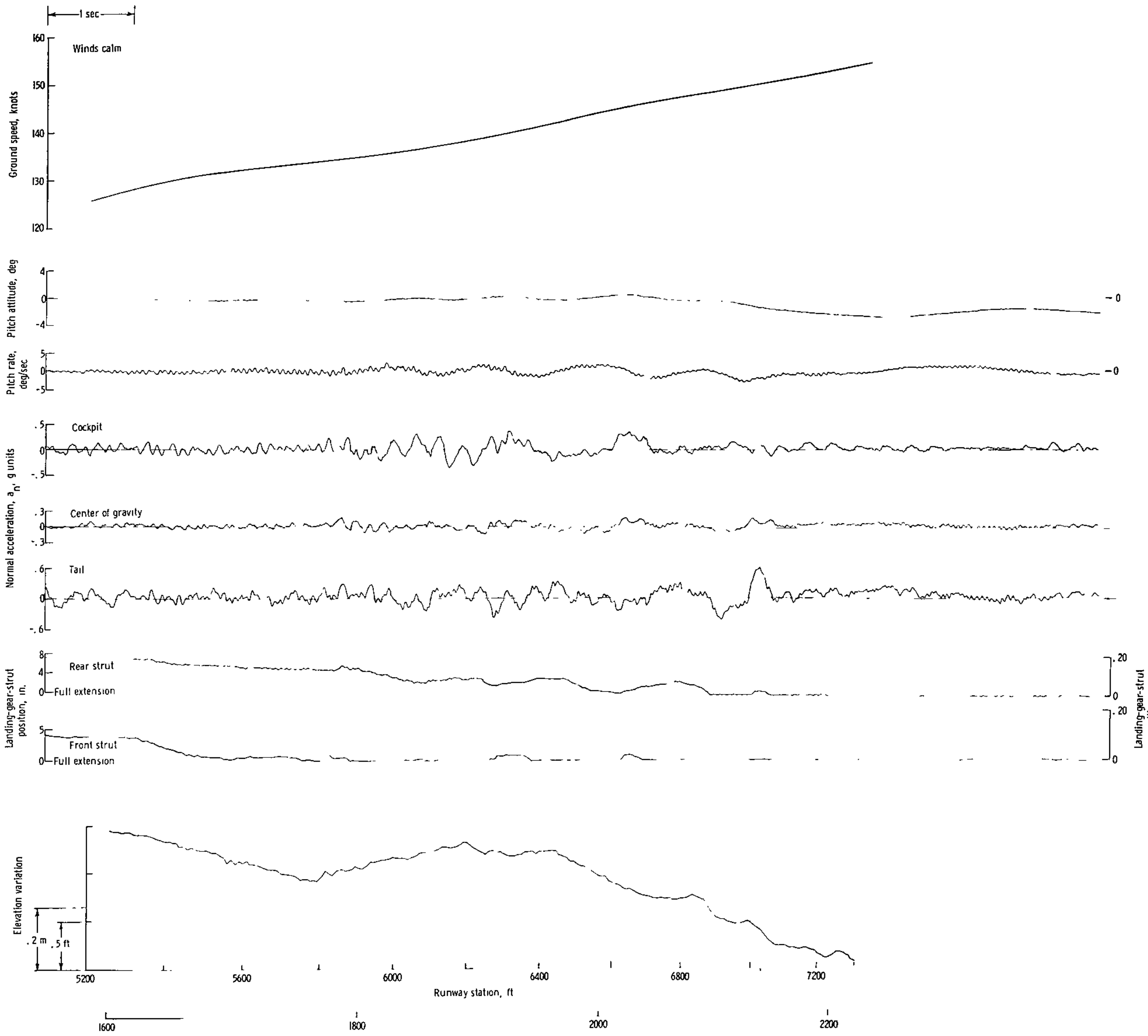
(b) Taxiing at 56 knots.

Figure 6.- Concluded.



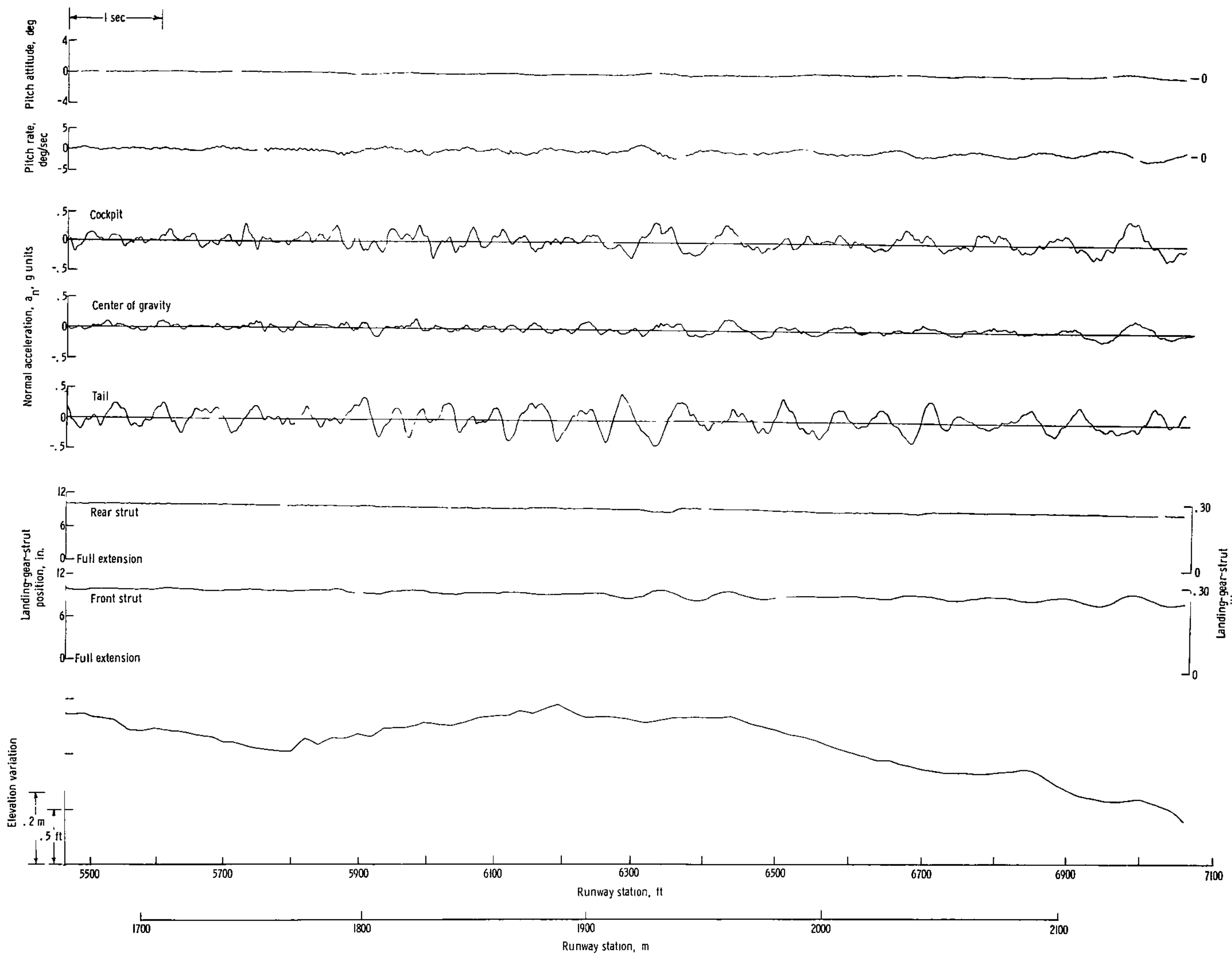
(a) Last seconds of first take-off. (Rear wheels lift off first.)

Figure 7.- Response of medium bomber on runway 4.



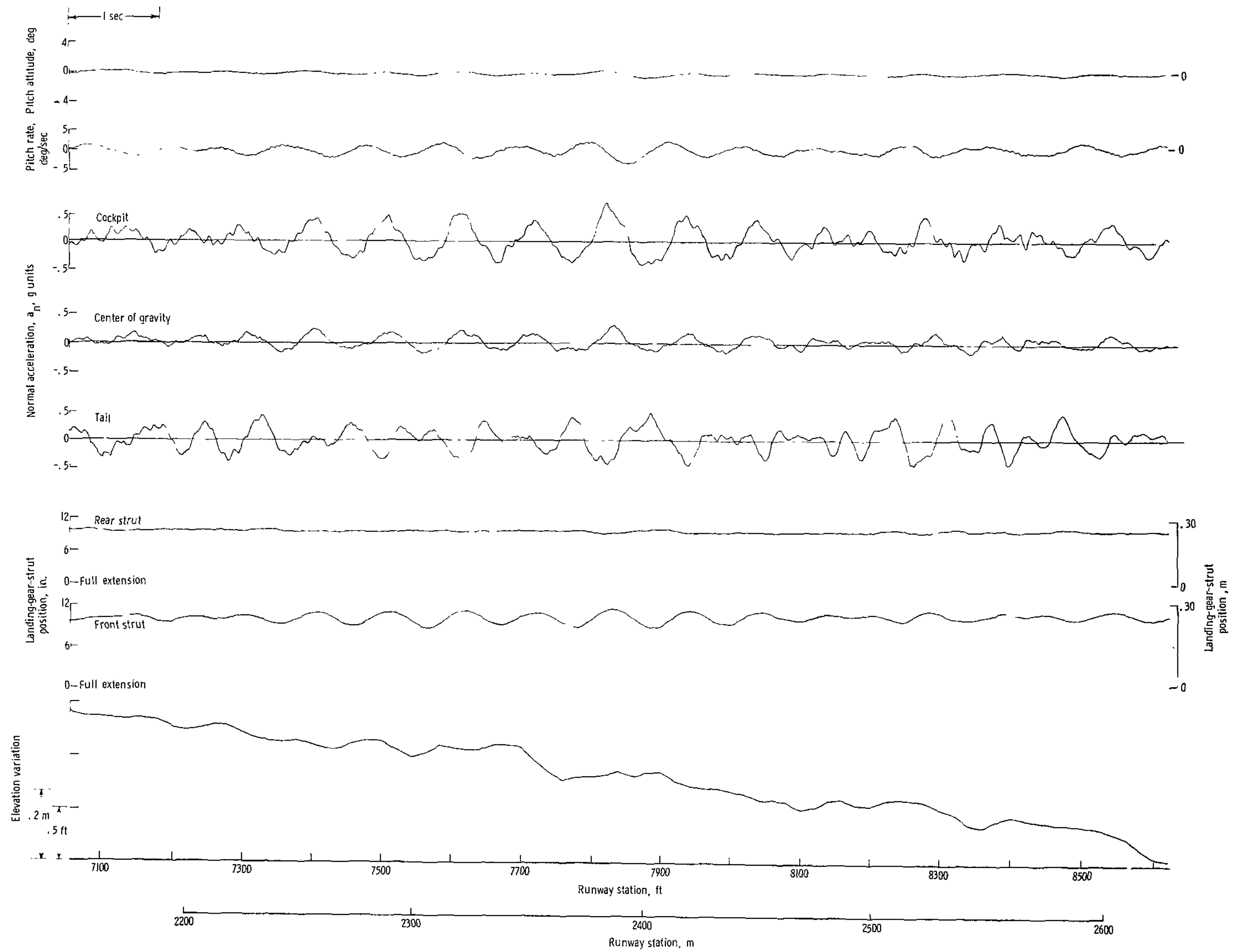
(b) Last seconds of second take-off. (Front wheels lift off first.)

Figure 7.- Continued.



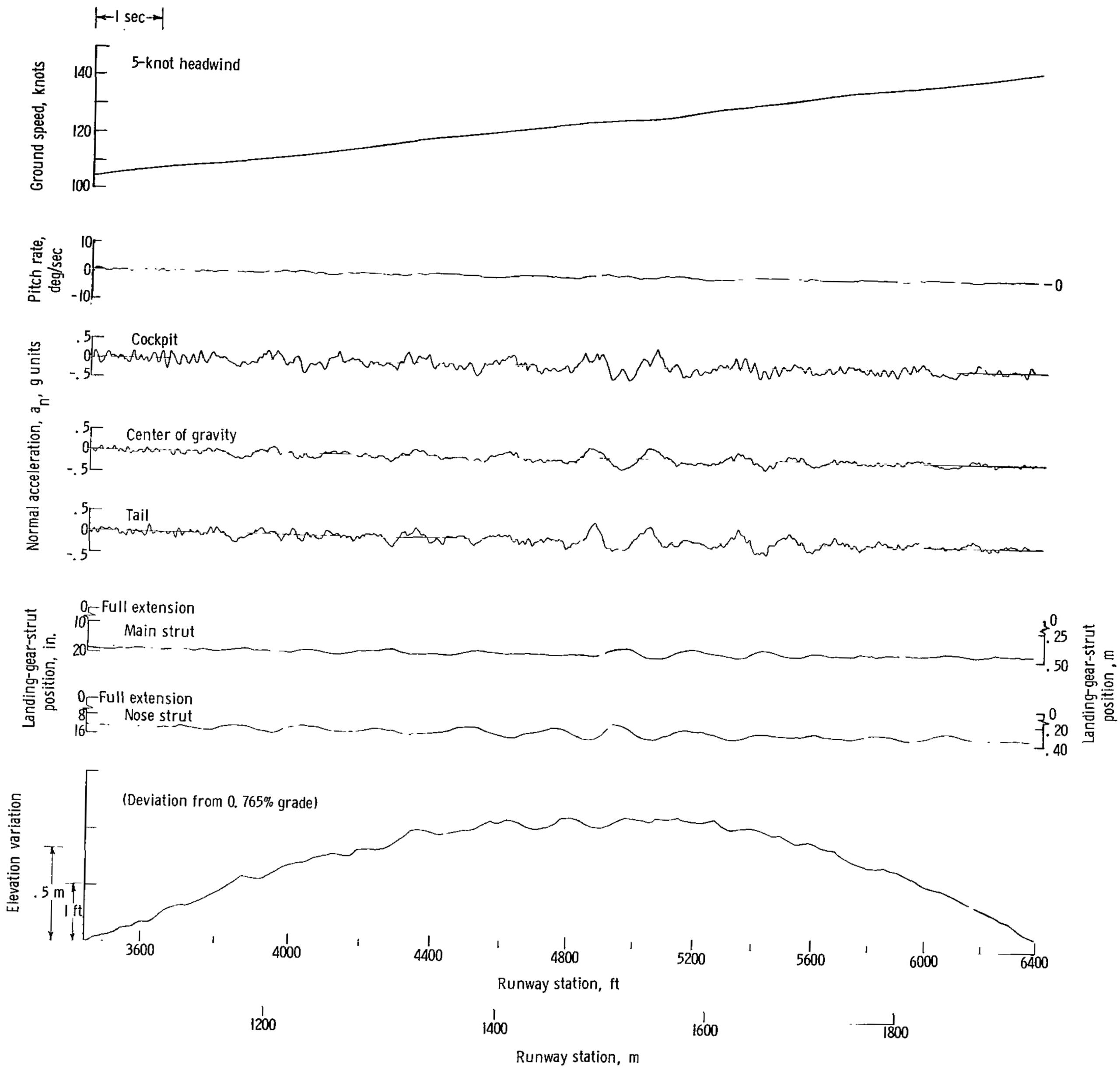
(c) Taxiing at 78 knots.

Figure 7.- Continued.



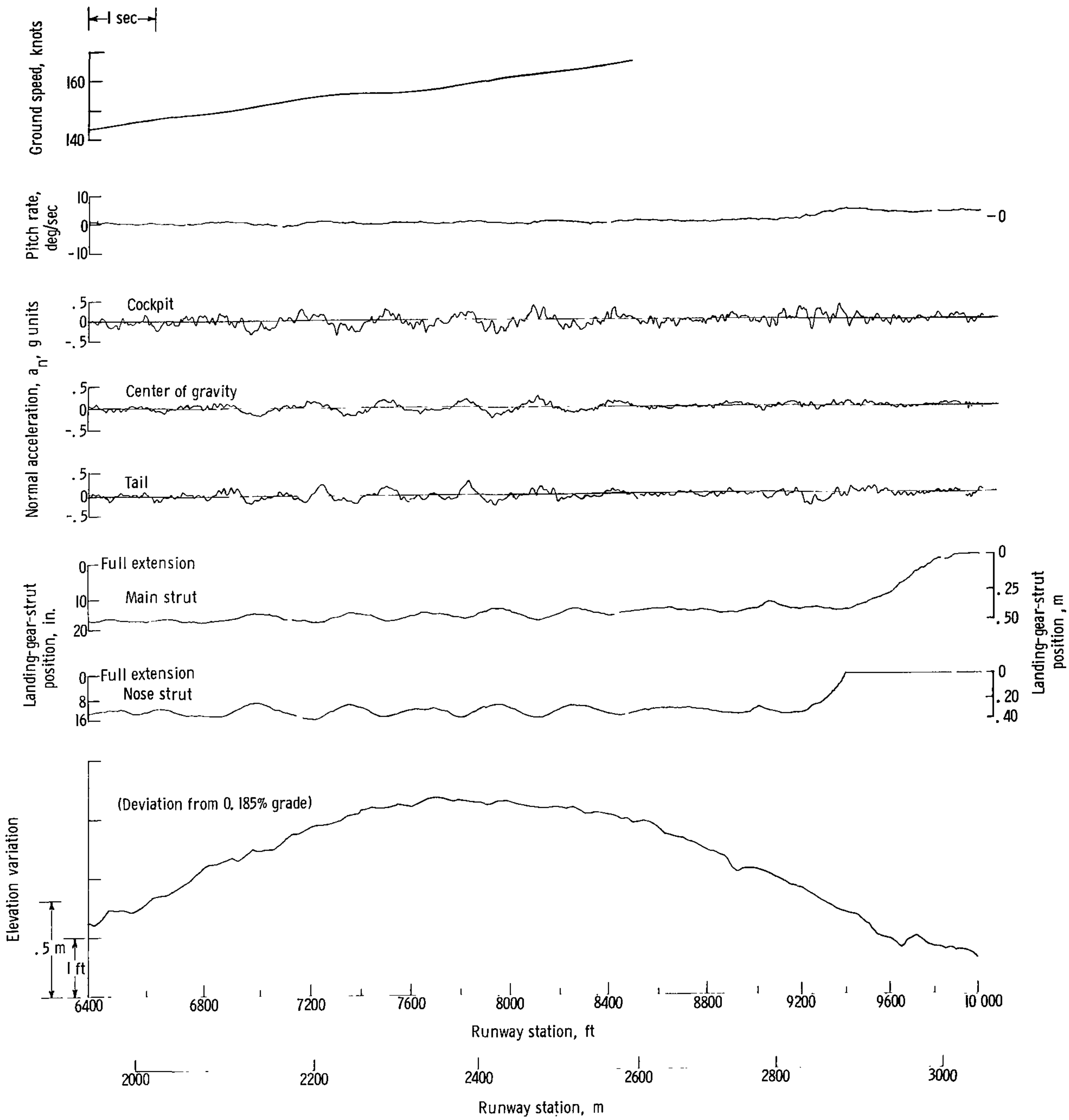
(c) Concluded.

Figure 7.- Concluded.



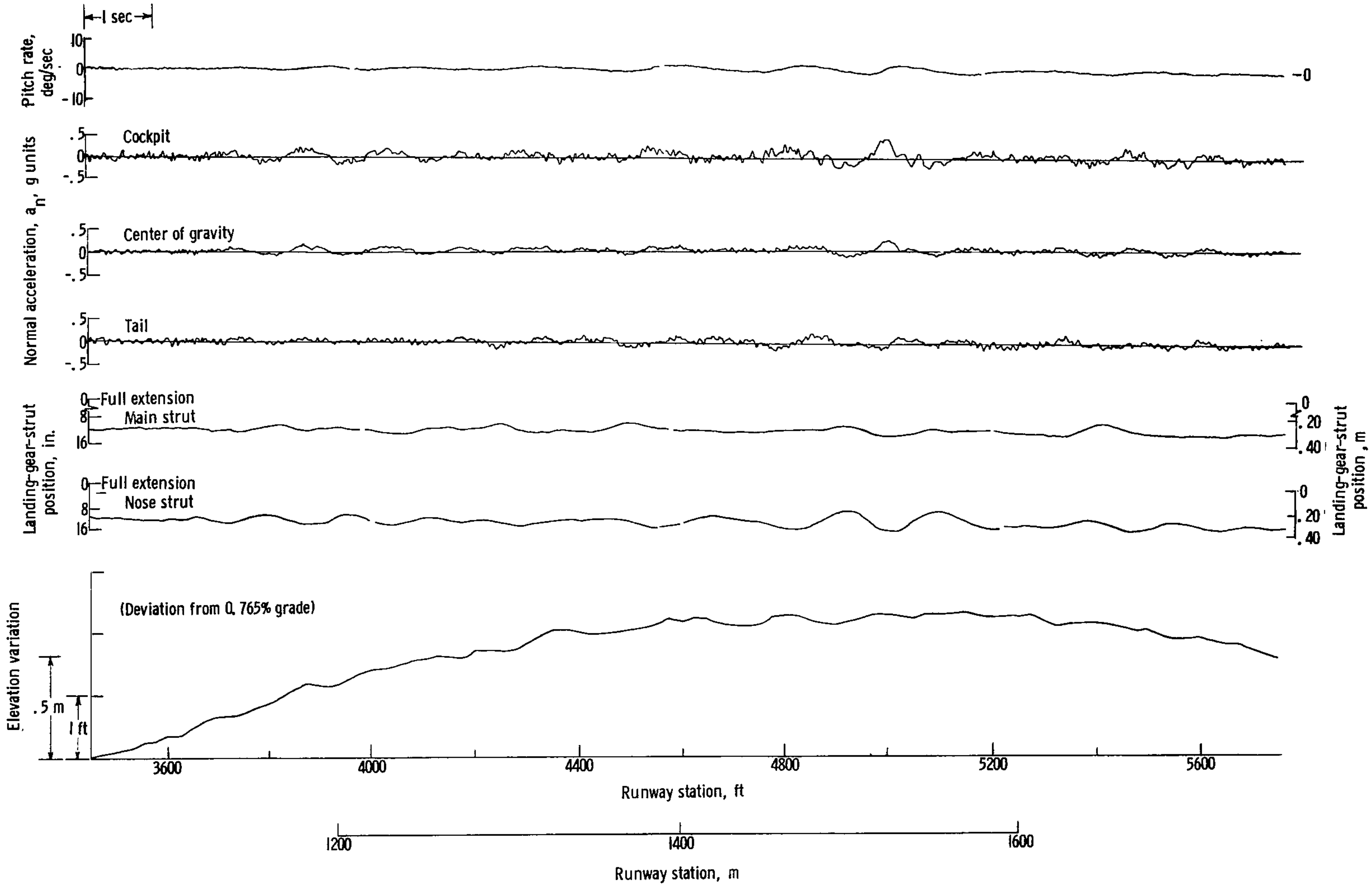
(a) Take-off.

Figure 8.- Responses of tanker on runway 5-1.



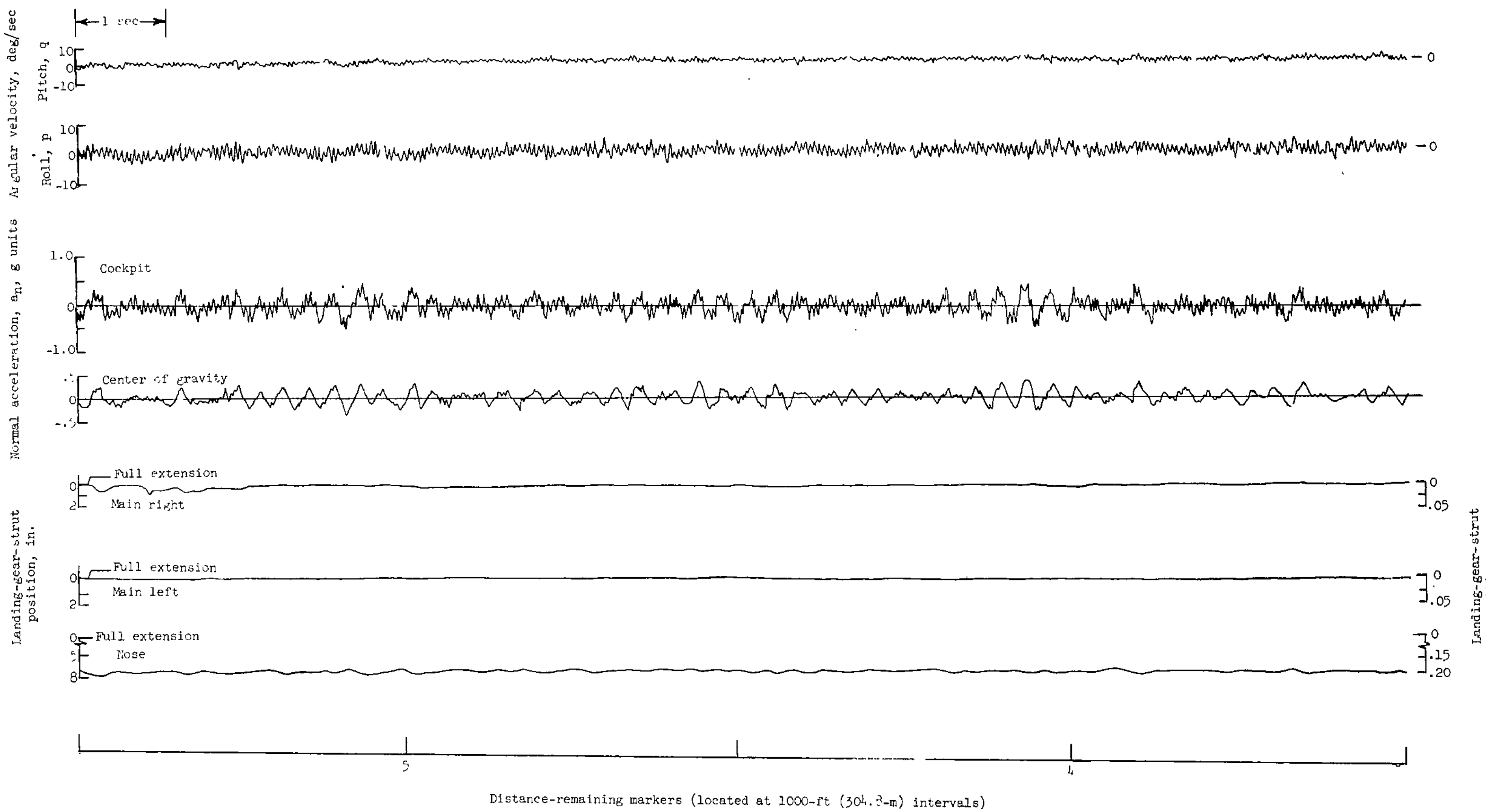
(a) Concluded.

Figure 8.- Continued.



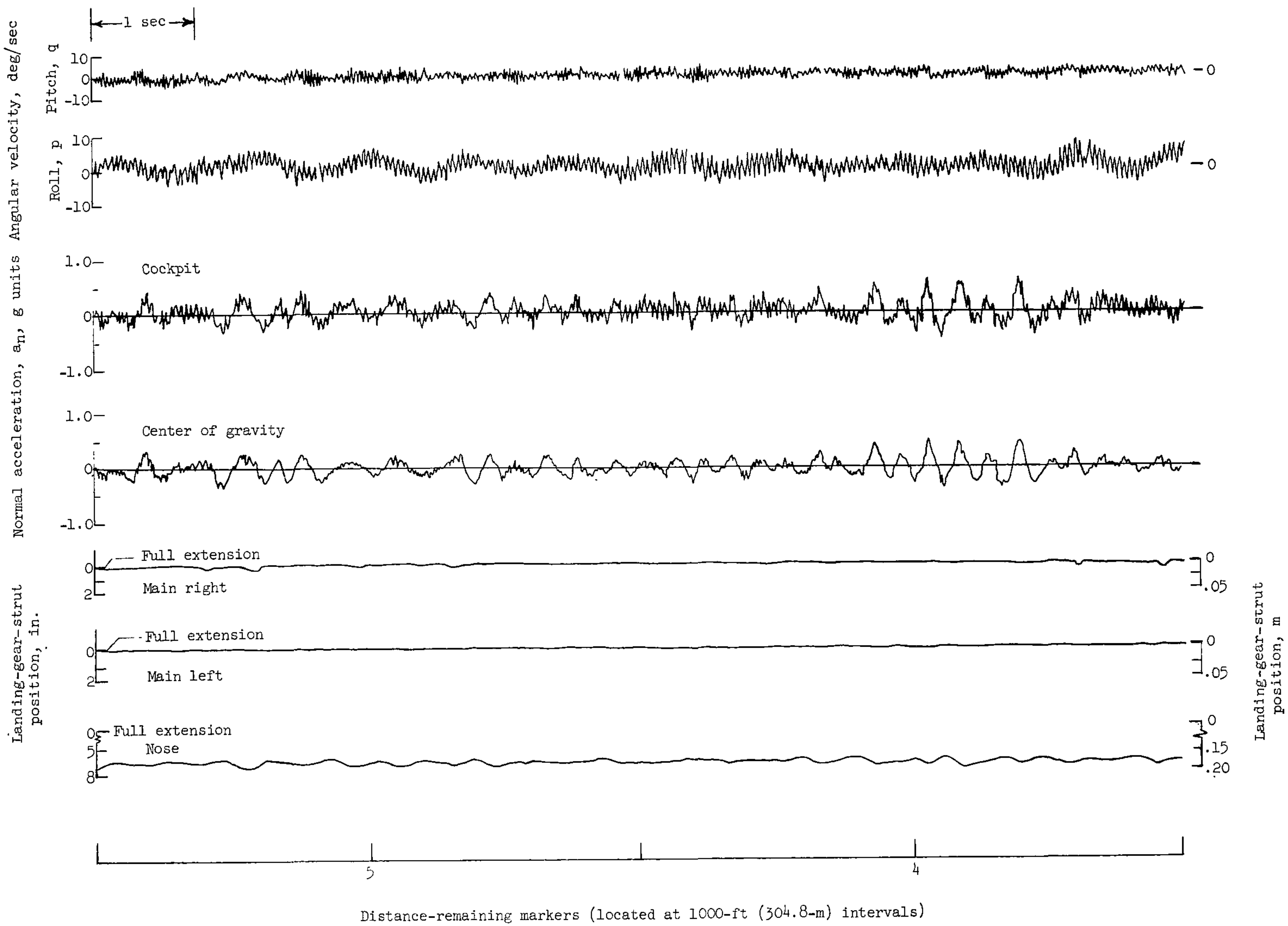
(b) Taxiing at 76 knots.

Figure 8.- Concluded.



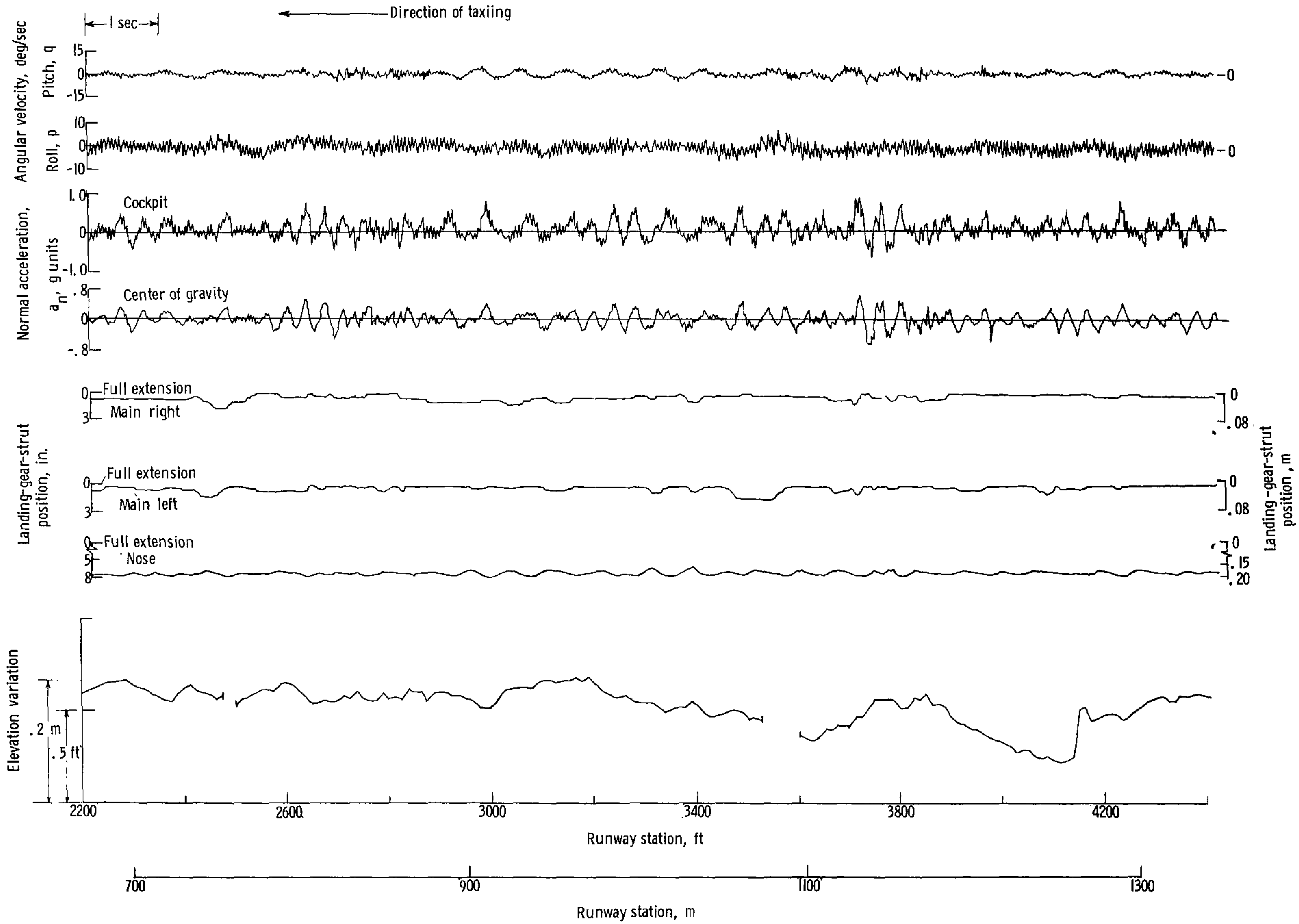
(a) Taxiing on runway 7-11 at 81 knots.

Figure 9.- Time histories of responses of trainer.



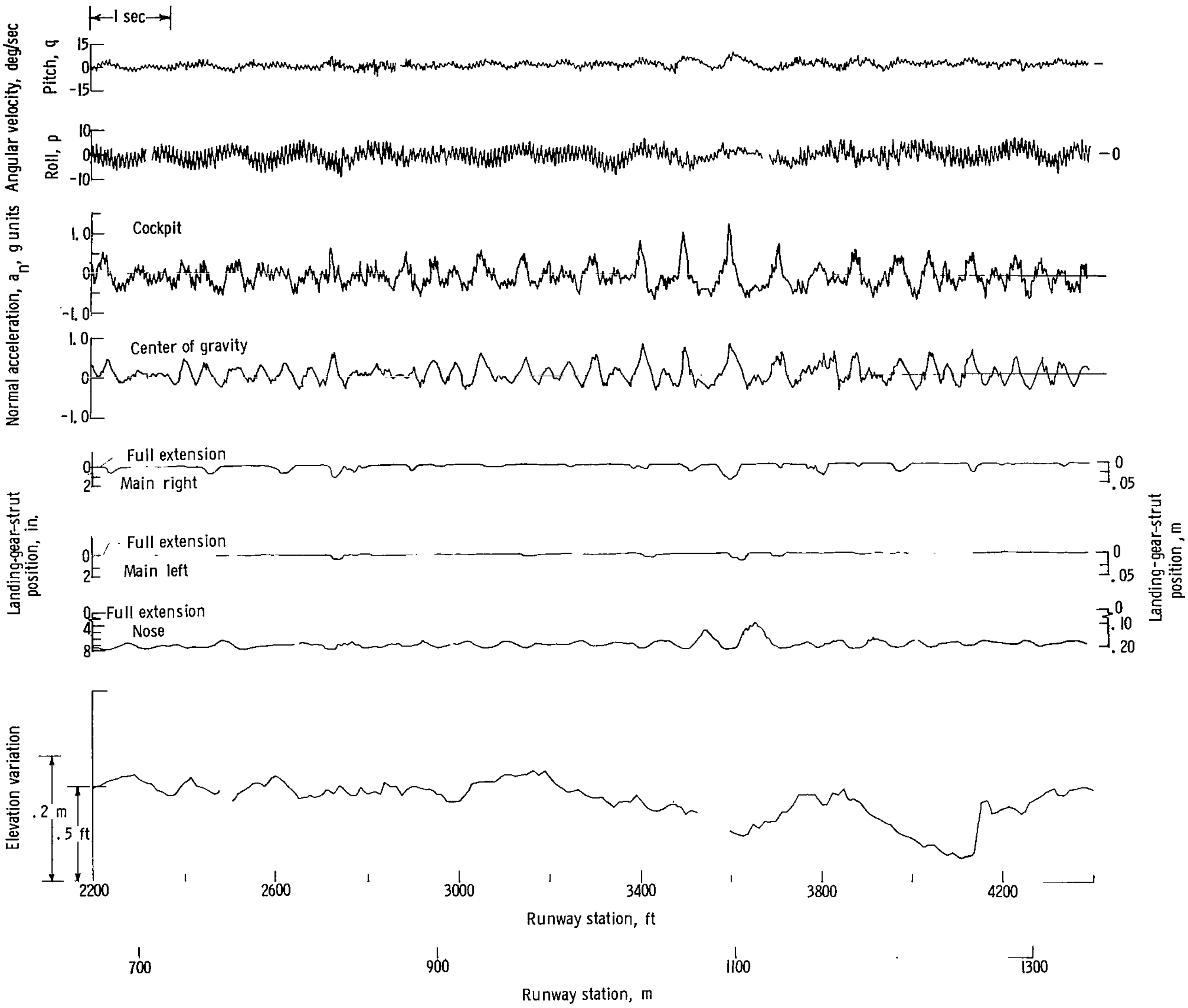
(b) Taxiing on runway 7-11 at 111 knots.

Figure 9.- Continued.



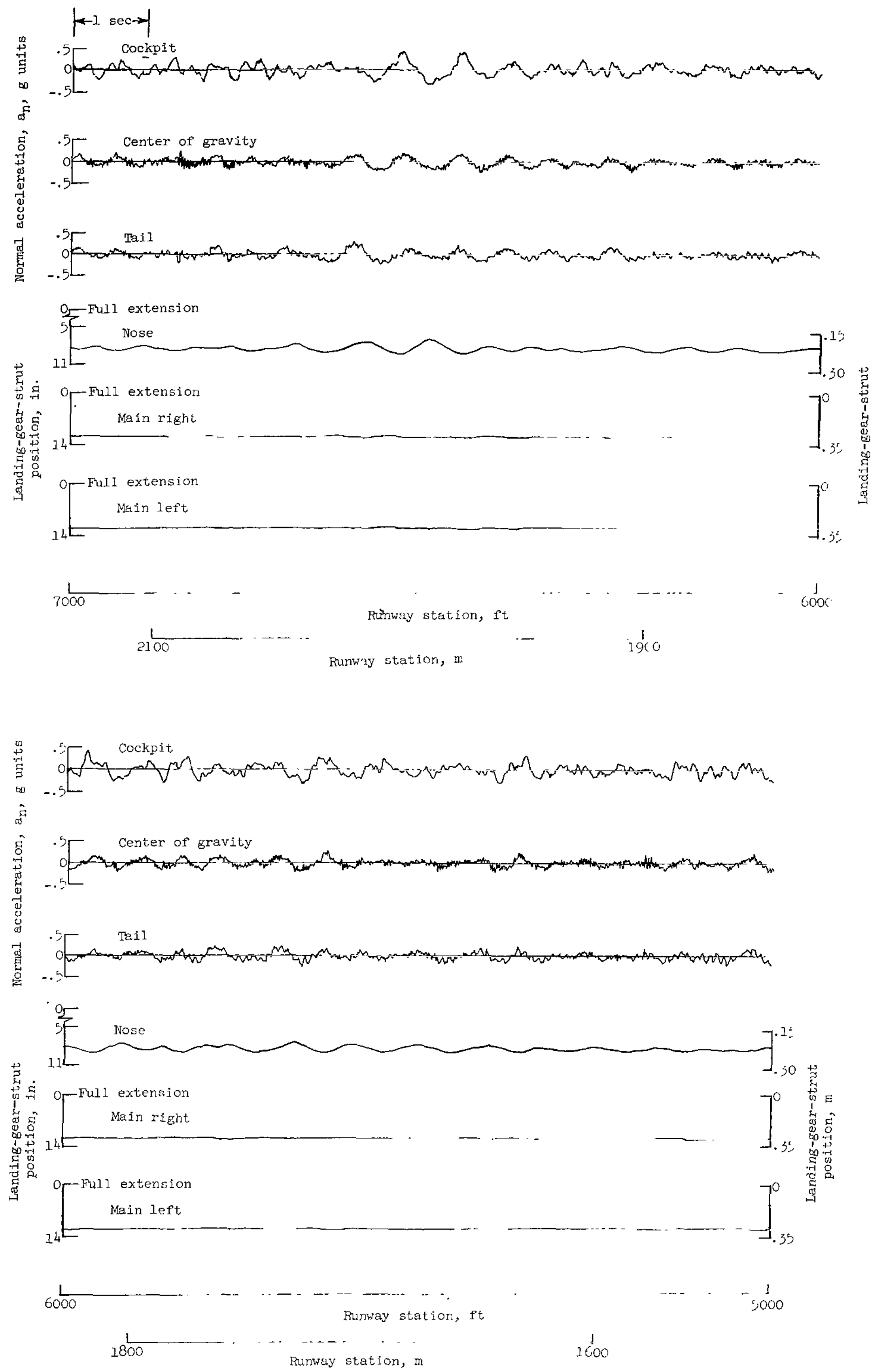
(c) Taxiing on runway 6-11 at 87 knots.

Figure 9.- Continued.



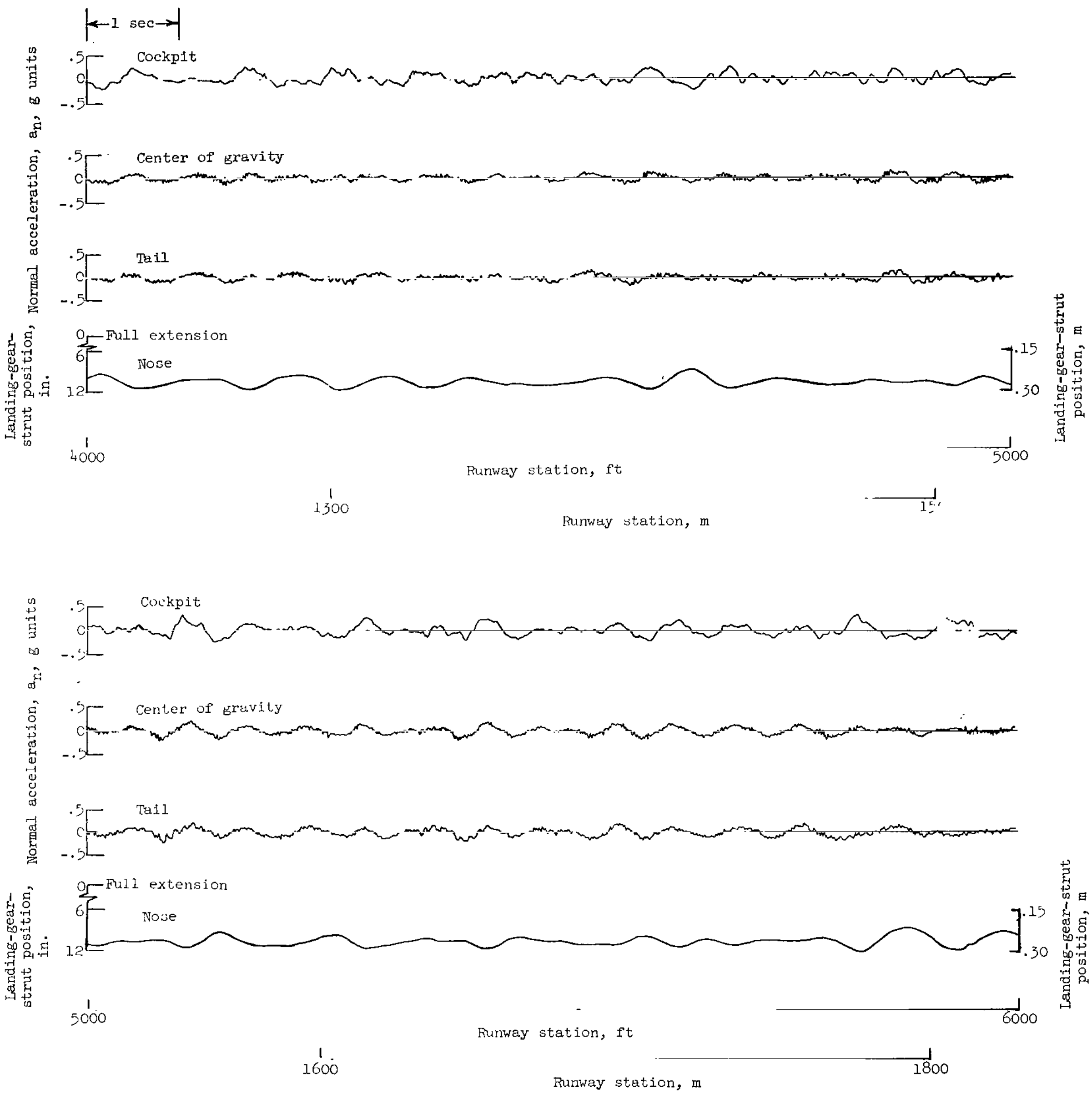
(d) Taxiing on runway 6-11 at 108 knots.

Figure 9.- Concluded.



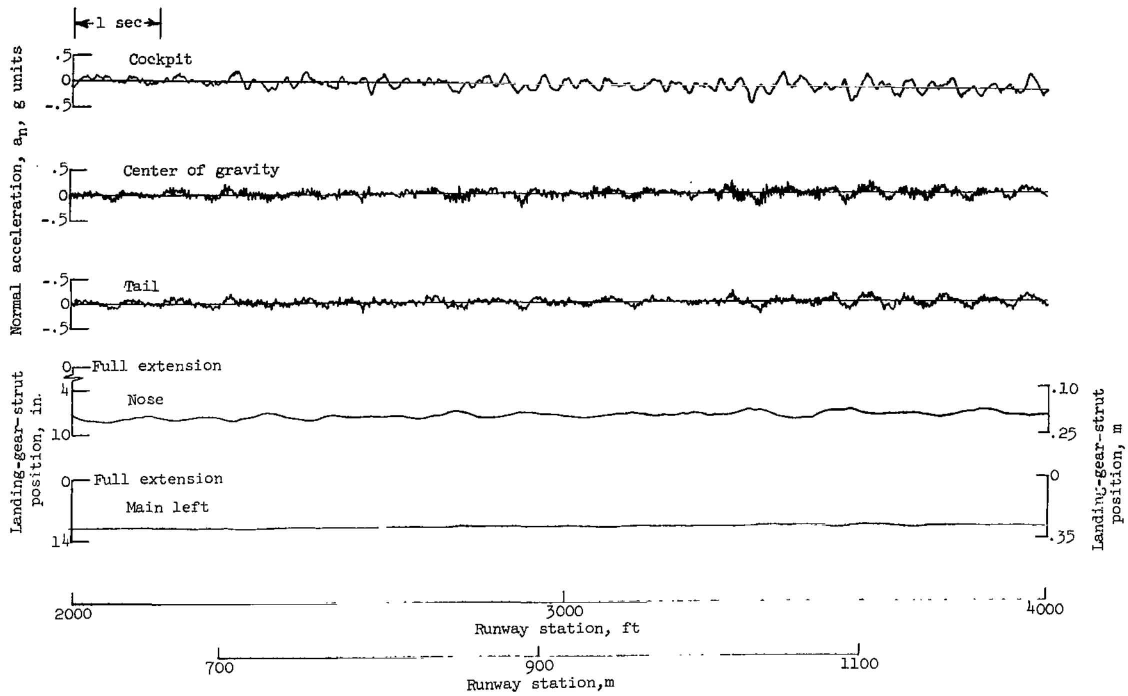
(a) Taxiing on runway 2 at 61 knots.

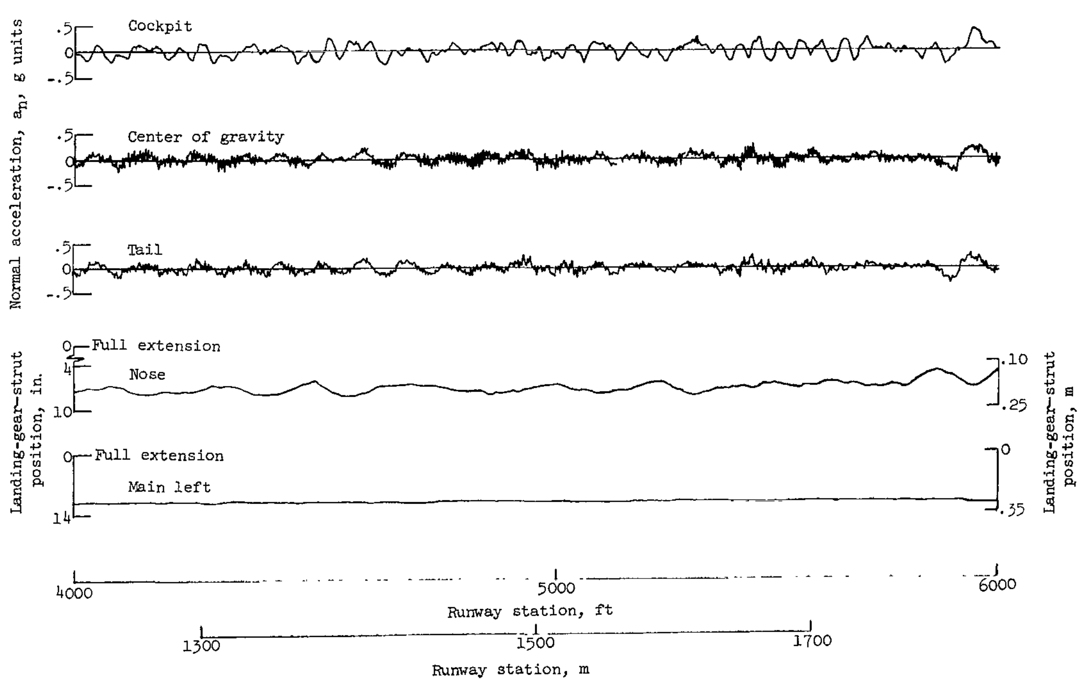
Figure 10.- Response of civil transport during taxiing on runways 2 and 3.



(b) Taxiing on runway 3 at 58 knots.

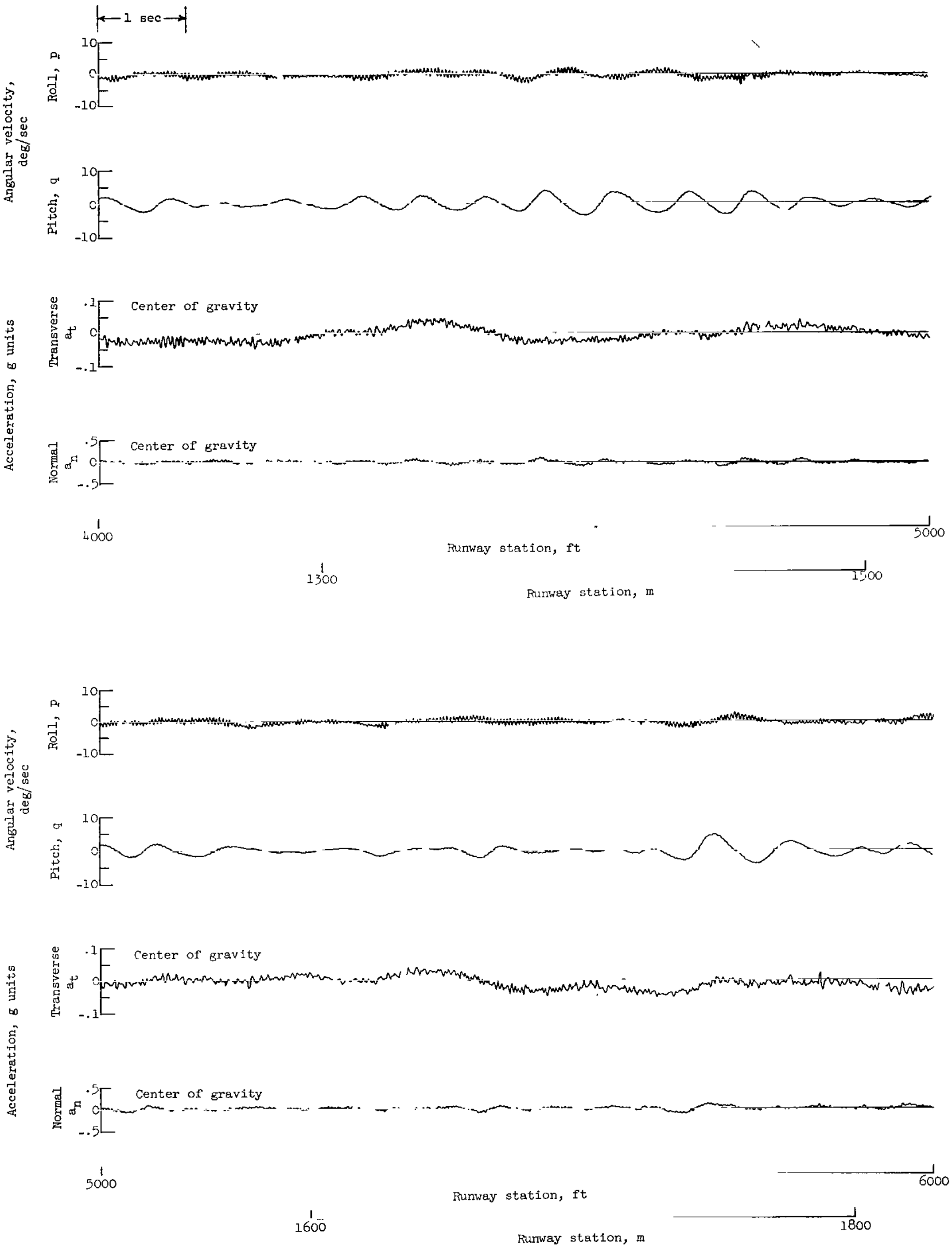
Figure 10.- Continued.





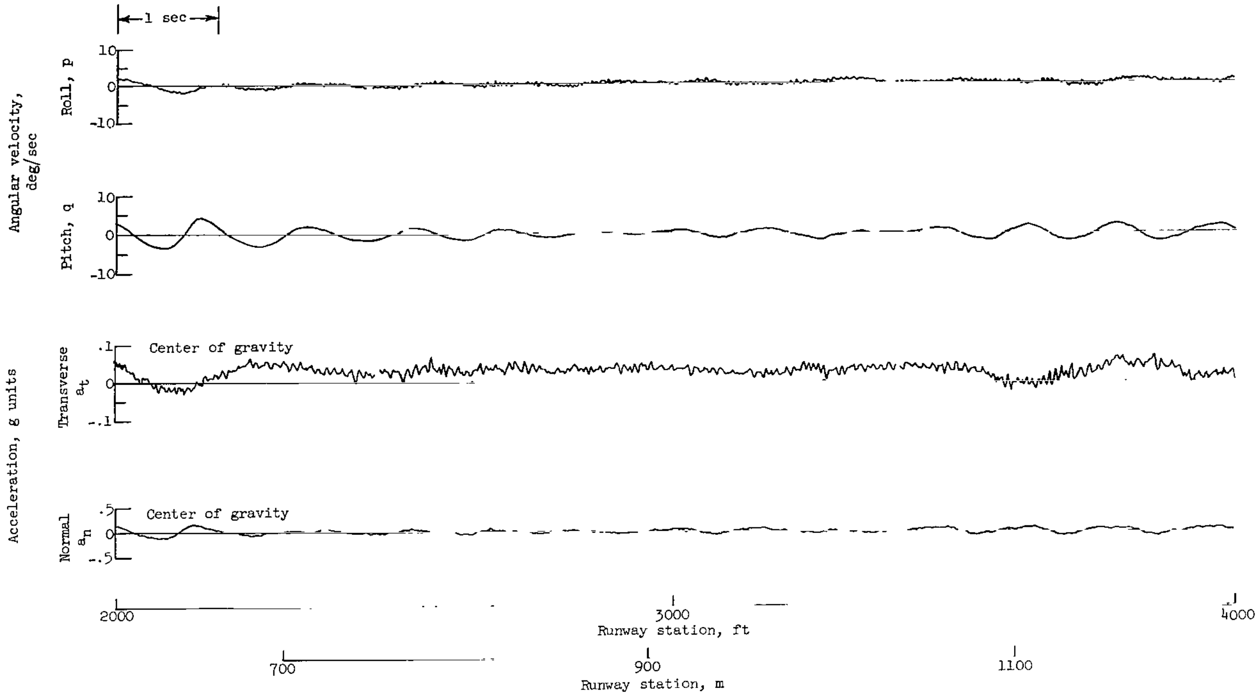
(c) Taxiing on runway 3 at 104 knots.

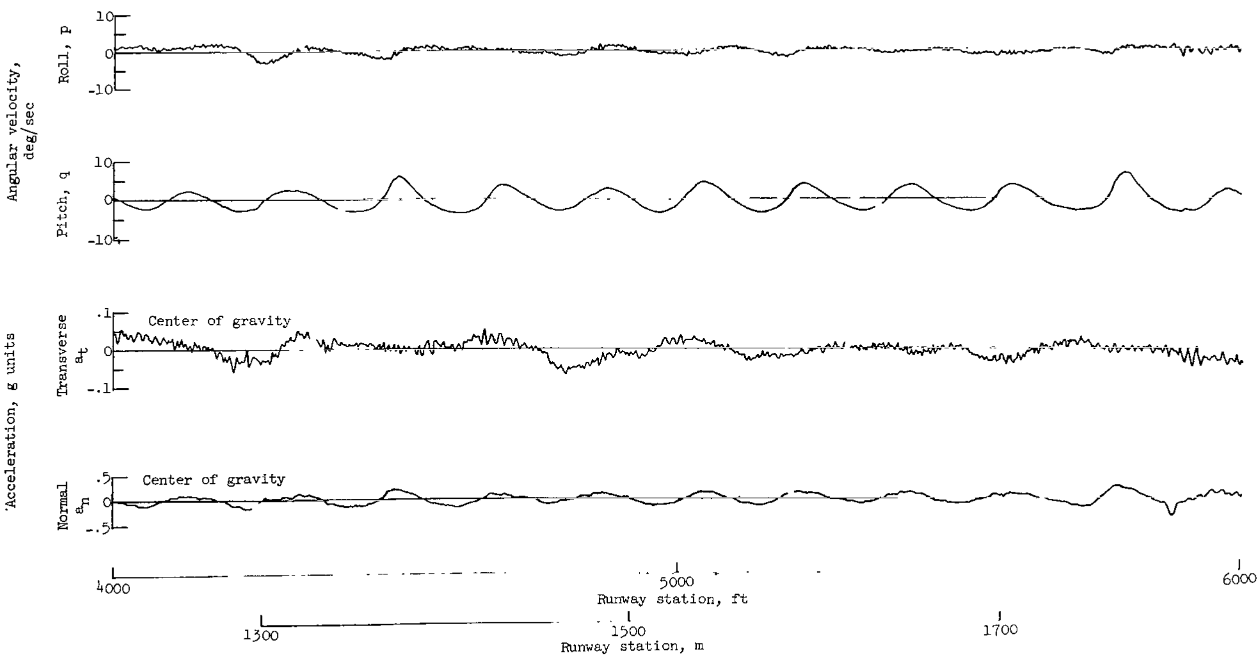
Figure 10.- Concluded.



(a) Taxi speed of 64 knots.

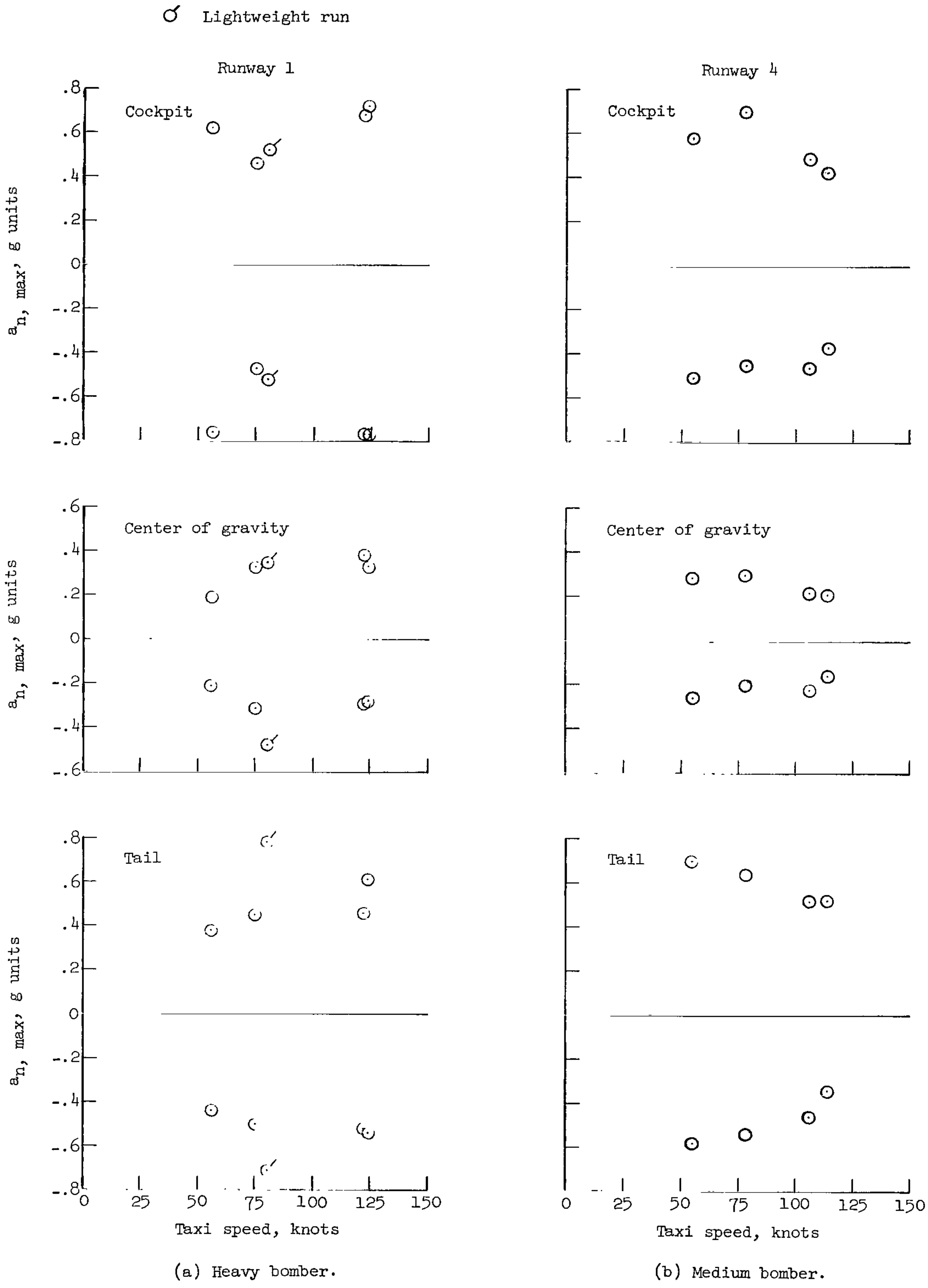
Figure 11.- Responses of business jet during taxiing on runway 3.





(b) Taxi speed of 108 knots.

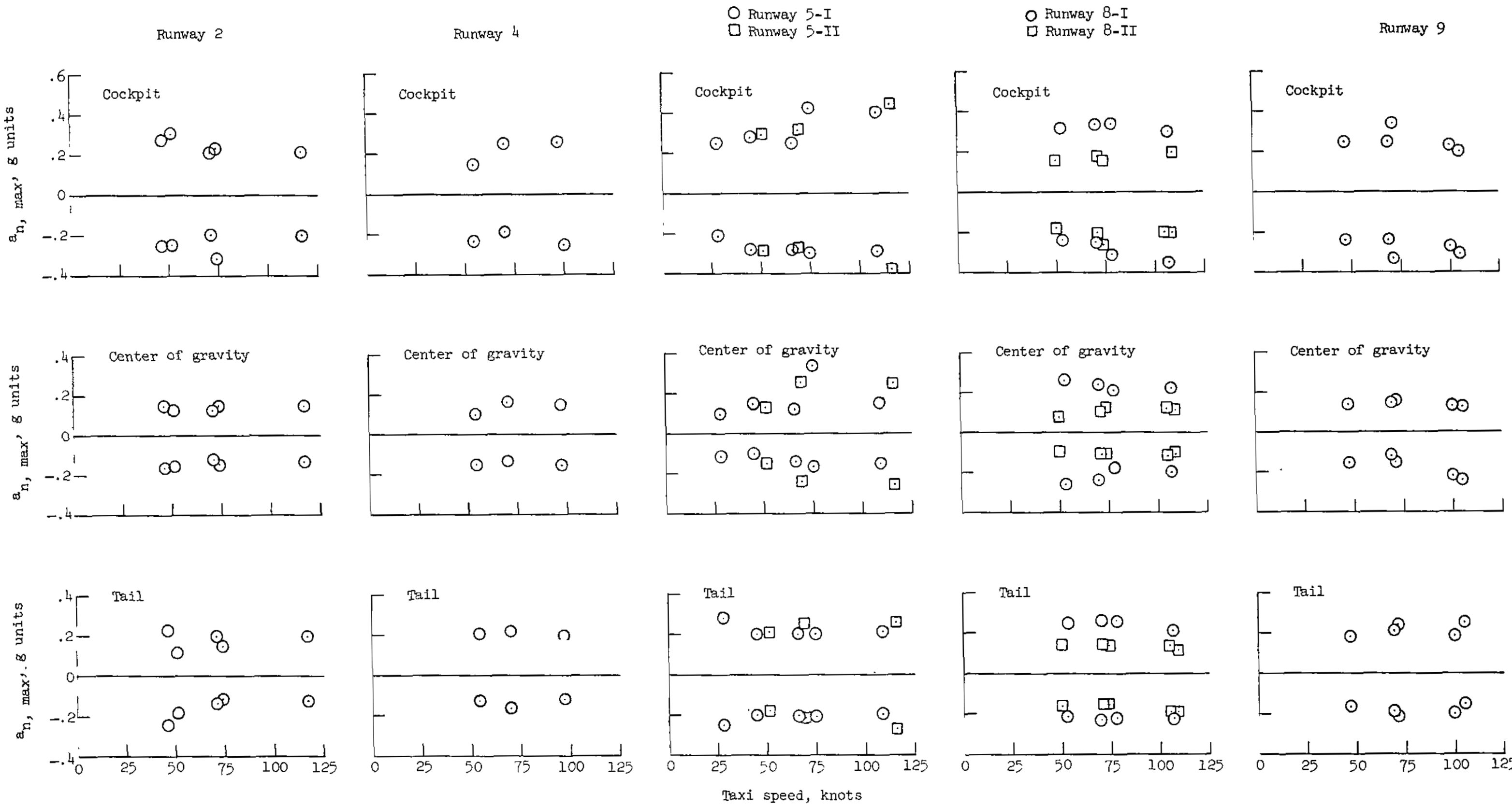
Figure 11.- Concluded.



(a) Heavy bomber.

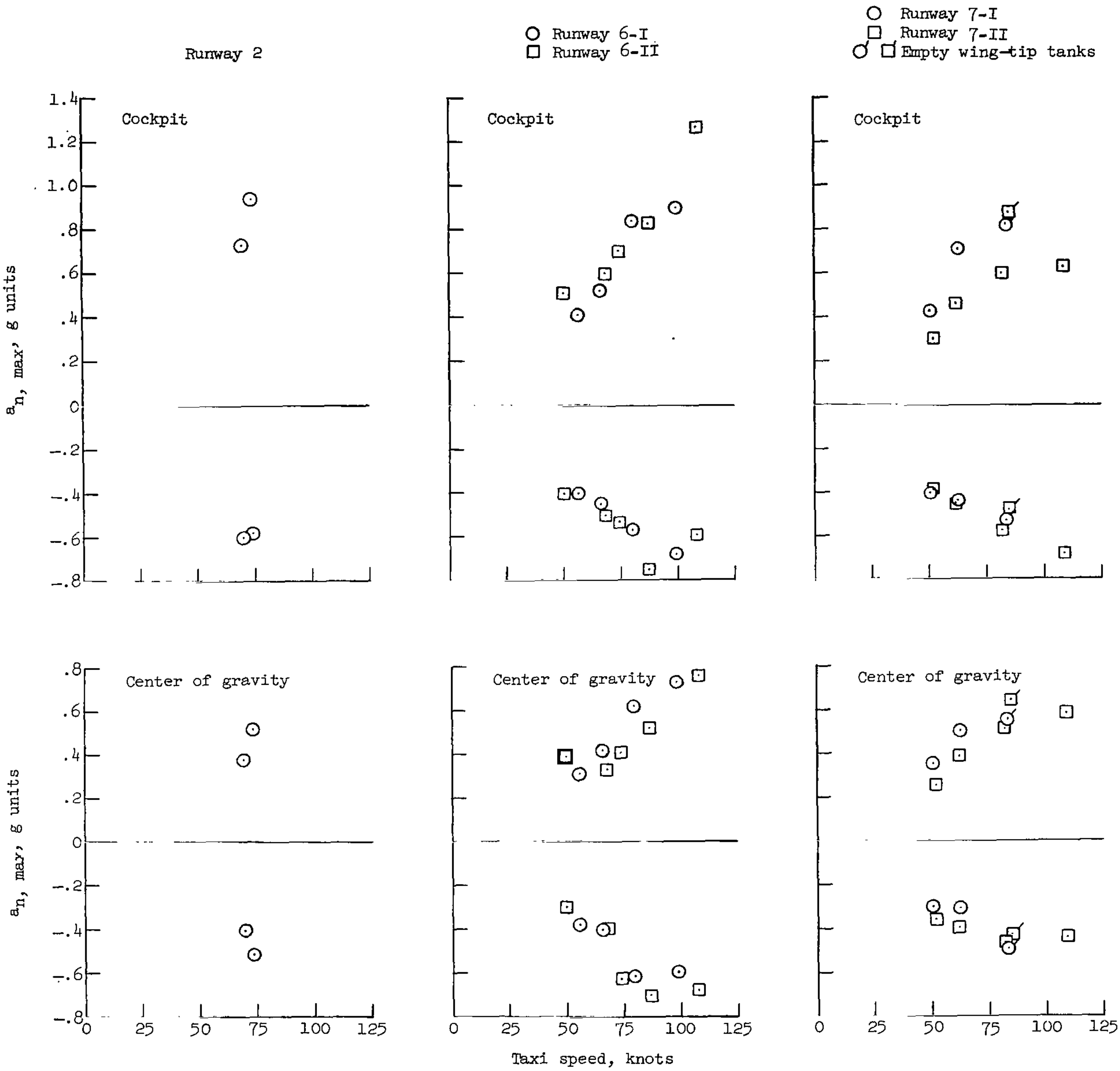
(b) Medium bomber.

Figure 12.- Maximum values of normal-acceleration response of test airplanes for various taxi speeds on various runways.



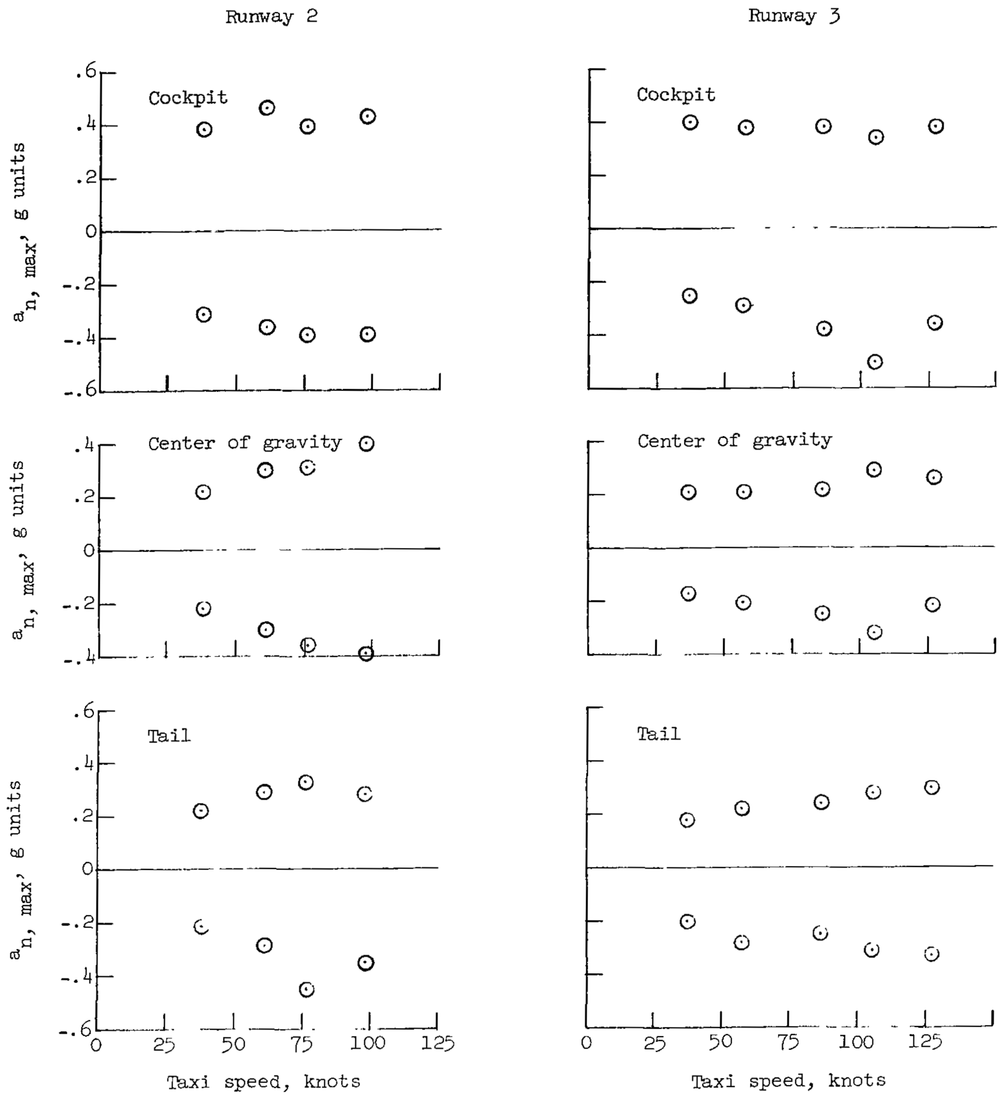
(c) Tanker.

Figure 12.- Continued.

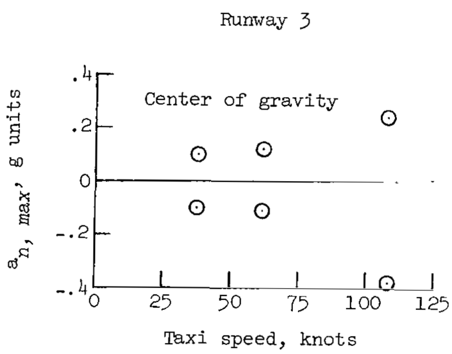


(d) Trainer.

Figure 12.- Continued.

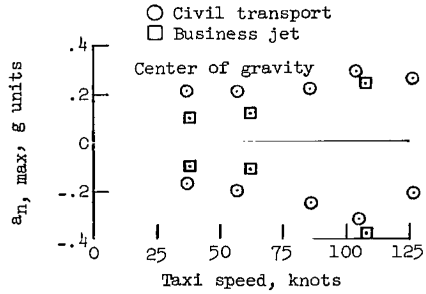


(e) Civil transport.

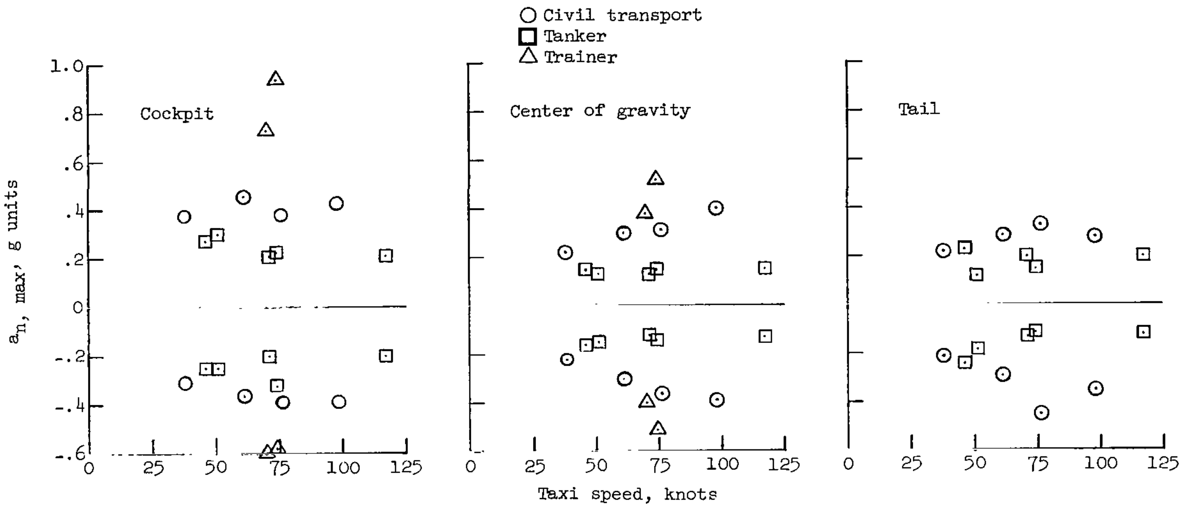


(f) Business jet.

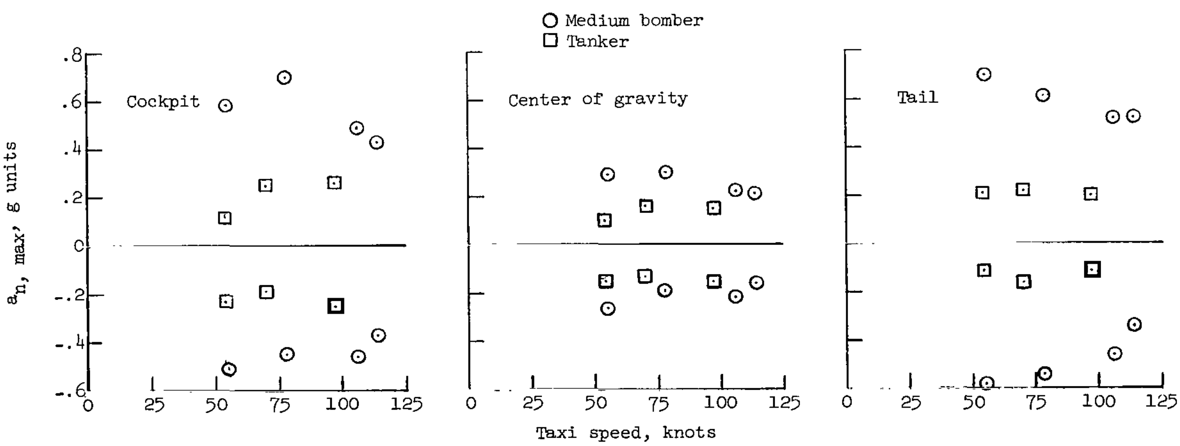
Figure 12.- Concluded.



(a) Runway 3.



(b) Runway 2.



(c) Runway 4.

Figure 13.- Maximum values of normal-acceleration response of several airplanes on the same runways.

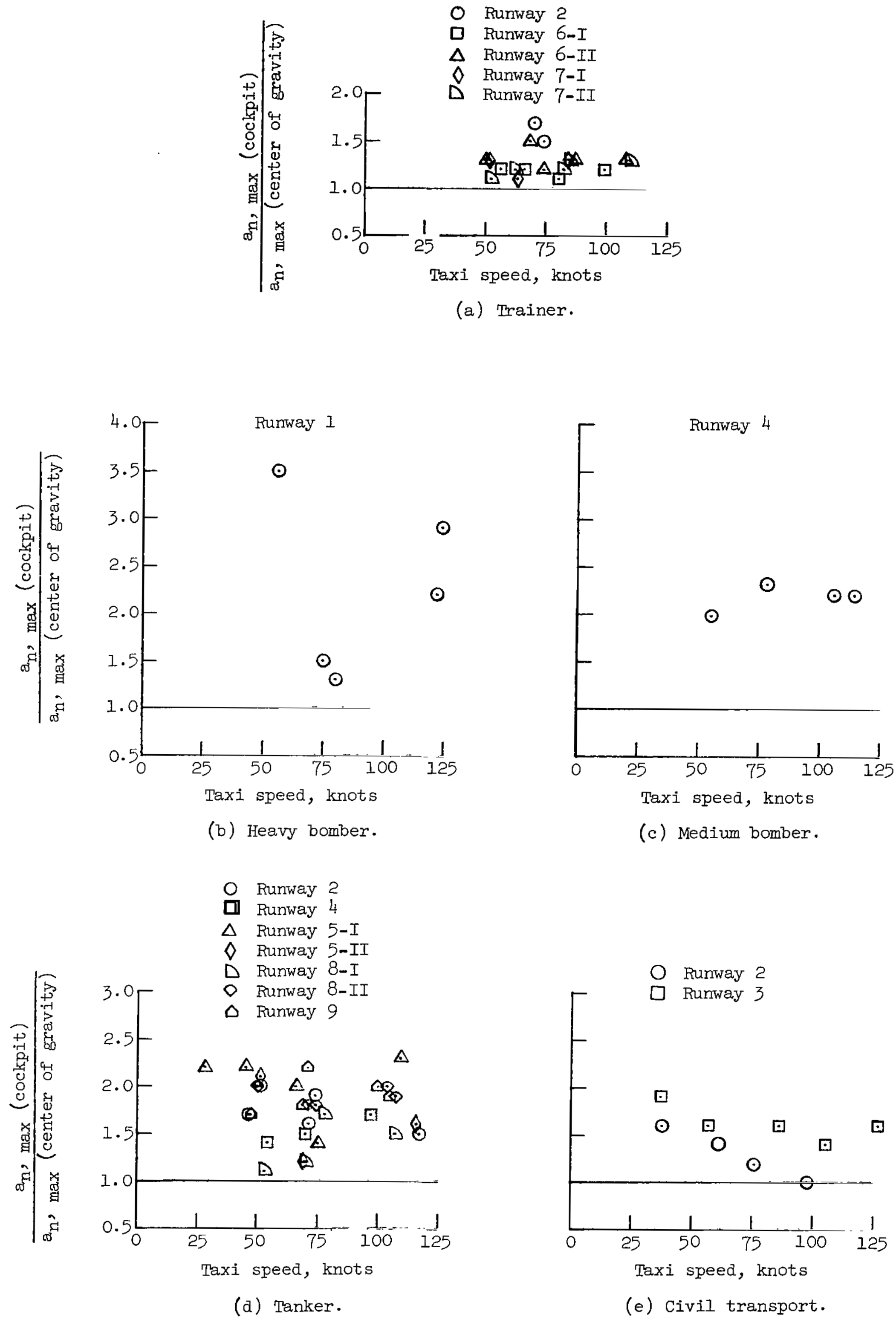
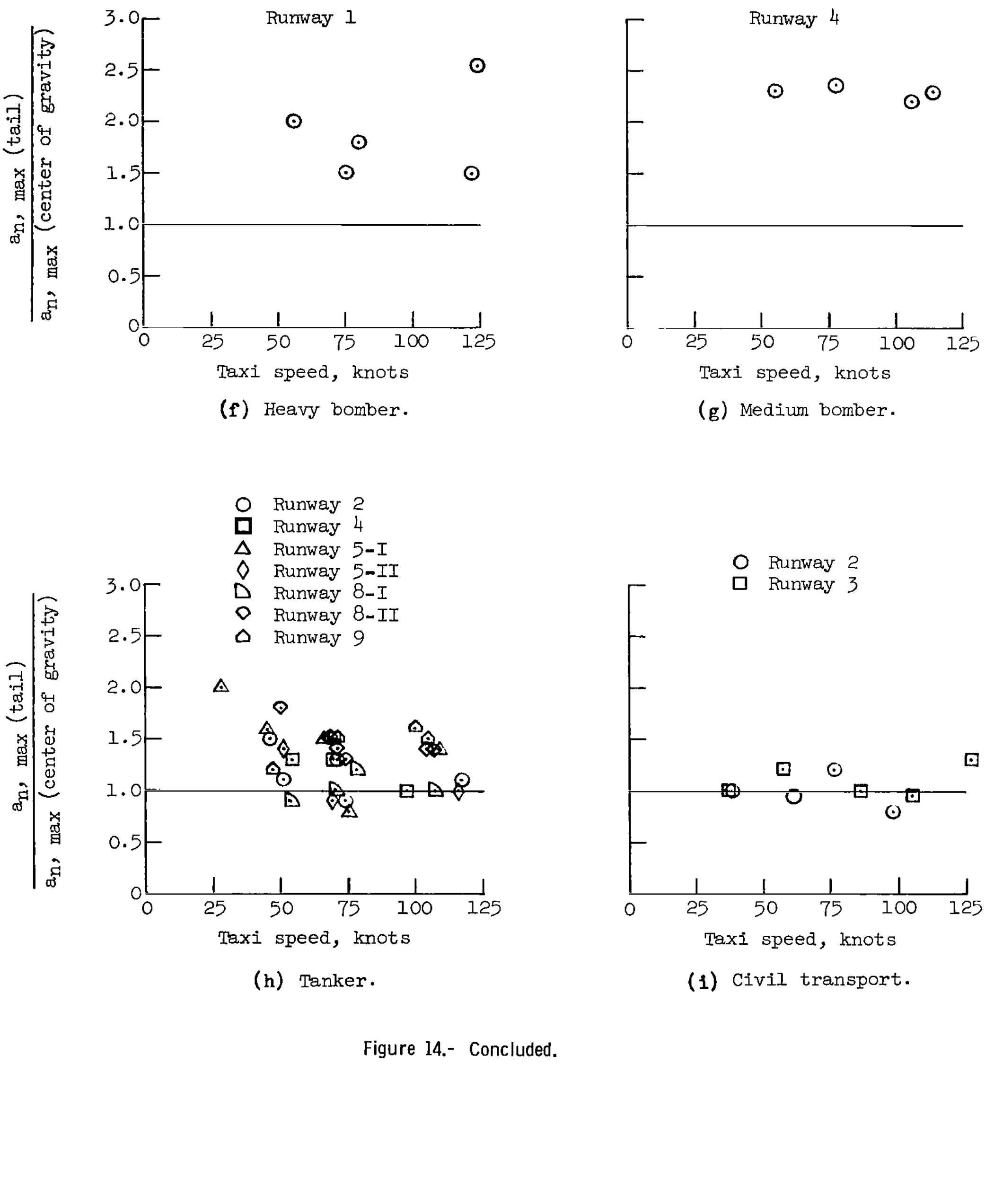


Figure 14.- Ratio of maximum accelerations at different locations of test airplanes.



(f) Heavy bomber.

(g) Medium bomber.

(h) Tanker.

(i) Civil transport.

Figure 14.- Concluded.

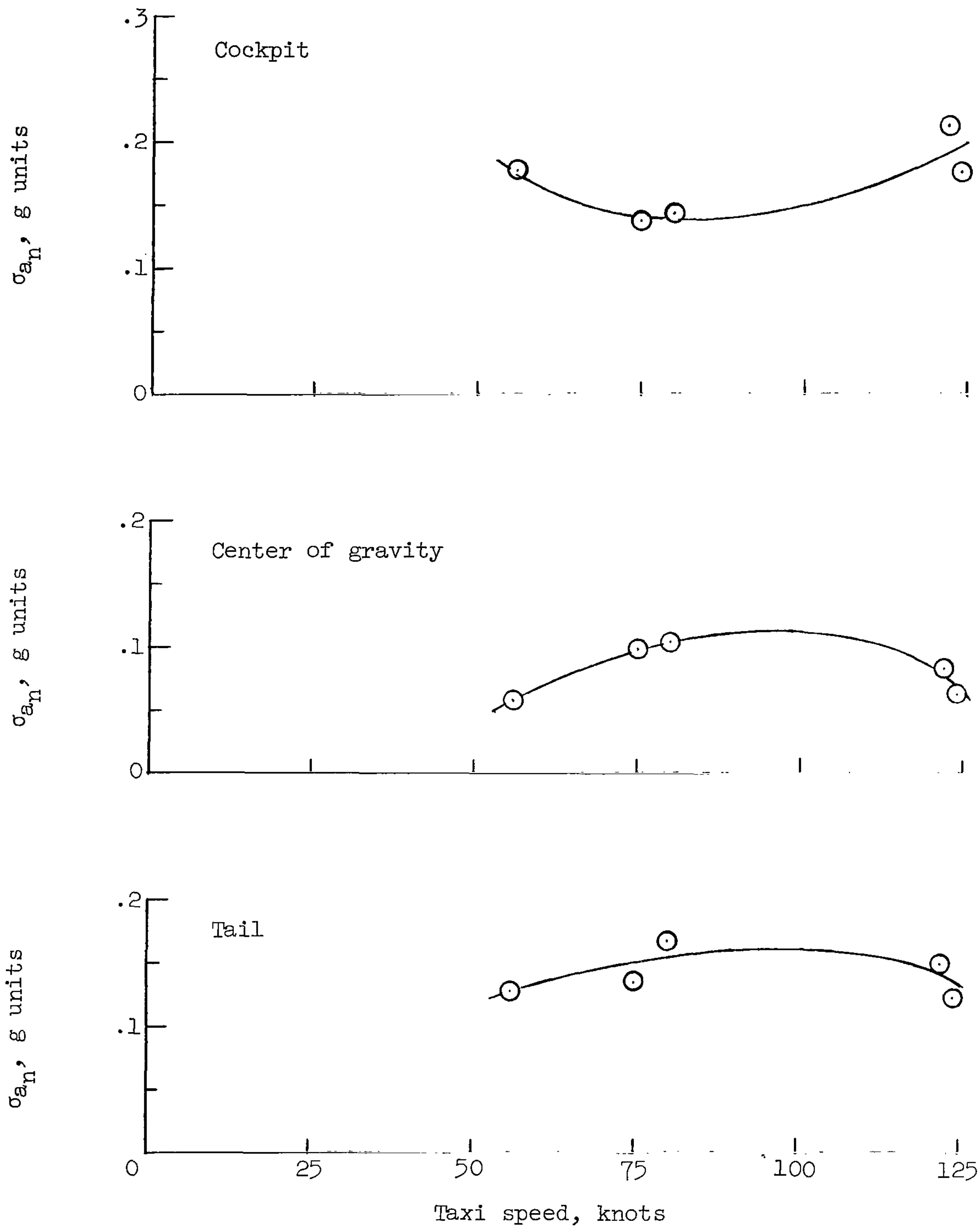


Figure 15.- Root-mean-square values of normal-acceleration response of heavy bomber for various taxiing speeds on section ABC of runway 1.

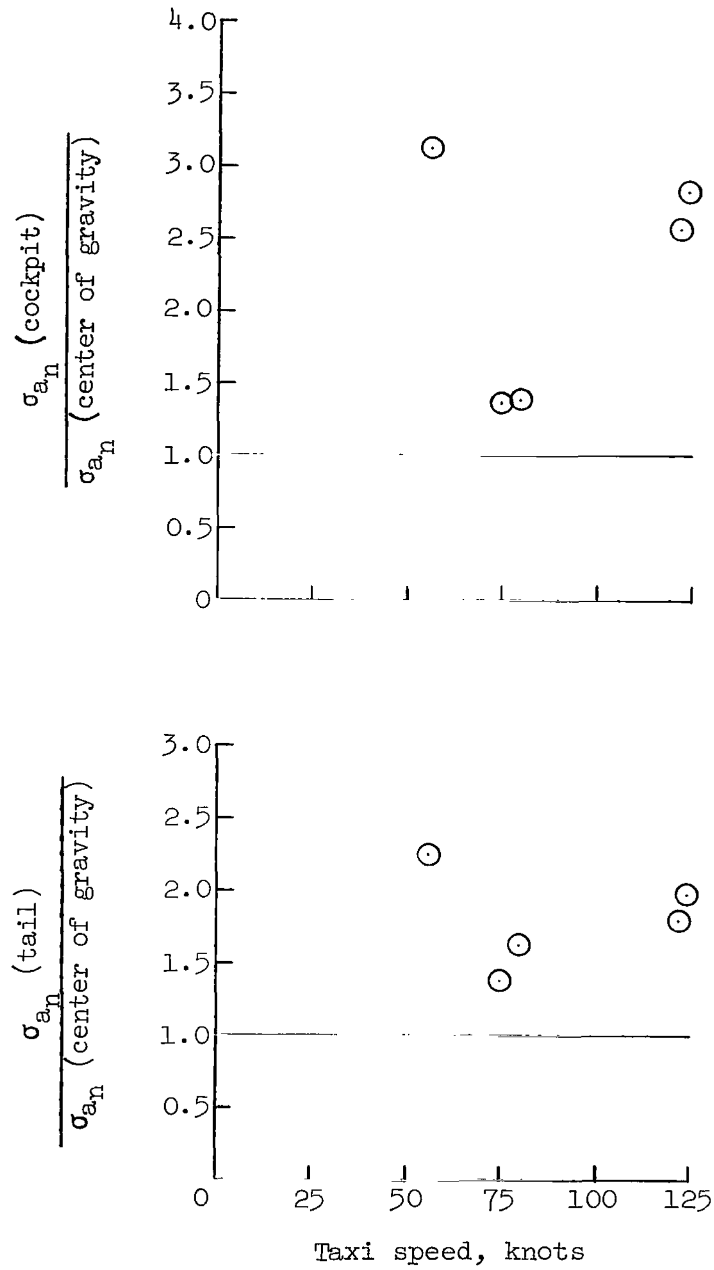


Figure 16.- Ratios of root-mean-square values of normal acceleration at different locations of heavy bomber on section ABC of runway 1.

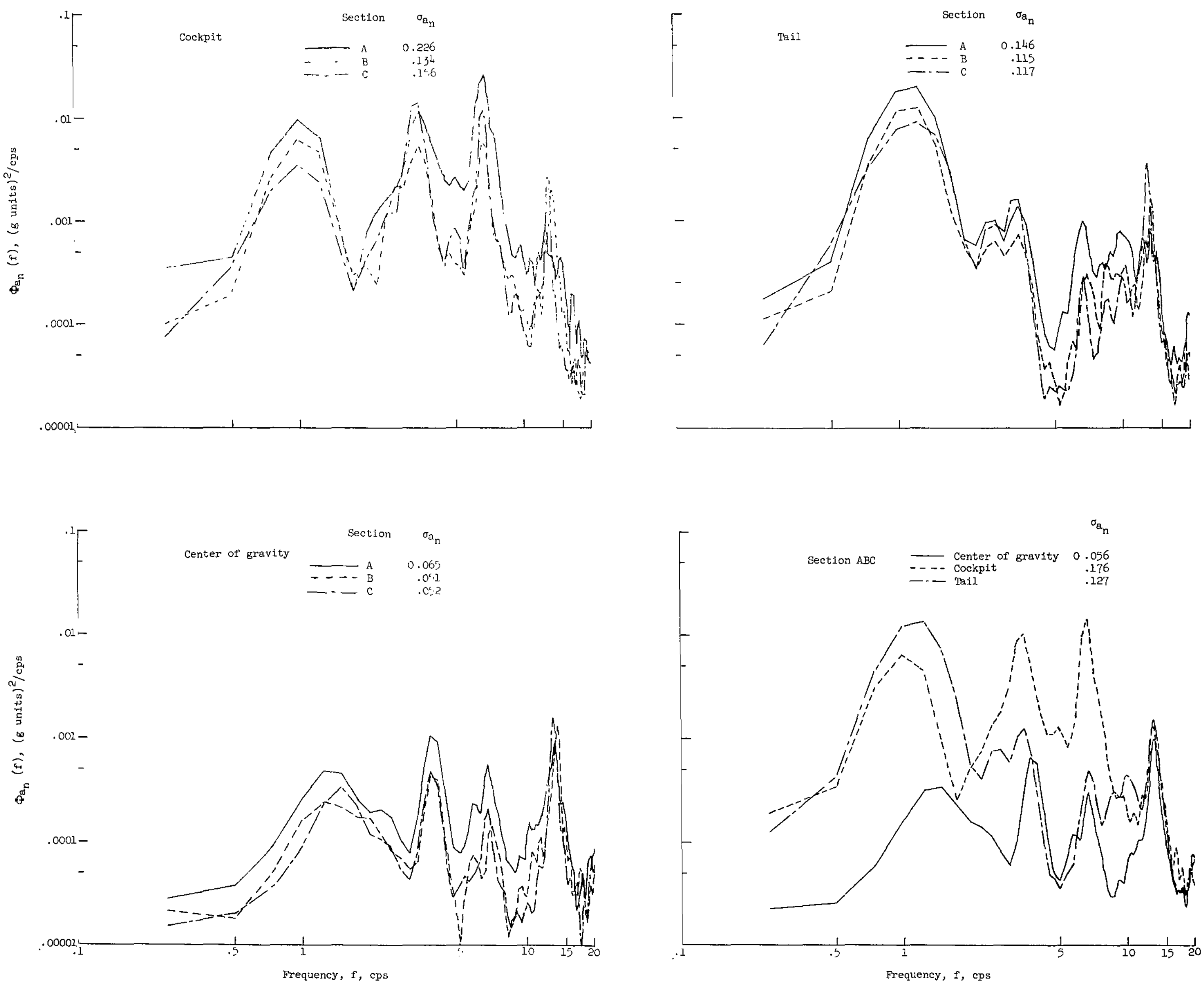


Figure 17.- Power spectral density of normal-acceleration response of a heavy bomber taxiing at 56 knots on different sections of runway 1.

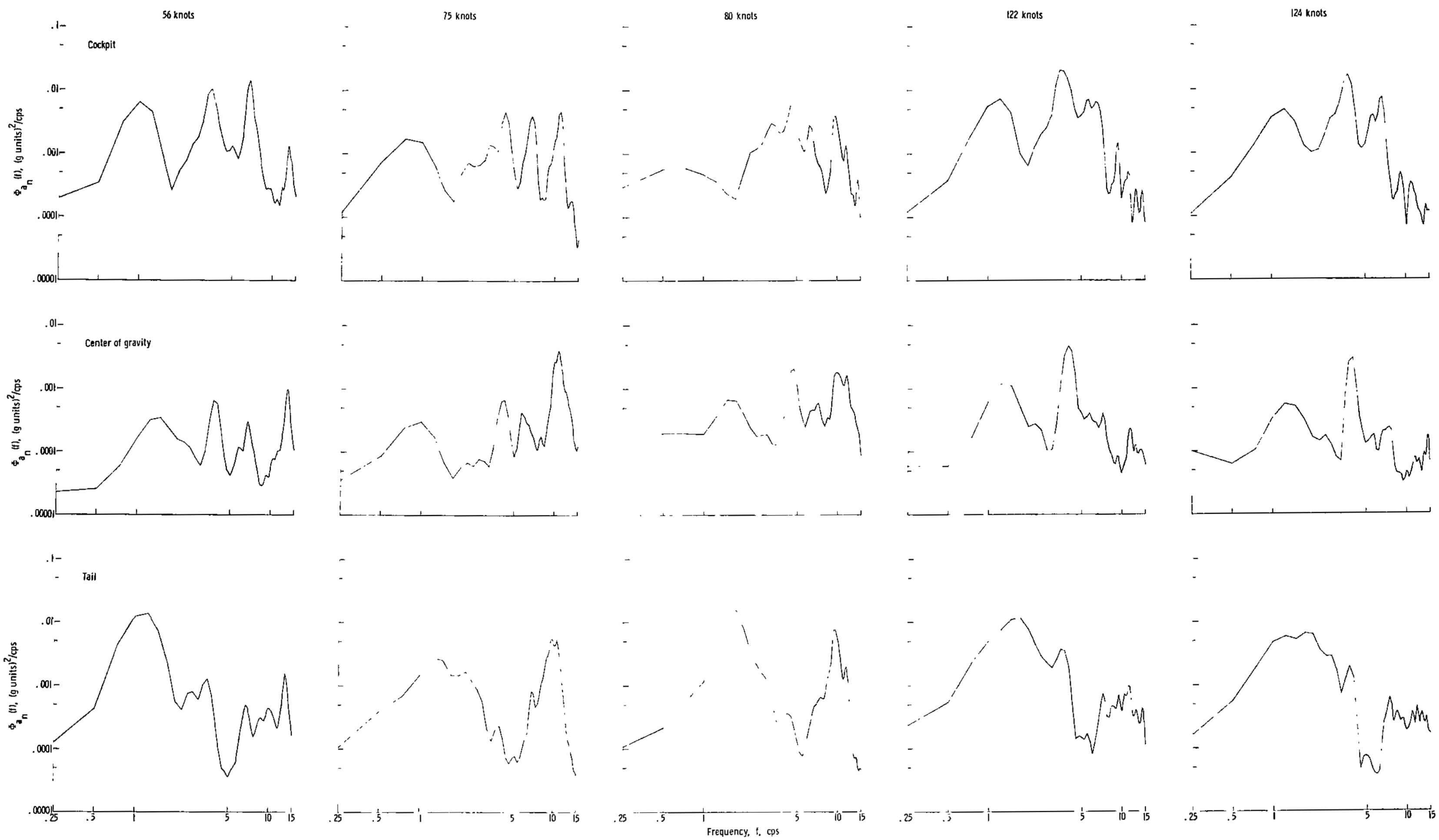


Figure 18.- Power spectral density of normal-acceleration response of heavy bomber taxiing at several speeds on section ABC of runway 1.

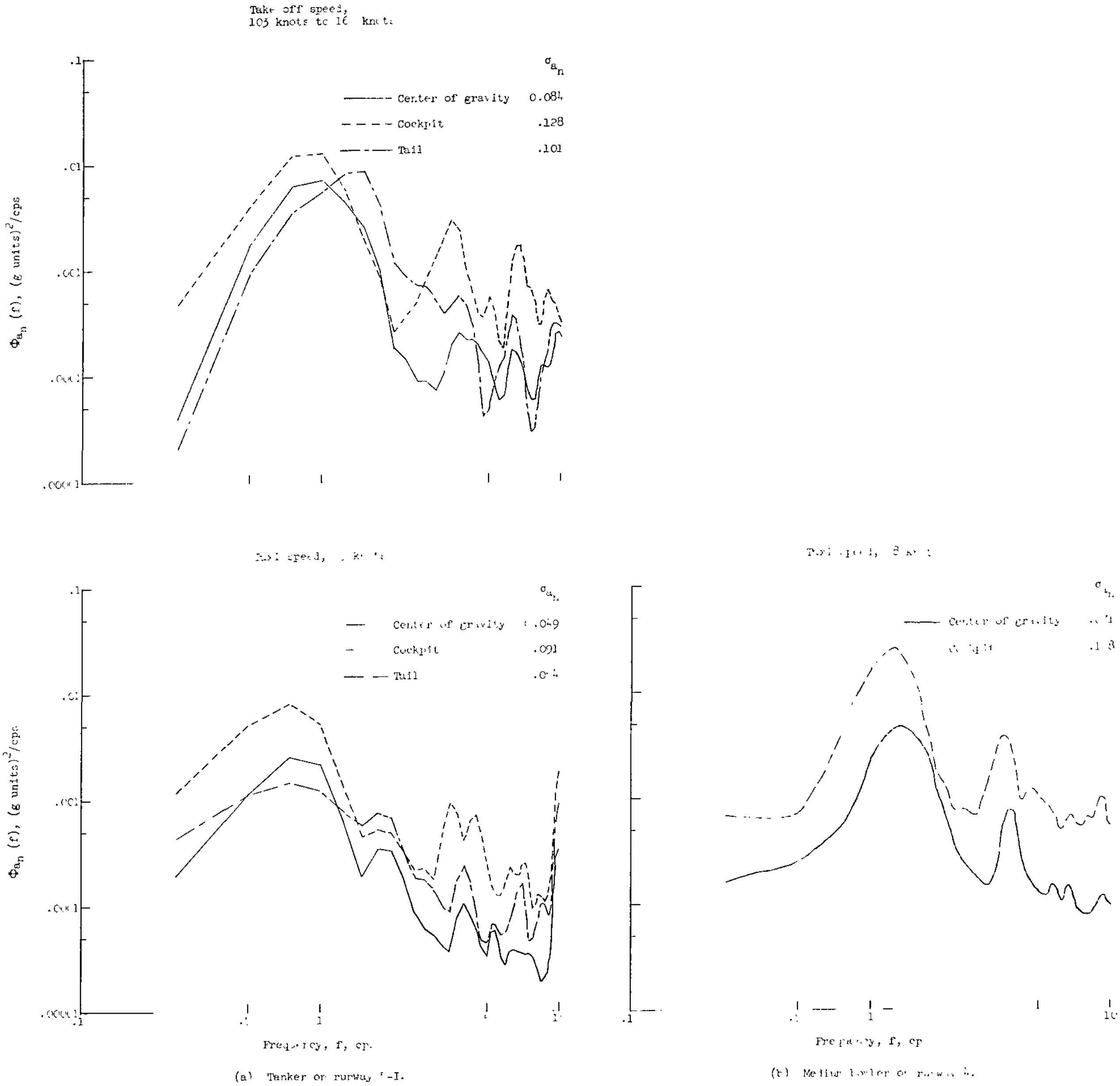


Figure 19.- Power spectral density of normal-acceleration response of a tanker and medium bomber.

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